Preliminary Draft Report

State-of-the-Art Review of Integrated Systems Control in the Steel Industry

by the staff of the

Integrated Industrial Systems Project

June 1975 WP-75-62

This report is a preliminary draft version of the final state-of-the-art report to be issued sometime after the IIASA Conference on integrated systems control in the steel indstry scheduled for 30 June - 2 July 1975. Distribution of this draft version is limited to expected attendees of the forthcoming Conference and to those who have participated in the state-of-the-art survey. The purpose of this document is to encourage feedback of comments, suggestions and supplementary inputs that will be useful in the preparation of the final state-of-the-art report.

PREFACE

This is a preliminary draft version of the report to be issued on the "State-of-the-Art of Integrated Systems Control in the Steel Industry". The draft is incomplete and not necessarily in final form. Its purpose is to provide background material for the IIASA Conference on "Integrated Systems Control in the Steel Industry" scheduled for 30 June to 2 July, 1975. A second purpose is to motivate feedbacks concerning omissions and additions generated by respondents and Conference participants which may be incorporated into the final report.

This report summarizes efforts of the Integrated Industrial Systems Project of IIASA over the period July 1974 to May 1975. The initial phase of the study involved visits by members of the project staff to various steel companies and research institutes around the world in a survey of the advanced state-of-the-art of integrated systems control. The list of companies and research institutes that participated in the survey is included as Appendix 1. We acknowledge with thanks the assistance given us by the many individuals who cooperated in this effort.

Primary responsibility for the contents of this draft report are identified as follows:

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The report preparation was a group effort and all members of the project team provided inputs to each of the chapters. In particular, we acknowledge general inputs and assistance on the parts of B. Mazel and G. Surguchev of the Integrated Industrial Systems Project.

We earnestly solicit your feedback of comments, corrections, suggested changes, etc. that we may utilize in preparing the final report, which we hope to have completed by August, 1975.

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6 June 1975

Chapter 1 INTRODUCTION

1.1 BACKGROUND OF THE PROJECT

There has been a growing tendency in recent years for scientists around the world to conduct multi-disciplinary studies of large scale systems. These studies embrace the whole spectrum of economic, technological, environmental and social factors which characterize the complex problems of advanced industrial societies. In search of ways to cope with these problems, many scientists have turned to the methodological tools of Applied Systems Analysis. An increasingly favorable international political situation has encouraged the hope of using this new approach in a context of supranational scientific collaboration. The International Institute for Applied Systems Analysis (IIASA) was founded in October, 1972 as an expression of this hope.[1]

In early 1973, the IIASA Council proposed a number of broad subject areas of research which might be considered by the new Institute. One of the areas suggested was the automated control of industrial systems. A multinational conference of experts was held on October 1973 to discuss the proposed project area and to come up with specific recommendations of research goals, tasks and guidelines. The results of these discussions were issued as a report;[2] briefly, they may be summarized as follows:

a) There was general agreement that systems analysis applied to industrial systems is an appropriate area for IIASA research in that (i) it was of general interest to most member nations of IIASA, (ii) it was consistent with the stipulations of goals and objectives of the Charter of the Institute, (iii) research tasks could be identified that were reasonable within the constraints of available resources at IIASA, and (iv) there were reasonable expectations

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1. See the brochure, IIASA Background Information for further information concerning the historical background of the Institute, its Charter, general research strategy and initial programs.

2. Proceedings of the IIASA Planning Conference on Automated Control of Industrial Systems, PC-8, Laxenburg, Austria, 1973.

that such efforts would produce useful results.

b) It was recommended that the project be oriented to the problem of systems integration of large-scale and complex industrial enterprises. The underlying motivation here is the achievement of maximum efficiency of production consistent with the various constraints that have to be satisfied (e.g. environment, product quality, etc.).

c) In order to keep the study within manageable bounds, it was suggested that the scope of effort be restricted to the the problems of integration of the information processing and decision-making system (e.g. planning, scheduling, production control functions). In particular, problems of technology, plant design, process control, and the like were to be avoided except where they impinged directly on the problems of integration and coordination (e.g. the interface of process control functions with production control functions, etc.).

d) The multilevel/multilayer hierarchical control approach was proposed as an appropriate conceptual basis on which to structure the system for information processing and decision-making.

e) It was recommended that the project focus on a specific industry in its initial effort in order to avoid the prospect of coming up with highly theoretical and philosophical results which would be of only limited value in practical application. The iron and steel industry was suggested as a first candidate for study, to be followed by a mechanical engineering type system and perhaps a chemical processing type system.

1.2 GENERAL GOALS OF INTEGRATED SYSTEMS CONTROL

The traditional concept of control, in application to industrial process systems, concerns the problem of how to vary certain inputs to the system so that (i) designated output variables are held at fixed values or made to follow predetermined time trajectories or (ii) the state vector of the system is transferred (optimally) from some initial value to a specified final value. However, there has been an increasing tendency to consider control from a broader and more general perspective. Strong contributing factors in this trend are

a) the increasing application of computers in process control, providing the hardware and software means for implementing more sophisticated control concepts, and

b) the growing awareness and acceptance of a "systems approach" in the design and control of industrial process systems.

The objective of Integrated Systems Control, in a very general sense, is to achieve most efficient utilization of resources (e.g. material, energy, environmental, labour, capital) in the production of products satisfying quality specifications and consistent with goals and constraints which may be imposed by society. Thus, Integrated Systems Control is concerned with the broad spectrum of decision-making and control functions (e.g. process control, operations control, scheduling, planing, etc.) which play a role in the effective operation of the system with respect to its production goals.

Performance of the processing system depends on a variety of factors including:

(i) product specifications and process design,

(ii) the nature of resources available and environmental constraints,

(iii) the choice of processing conditions, allocation of resources, scheduling of operating sequences, etc.

Thus, we distinguish two phases of system evolution with respect to information processing and decision-making functions.

a) Design Phase. This phase concerns implementation of overall system objectives through the design of the production means. It is characterized generally by very long time horizons and by high costs for implementation (e.g. analysis and design effort, capital investment). There are a variety of disturbances which affect the design process and hence can stimulate consideration of a design modification or even reinitiation of the design process. These include: major changes in product specifications or quality requirements, technological developments with respect to a new product or a new method of production, equipment failure, major changes in resource availability, and the imposition of a new constraint (e.g. stricter environmental standard, etc.).

Decisions at the design phase tend to be strongly conditioned by subjective and non-quantifiable factors, hence the human traditionally plays a dominant role. Methods and techniques of computer-aided design are becoming increasingly important, however, in coupling the capabilities of the computer (rapid computation, handling of large data bases, fast-time simulation of the consequences of alternative policies, etc.). with the judgement, experience, and intuitive aspects of the design process to which the human designer makes the best contribution.

b) Operating Phase. Here decisions and control actions have to do with determining operating conditions, throughput rates, sequencing of operations, etc. so that product specifications are satisfied along with the constraints imposed by environmental interactions, technological factors, etc. Further considerations may then include the optimization of performance with respect to production efficiency, utilization of resources, etc.

Thus, the decision-making and control functions tend to be:

(i) continuing and repetitive and based on real-time processing of information,

(ii) strongly conditioned by feedbacks which describe the present state of the system and the results of prior operating experiences,

(iii) based on technologically oriented deterministic models which lend themselves to computer-implemented algorithms.

Further, the decision-making processes cover time scales ranging from very short span control operations to long-range planning processes.

The decision-making and control actions are carried out on a system that is evolving in real-time; hence, they must respond to the effects of:

(i) variations in input conditions (e.g. changes in product demand, order sequence, raw material composition),

(ii) time-varying characteristics of processing units (e.g. fouling of heat transfer surfaces),

(iii) changes in the objective function due to economic factors, environmental constraints, etc.

(iv) errors and inadequacies of the models used in determining the decisions and control actions.

We note that the boundary separating the design and operating phases of the evolution of the system may not be sharp and indeed, aspects of long-range planning associated with the operation of the system may well imbed aspects of the design functions, e.g. replacement of a production unit or modification of a process design. Further, there is a strong coupling between plant design and operation, and in order to achieve the maximum overall performance of the system, these interactions and the related trade-off factors must be appropriately considered.

1.3 HIERARCHICAL CONTROL APPROACH

Industrial systems are characteristically large, complex and time-varying; hence the solution of the overall problem considered above is extremely difficult if not infeasible with existing analytical and computational capabilities. Consequently, current practice tends toward empirical and suboptimal solutions to locally defined problems with perhaps only an ad hoc procedure for their integration and coordination.

The multilevel and multilayer hierarchical structuring of the decision-making and control system was considered as the basic approach to handling the overall problem. The approach embodies the following features:

a) The complex system is decomposed into a number of coupled subsystems, each with its own decision-making and control functions based on local criteria and on local information sets. Because of subsystem interactions, it is necessary to coordinate the objectives/actions of the local controllers to make them consistent with overall system objectives and constraints.

b) The overall system decision-making and control problem is decomposed into a set of subproblems, each with its own objective function, model, constraint set, etc. These subproblems are generally distinguished with respect to time scale (e.g. planning, scheduling and control functions). Since the subproblems essentially interact, e.g. the solution of the planning problem affects the scheduling problem, integration of the subproblems is necessary to ensure satisfaction of objectives and constraints associated with the overall system.

c) The complex system relationships are approximated by simplified and aggregated models corresponding to each stage and level of decision-making. This is necessary in consideration of the costs associated with model development, on-line computations, etc. Further, since industrial systems are characteristically time-varying (aging of components, etc.), subject to a variety of continually varying inputs, and also subject to more or less frequent contingency occurrences (e.g. equipment breakdown, emergency order), the incorporation of means for on-line updating of the models through feedback of relevant data and experience indicators is an essential feature of the information system.

1.4 SCOPE OF THE CURRENT STUDY AND MODE OF OPERATIONS

The steelmaking industry was selected as the first system for a case study of the integrated systems approach. There were several reasons for this choice. First, steel is a basic industry and of direct interest to most of the countries supporting IIASA. Second, it is a very complex industry with a wide variety of different types of processing and manufacturing facilities and hence, rich in the broad spectrum of systems problems likely to be encountered in industrial applications. Third, and most important, the steel industry represents, at the present time, perhaps the most advanced area of technology with respect to the application of an integrated systems approach and in the application of computers for real-time information processing and decision-making. Thus, it was felt that the steel industry provided a good base to start our investigation.

Having settled on steel-making, the next step was to carry out a "state-of-the-art" survey based on information in the literature, plant visits and dicussions with various experts in the field. Among the objectives of the survey were:

(i) determining the "leading edge" of current planning, scheduling, and production control functions and their integration as practiced in advanced steel works around the world,

(ii) identifying problem areas and limitations inherent in current practices, and

(iii) identifying people and information sources (e.g. simulation models) which may be useful in the further development of the project.

The results of the survey are presented in this draft report of the state-of-the-art. Its primary purpose is to provide a background of source material for the discussions planned for the forthcoming IIASA Conference scheduled for 30 June - 2 July 1975. A final report on the "State-of-the-Art of Integrated Systems Control in the Steel Industry" will be issued after the Conference and will incorporate any revisions and additions that are motivated by this draft document as well as those generated through the Conference.

As implied earlier, the primary purpose of the survey was to identify what are the most advanced practices in planning, scheduling, and production control , and how these are implemented and coordinated to achieve systems integration. In particular, the results contained in this draft report are not concerned with the cataloguing of the current state of these practices according to company, country or society; hence, there is no attempt to identify who is doing what, except as the identification may be relevant to the discussion at hand. Also, the report avoids discussion of specific hardware used in the various advanced systems referred to, or of the technological models, scheduling algorithms, process control functions and related details - these are all very important factors that enter into the ultimate realization of a working system; however, they were considered (for various practical reasons) to be outside the scope of the present study.

Besides describing the results of the state-of-the-art survey, and providing an interpretation of our observations, this report presents a formalization of the multilevel/multilayer hierarchical control approach oriented to the problem of integration of complex industrial systems. The approach reflects a number of modifications of the hierarchical structuring of the decision-making and control system, motivated by some of the experiences gained from the steel study.

The objective, ultimately, is to develop a conceptual framework for design of integrated control of industrial systems which will lead to the formulation of general guidelines applicable to a broad class of industrial systems. The results of the steel industry study will provide the initial background experience for assessing the effectiveness (and limitations) of the proposed hierarchical approach. Further case studies based on a mechanical engineering type system (e.g. discrete manufacturing) and finally, perhaps a chemical processing system should then broaden the base upon which the general guidelines are validated.

1.5 ORGANIZATION OF THE REPORT

Following this introductory chapter, a general review of advanced practice of integrated systems control in the steel industry is presented in Chapter 2. This chapter emphasizes the descriptive aspects of the state-of-the-art survey, organized according to the planning, scheduling and operations levels of the decision-making hierarchy.

Chapter 3 provides some generalizations and interpretive aspects of various experiences gleaned from the steel study, e.g. a discussion of motivating factors for steel works integration, and summarizes the salient features of the observations described in the preceding chapter.

Chapter 4 attempts to develop some of the basic concepts and analytical tools that will be useful in the formulation of general guidelines for integrated control of industrial systems. Specific focus of the chapter is on the multilevel/multilayer hierarchical control approach which is illustrated through references to various examples taken from steelmaking practice.

The final chapter presents conclusions and a summary of results. This chapter is incomplete and is to be augmented by the results of the conference discussions.[1] Among the topics to be included are: limitations of current theories and approach, directions for future development of integration and computerization in the steelmaking industry, identification of some common themes, general guidelines, and recommendations for further study.

1. IIASA Conference on "Integrated Systems Control in the Steel Industry" scheduled for 30 June - 2 July, 1975.

CHAPTER 2. A REVIEW OF INDUSTRIAL SYSTEMS CONTROL IN THE STEEL INDUSTRY

2.1. INTRODUCTION

A modern integrated steel works represent an extremely large capital investment, a plant with an annual capacity of 5 million tons of steel could cost about $ 5.000 million if built from scratch at 1974 prices.

The number of people invoved in such a plant greatly depends on the capacity of the technological equipment, its organizational structure, the level of automation of the production processes, and the level of computerization of the management information processes.

In some steel works, the productivity per employee reaches 750-800 tons of steel per year, in others it is only about 200-300 tons. There is a tendency to use equipment of increasingly high capacity. Thus, in 1960, blast furnaces of 10 m hearth diameter and a capacity of some 1,2 m tons/year were installed for the production of hot metal. Nowadays, blast furnaces with hearth diameters of 14 m and capacities of over 3 m tons/year are being constructed. In 1962, oxygen-blown furnaces of some 150 tons capacity were used for the production of crude steel. At present, oxygen-blown furnaces for heat weights of over 400 tons are in operation. In 1960 the transformer rating of electric arc furnaces averaged some 350 kVA/ton. Now, electric arc furnaces with transformer ratings of over 600 kVA/ton are in operation.

The capacity of rolling mills has greatly increased due to the use of higher rolling speeds, (up to 60 m/sec for the wirerod mills and up to 35 m/sec for strip mills), use of larger weight ingots, slabs, blooms and also the billets. There has also been a trend toward increasing the capability of steel works (up to 20-30 million tons annually).

Many other industries which rely on the use of steel in some shape or form, e.g. for buildings, plant, equipment, machinery, tools and transportation may be located near the steel works. Thus, in many cases the steel works become a center of the industrialized region with populations ranging from 50 thousand to several hundred thousand.

Living conditions in the communities located in this area depend very much on the kind of pollution control exercised by the steel works and other industries of the region. The effectiveness of this control also influences the geographical location of the settlements and their investment costs.

In some countries, all steel-making plants are nationalized and all the normal business functions relating to running such plants are carried out in strict accordance with government policy. These countries have a national plan embracing all manufacturing industries and the types and quantities of steel required over a specified period are stated as part of the plan.

At the other extreme, some steel companies are financed completely by private capital and are run as profit motivated businesses. Such steel companies, in what can be described as "market oriented" economics, must take their own estimates of the steel demand and plan their capacity and operations accordingly. In these situations there are normally competing companies and so the problem of estimating demand is further complicated by the need to decide what share of the potential market is realistic to assume can be captured.

Plans

It is commonplace to hear the word "planning" used to describe a wide variety of activities, each with different objectives, relating to different time scales and involving different degrees of detail. The word "plan" often refers to a statement of intentions based on, and conditional upon, a given set of assumptions. The longer the time-scale involved and the larger the number of factors that have been predicted or forecast, the higher is the chance that the plan will be modified before implementation.

Objectives

Planning objectives themselves vary a great deal depending on purpose. Some are general policy decisions and some are basically targets which are usually employed in sales situations or simple manufacturing activities where speed of working does not affect quality and time is a critical resource.

In the context of this report the majority of plans are, as previously mentioned, statements of intent and as such the objective is to ensure that all factions of an enterprise know what to expect at what time and what actions to take. It provides the guidelines necessary to help lower level decision-makers to take actions consistent with overall goals. The level of detail can range from extremely fine to very general, again depending on the situation and purpose.

Plant Loading

Production planning on an annual time scale is usually based completely on a forecast of demand. By the time quartely production planning takes place it is likely that some, but by no means all, orders are known. Plant loading is the allocation of demand to production units for processing during some specified period, which could be a month or a week, for example. Loading can be undertaken using a forecast of orders but, in general, the receipt of an order initiates the loading activity.

The final result of the plant loading is a detailed production plan,i.e. statement of all the items to be processed at a given department or shop, e.g. a rolling mill, during a given production period.

Scheduling

The production plan is divided into parts corresponding to shorter time intervals, e.g. a week or a day. The plant loading is transformed into a definite list of items in the processing sequence, considering the time required for each operation, the capacities of equipment, order due dates, etc. This becomes the production schedule which is the key document for coordinating activities at the operations control level.

In compiling the production schedule, the technological constraints are to be considered. For instance, the hot strip mill operation gives rise to constraints which considerably limit the sequencing choices. On top of this, constraints due to the relative urgency of order items and constraints dictated by the needs of adjacent processes severely limit the options. Occasions frequently occur when the problem is not one of simply selecting the "best" of a number of feasible solutions but rather one of knowing which rules to bend and which constraints to relax so as to get a feasible solution at all. This can still be called the "best" feasible solution!

2.2 THE PLANNING HIERARCHY

Timing is one of the critical parameters of planning, loading and scheduling. In many ways, progress from the longest term planning through to detailed production scheduling can be thought of as a continuous process in which the degree of detail that it is both practical and sensible to work in, increases as the period covered shortens. Since at any particular stage there is a limit to the reliability of data and to the amount of detail available, there is little point in producing plans or schedules in any more detail than the accuracy of the input data permits.

This conceptually continuous spectrum of planning is divided into definite manageable stages of discrete planning horizons in a formalization of the whole planning procedure. Plans are developed from one time horizon to the next when either the timing, the availability of further information or the occurrence of events demands that further plans be determined. Below are given planning horizons most frequently found in the companies visited, and Figure 2.1 illustrates the main relationships involved in the planning, scheduling and handling of orders.

The long term, medium term and annual planning are based mostly on forecasts. This planning considers the company's available resources and is performed by the company's head office. Only the detailed planning based on received orders is done by the steel works.

a) Long Term Planning

The long term plan usually covers a time horizon of 10 to 20 years. It is of necessity almost completely based on forecasts and is intended to guide thinking concerning the general direction of a company's policy. Where it is prudent to make long term contracts for, say, raw materials or to accept long term order commitments, these become constraints in the years to come. Only time can tell whether these were good or bad commitments. A complete new integrated steelworks can take from 5 to 8 years to design and to build up to working capacity, as such the decision to invest on this scale must be taken in the context of long term planning.

b) Medium Term Planning

The medium term plan usually covers a period of from 1 to 5 years. Over this type of time horizon the major changes in productive capacity are known and so the emphasis is on making profitable use of the known capacity. Effective capacity can be adjusted within certain limits by working more or less shifts and some units can be shut down for a period (a virtue can be made out of this situation by devoting the "unwanted" to major maintenance

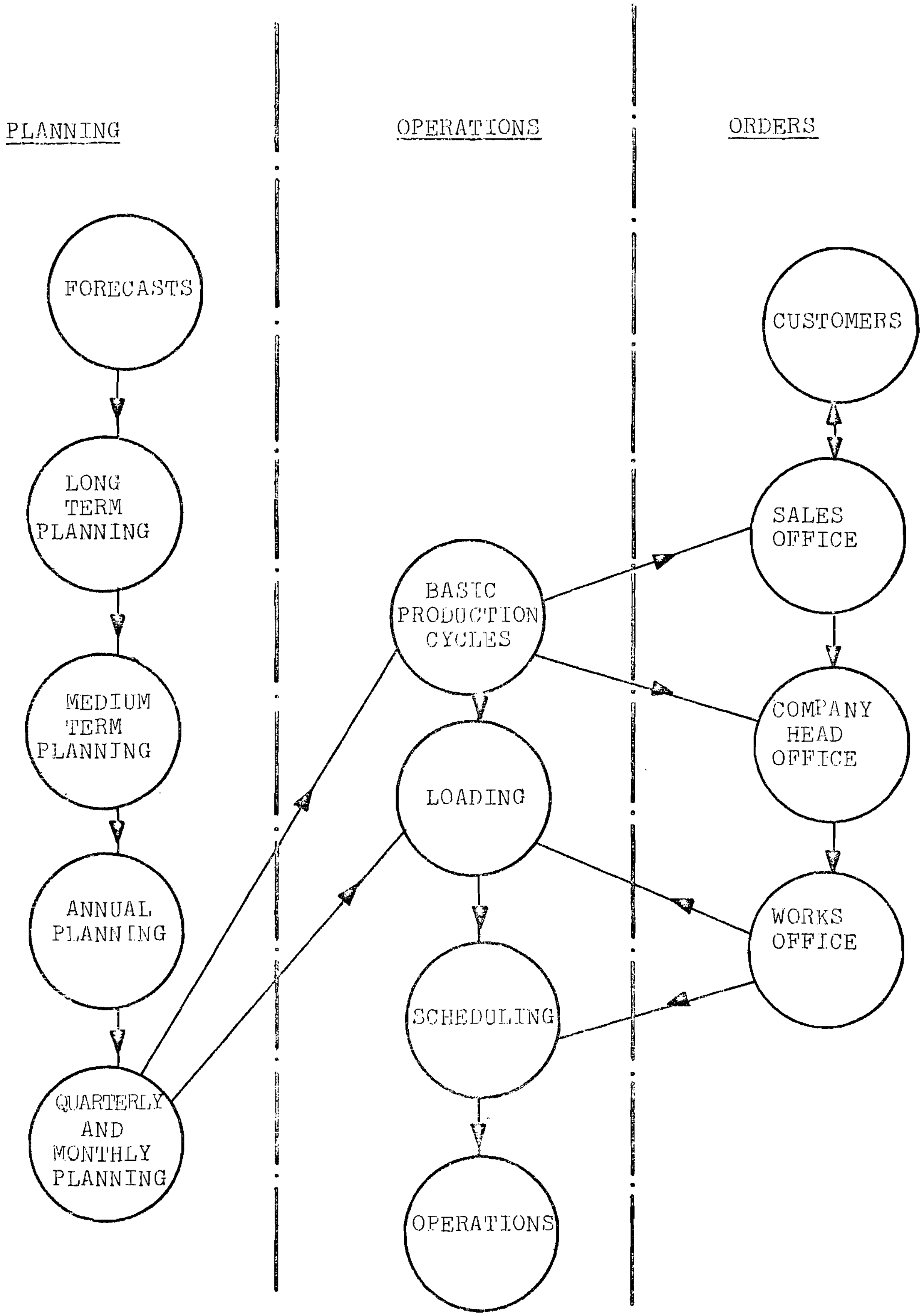


FIG. 2.1 MAIN PLANNING, SCHEDULING AND ORDER PROCESSING RELATIONSHIPS

activities). In general, it is the product demand that is the major unknown, followed closely by the costs of raw materials, labour, etc., and the price that can be realised for finished products. Both long and medium term plannings can be considered as strategic.

c) Annual Planning

Planning for "next year" often seems to be the turning point between strategic and tactical planning. There are still a number of unknowns but annual contracts must be negotiated and the lead time for recruiting labour, planning major maintenance operations, etc. is a few months. In practice, therefore, the most detailed planning seems to start on the annual basis. Much attention is paid to costs, productivity levels, sales forecasts or annual production allotments, etc. and as a result, the year is mapped out in terms of raw material purchases, expected production requirements, production capacity, budgets, personnel requirements, etc.
Annual plans are frequently broken down into 4 quarters at this stage and sometimes into months.

d) Quarterly Planning

Quarterly planning is usually the first step in turning a basically predicted plan into one based on real production demands. It also represents an opportunity for adjusting any details of the annual plan which must be modified in the light of changing circumstances. Otherwise, apart from perhaps including some production loading, the form and purpose of the quarterly plan is much the same as the annual plan.

e) Monthly Planning

At the monthly planning stage, production planning, especially order processing and plant loading, begins in earnest and to a large extent everything is based on actual orders. Schedules as such i.e. detailed item sequences, are not normally started at this time scale although there are exceptions.

f) One Week or 10 Day Scheduling

Breaking the monthly plan into the shorter time assignments leads to the production schedule. The majority of companies produce schedules on a weekly basis since a high percentage of the orders are definite and realistic scheduling can be undertaken. In some steel works with computerized control systems, a 10 day base for scheduling is used instead of 7 days because of increased confidence in performance to specifications. Some indications of a daily breakdown is often shown in conjunction with the weekly or 10 days schedule. Again there is the opportunity to adjust previously laid plans if actual events warrant some change.

g) Daily and Shift Scheduling

The daily schedule is usually an updated version of the weekly plan with any changes or adjustments effected which may have been caused by an earlier failure to keep to schedule or by the hurried rescheduling of urgent items. The division of the daily schedule into shift schedules is rarely explicit. Each shift makes as much progress as it can and the next shift takes over according to time.

2.3 LONG TERM PLANNING

The management of any business concern must face up to it's objectives and determine it's basic policies.

The freedom of choice of the objectives is usually broader for a private company than for nationalized ventures. The private company is also likely to have grown and developed from small beginnings and it's objectives may have been modified on several occasions especially as each major development decision was faced. Nationalized industries on the other hand are likely to start life as vast concerns comprising a heterogeneous collection of existing ventures. Some act of a parliament or government law etc. may well define all the relevant guidelines and management's task is to run the concern satisfactorily within these guidelines.

The main end product of this stage is clearly a set of statements, covering all aspects of a company's activities, e.g. products, plant, equipment, supplies, personnel, finance, marketing, development, research, social policy, etc.

Private and nationalized concerns must be considered separately. All the nationalized concerns visited have some form of government bill, charter of law which spells out the purpose, objectives and constraints. Many of the statements are of a political nature and phrases of the type: "meeting the country's demand at minimum cost" and "all developments must be considered in the light of their sociological and environmental consequences" are commonplace.

Private companies were very reticent to talk about their own formal strategic policy documents and certainly unhappy about divulging the contents to anybody outside the company. But it is clear that many reviewed their long term strategies in some depth on an annual basis - this is opposed to specific long term planning.

Although data may be hard to come by and many factors defy scientific analysis, companies do use models for building up costs, cash flows, and discounting. One complete commercial, financial plus production model was located which was used to test out the validity of a new venture under many different scenarios. Factors such as product mix, costs, prices, equipment configuration were all "flexed" and although the model itself contained no optimizing mechanisms, the man-computer interplay was instrumental in arriving at a robust solution.

It is interesting to note that the comprehensive model referred to above was used <u>only</u> during the strategy formulation stage and has not been used at all since. The company employs extensive models for long term and shorter term planning but these are tailor made for each task. The main difference between the strategic and long term models are:-

a) The strategic model was built to include extensive facilities for varying all parameters over wide ranges. Such facilities are not needed to the same extent for long term planning.

b) The product groupings, cost structure and the description of production facilities were all needed to different degrees of detail in the two models. For example, the products to be made at the new plant were completely flexible in the strategic model but "limited" in the long range model by existing and planned plant configurations.

Many companies do not make a firm division between this strategy stage and long term planning and it can be argued that any such division is artificial or forced. Enough cases exist, however where the difference is clear to justify a separate classification in this review.

By far the majority of companies visited considered long term planning to cover a 10 year period. Some claimed to consider later years but not as a formal extension of the 10 year plans. A common view was that if any discounted financial appraisals were undertaken, the years in excess of 10 made a minimal contribution to present value.

The long term planning horizon is closely connected with the capital plant depreciation period. The two periods commonly are 10 or 15 years, with the former sometimes favoured even by those actually using the latter. Arguments for using the shorter period are often based on a fear that the company may find it difficult to adapt to new processes and technologies if too high a capital value is placed on existing plant.

Long term planning is a complex process and less easily structured compared to a very short term planning operation. With so many unknowns and every facit seen as dependent on another, or at least strongly interactive with others, there is not an absolute starting point.

Figure 2.2 shows an attempt to provide a workable structure and dependence tree. It is a gross simplification and, in practice, many feedback loops exist inside the main loop as shown and many less formal links exist. For example, the sales plan will be initially drawn up with a very good idea of what production capabilities, both type and quality, will or could exist over the period and devisors of the plant development plan will know within reasonable limits the amount of capital which the company would be able to invest in new plants.

Forecasting Economic Growth

The demand for steel arises out of many activities, e.g. capital projects such as new buildings and bridges; consumer goods such as motor cars and washing machines; and disposable items like cans and paper clips. A country's economic position will influence the demand for such different classes of steel products and any attempt to make demand forecasts for a steel company would be well advised to take a view of the economic situation over the period in question.

This is in fact done by a number of steel companies, as often as not in conjunction with other bodies such as government departments and universities. Models do exist which, while certainly not perfect, do go a long way in helping to form a reasoned view. The fact that no details were made available together with an obvious satisfaction with the contribution made, suggests that such models are not the full answer but are well worthwhile.

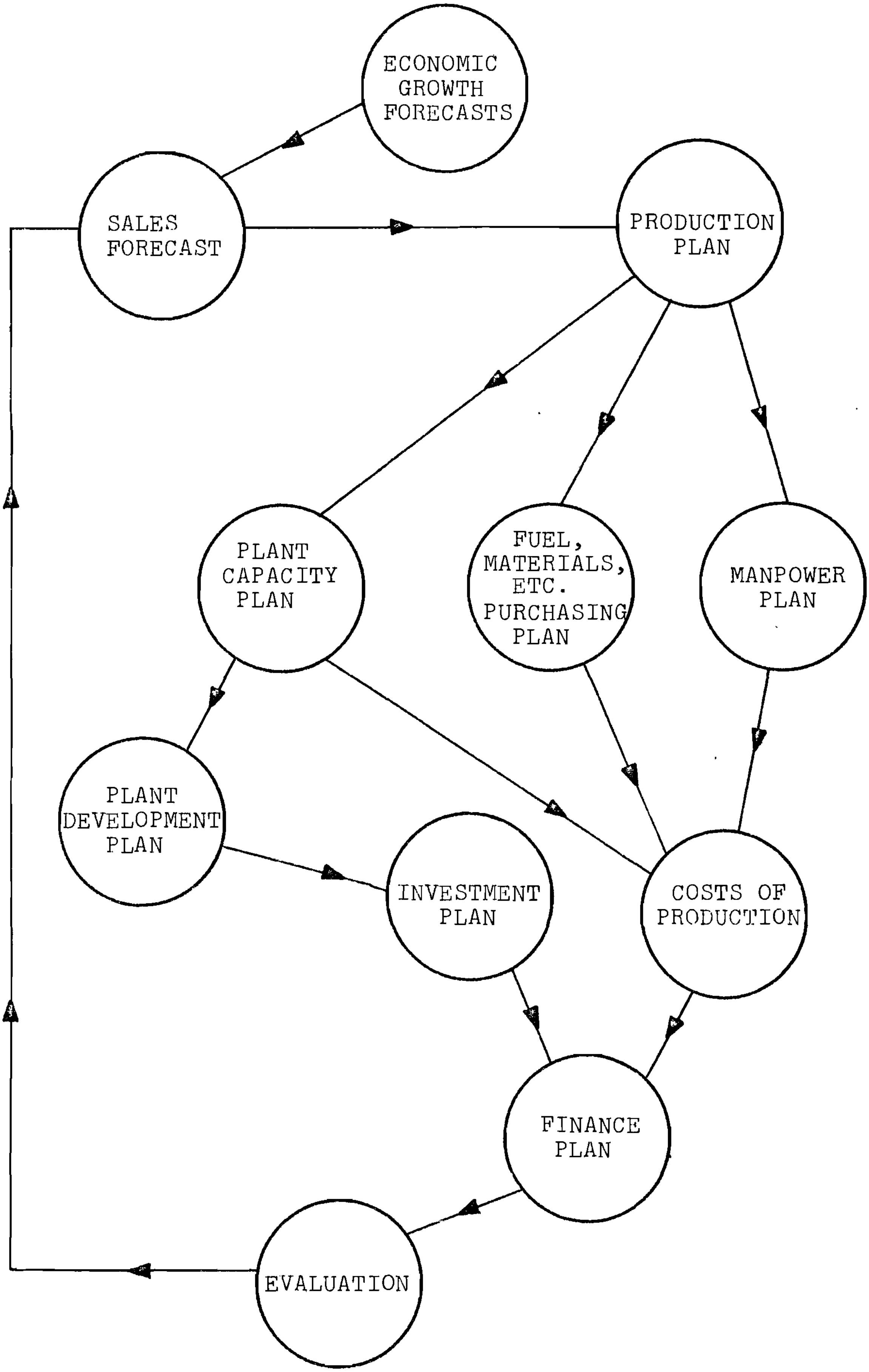


FIG. 2.2 LONG TERM PLANNING - MAIN COMPONENTS AND RELATIONSHIPS

Sales Plan

A company is not viable without orders and there is some logic in starting the planning cycle by considering how much of which products could be sold over the period. Every company visited has some form of model or models which are used to forecast demand. The simplest are statistical extrapolation models which exploit any detectable trends and cycles while predicting the future. General opinion suggests that this approach is useful but, quite naturally, does not predict any basic changes in direction. Thus, most companies use such methods as providing but one of a number of viewpoints to be taken into consideration.

Most companies also build up a total demand forecast by breaking down their sales outlets a) geographically b) by product and c) by user. This approach allows individual and detailed trends to be sought and projected. Any known discontinuities e.g. the start of a major shipbuilding programme or equally, the cancellation of a large contract, can be included in the reckoning at this stage. It is at this level that use can be made of the national economic forecasts previously mentioned.

It is common to find that all functions within a steel company that have any view at all on sales levels are encouraged to put forward an assessment of likely trends. It is a senior management level that attempts to resolve the host of conflicting advice that results, and the marketing or sales function has prime responsibility.

Where there exists a strong competitive marketing situation, the above procedures are first arrived at over the full market, that is to say the combined market of all competing firms. There comes then a further level of uncertaintly namely, how much of the total potential market can the one steel company reasonably plan to attract as firm orders? At this level, there seems to be little that can be called a scientific analysis. The procedure usually consists of making assumptions, working out some of the consequences and assessing the outcome. The assumptions may then be adjusted depending on the view taken of the likely consequences. It can be argued that this conforms to the "true scientific method" namely hypothesis, test, evaluate and reconsider the hypothesis, perhaps only the tests and evaluations are less than precise.

Whatever methods are used, the end result is a plan of expected sales by product by year, and as such represents a ten year demand on production. The next step is to consider if and how the production function can meet the demand.

Production Plan

Those responsible for long term production plans will be aware of the combined capacities of all the company's works. They will also be aware of any, already committed, developments in terms of capability, capacity and timing. The task, therefore, boils down to deciding how to allocate the sales plan elements to the available production facilities.

Many factors must be taken into account e.g. transport costs, production costs, minimum cost product balances, and the objective will be to calculate a plan which minimises the total cost of producing the required products. This sounds like a natural computer application since just about everything can be quantified. In fact nearly all companies visited do have such an allocation program but the permutations and combinatons are so enormous and the constraints so complex that fully automatic optimising facilities are not possible. Many programs include some optimising sections but interaction with manual planning is necessary. A sound evaluation of whatever plan results is the main outcome.

Success or failure in allocating the sales plan will indicate whether or not there is too much, adequate or too little production capacity to economically accomodate the plan year by year. If there is over capacity in some period, alternative strategies include shutting down departments, delaying any projects designed to increase relevant capacity, suggesting that the marketing and sales functions should explore further markets. The discovery that capacity is adequate must happen sometimes but the occasions seem rare. If under capacity is detected, it will mean that some specific extra plant is needed, perhaps another steelmaking furnace or rolling mill.

In a similar way, the production plan determines raw materials, fuels, manpower, etc. which are needed if the plan, as it stands, is to be implemented.

Plant Development Plan

All works review the suitability of existing equipment vis-a-vis their needs at regular intervals and some replacement or extension projects will nearly always be under consideration. The engineering departments are usually responsible once a specific project has been agreed upon, but before that, they will be expected to work together with production staff and specialists (e.g. operational research) in order to define the most suitable design. "Suitable" includes the implication of economic as well as technically competent.

A wide range of programs are available in most companies for technical calculations, project cash flow prediction and simulation studies. All such programs provide assistance in arriving at a reasoned solution to the development plan.

The final development plan will comprise those projects necessary to match the production plan and, in financial terms, constitutes an input to the investment plan.

The Investment Plan

As shown, the only input to the investment plan is from the plant development plan. In practice, however, there may well be other inputs, e.g. items investment in associated companies, office buildings, iron ore mining ventures. Summed together, the effect is a time task showing at which point in time given sums of money will be required. As such the investment plan becomes a demand on the company's cash flow.

Programs which facilitate the calculations involved are commonplace and have few remarkable features.

Purchasing Plan

It is normal for supplies of major raw materials e.g. iron ore, to be secured by means of long term contracts. For this reason, a long term purchasing plan which reflects the demand implied in the production plan is essential.

The task is not as straight forward as might be assumed since the alternatives can be numerous and selecting the considered best strategy may involve much thought and calculation. For example, the requirement for iron ore, may be met in several ways with different proportions of various ores at different prices. Linear programming routines are used to select minimum cost combinations and so guide the contract negotiations. The many problems of choosing wise financial arrangements as opposed to unsound ones cannot be solved by computer but again the technique of using evaluation routines speeds up the process and allows more time for thought.

Manpower Plan

Not every company tackles manpower planning with the same dedication as, e.g. plant capacity planning. However, companies do calculate manpower requirements over the long term, taking into account growth, process development, age distributions, training times and current skills. Some computer programs exist to carry out the calculations and the end result guides recruiting and training programmes.

Costs of Production

The sales plan has been sucessively turned into a production plan, investment plan, material purchasing plan and manpower plan. Each one costs money and it is necessary to calculate the overall cost, year by year, of fulfilling the sales plan in the manner so far selected.

All the usual problems of costing and cost allocating are encountered this is the normal challenge to cost accountants. From a systems viewpoint, once the policies have been clarified, the calculations are tedious but not overly difficult. Most companies are heavily computerised in this area and many cost build-up and allocation routines are in regular use.

Finance Plan

Demands for cash have now been built up from several sources and it is necessary for a company to examine the overall position. Not only must the anticipated activities, sales, investment, production etc. show an overall profit at the end of the day (or a 10 year period!), the company's ongoing cash flow must be feasible. Computer programs exist which calculate the cash flow throughout a period and indicate any shortfall or surplus over each sub-period.

Knowing the cash position is one thing, deciding what to do about temporary surpluses and shortages is another. In general, there are a finite number of financing possibilities, each with different terms, amounts and interest rates. Because the interest payments themselves generate further cash flows, both in and out, programs exist which seek the minimum cost/maximum profit solution.

Evaluation

The components of long term planning have been described at some length and mention has been made of the numerous interdependancy relationships between the individual plans. If planning is looked at in a pedantic, step by step manner, the final task is to review the overall financial position i.e. income, costs, capital required, interest, and take a view about its feasibility and desireability. In other words, a managerial check on credability.

In practice, the process is rarely, if ever, considered satisfactory the first time through. It is likely that each element of the plan has been biased by an individual's optimism, pessimism or even deliberate attempt to overstate the case in the hope of being forced back to where he really wanted to be anyway. So the evaluation may well conclude that the investment programme is too costly and must be cut by x%. Everyone involved must calculate or take advice as to how the cut will affect his own area of responsibility and replan accordingly. The merry-go-round can then start all over again and may be re-iterated several times.

If too many iterations are called for, the sheer volume of work will defeat a manually handled system, time will run out and a "best guess" solution may well be adopted. Even with computer routines to carry the bulk of the calculation load, the procedure is lengthy and tedious.

Several companies have attempted to build a computer based system which incorporates all the major computational components into one system. One or two such systems are claimed to be satisfactory but no one yet claims to have developed the ultimate.

Figure 2.3 shows the broad outline of such systems. The sales forecasts are manually determined with or without computer assistence. Likewise, the plant characteristics and standard costs are determined. The loading stage is not fully optimal but some attempts are made to select the most economic routes whenever feasible. Management still needs to examine the results and generate alternative strategies by changing costs, sales

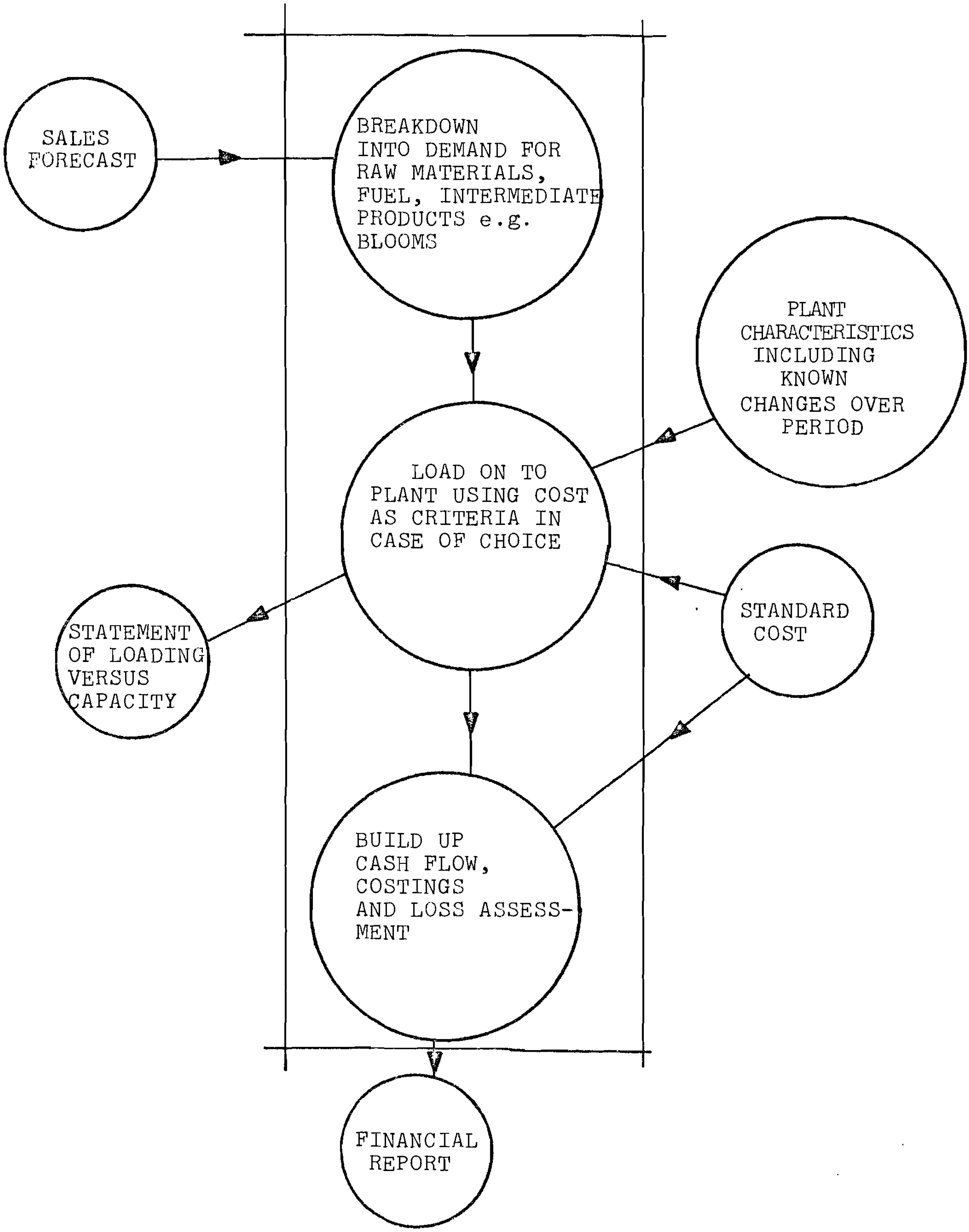


FIG. 2.3 LONG TERM PLANNING EVALUATION SYSTEM

forecasts or plant capacities. Such a system enables alternative plant development and marketing strategies to be evaluated.

Action

Long term planning activities absorb much company effort, both human and computer. The result is a clarification of a company's direction over the ten year period and provides a reasoned framework within which decisions may be made at some later time. In general, the exercise is repeated each year when a further year is added to the far horizon and the most imminent year becomes a reality.

The main action which comes from the exercise is to place long term contracts for raw materials etc. and to initiate the longer term plant building or extension projects. Ten years ahead is none too soon to start planning a venture which could take 7 or 8 years to implement.

Apart from such types of decisions, not a great deal is irrevocably committed since there will still be time to adjust e.g. the timing of projects. Only negative decisions may be regretted if realisiation of a mistake comes too late for a missed opportunity to be salvaged.

2.4 MEDIUM TERM PLANNING

Long term planning determines strategies and the policies are implemented as time goes by. Some companies visited think that they work through the long term plans in sufficient detail, revised annually, to guide all necessary decision making up to a year or so ahead of real time. Thus all matters which take place on more than an annual time scale (this includes plant construction and exploring new markets) are decided as an integral part of the 10 year horizon plans.

Those companies who do not consider their long term planning to be sufficiently refined, e.g. on the question of detailed costs or the timing of major developments, take a more careful look at the first 5 years (3 years in one case only) once a year. The basic approach to medium term planning is the same as for long term planning except for the level of detail. Essentially, the same topics are covered, the main difference being that there is less flexibility of choice.

2.5 ANNUAL PLANNING

As a result of long term plans, plant capacity will by now be determined and apart from the small changes in working capacity that can be brought about by working more or less hours, the available capacity becomes a constraint.

Similarly with raw materials such as iron ore and fuel, it may be possible to make some adjustments to contracted quantities but this will normally be difficult and costly. The available raw materials therefore becomes another constraint.

All planning activities at this stage still rely on a demand forecast to provide the main motivation. Since time has passed and it is now much nearer to the time when actual orders should arrive, there will be much better information about trends etc. than when considering a 10 year cycle, but forecasts are still liable to be wrong.

Figure 2.4 shows the main stages and relationships of a typical annual planning system in use today.

Sales Planning

With the longer term sales plans as background and the knowledge as to how these plans have stood the test of practice over previous years, the marketing and sales functions are in a position to refine their forecasts.

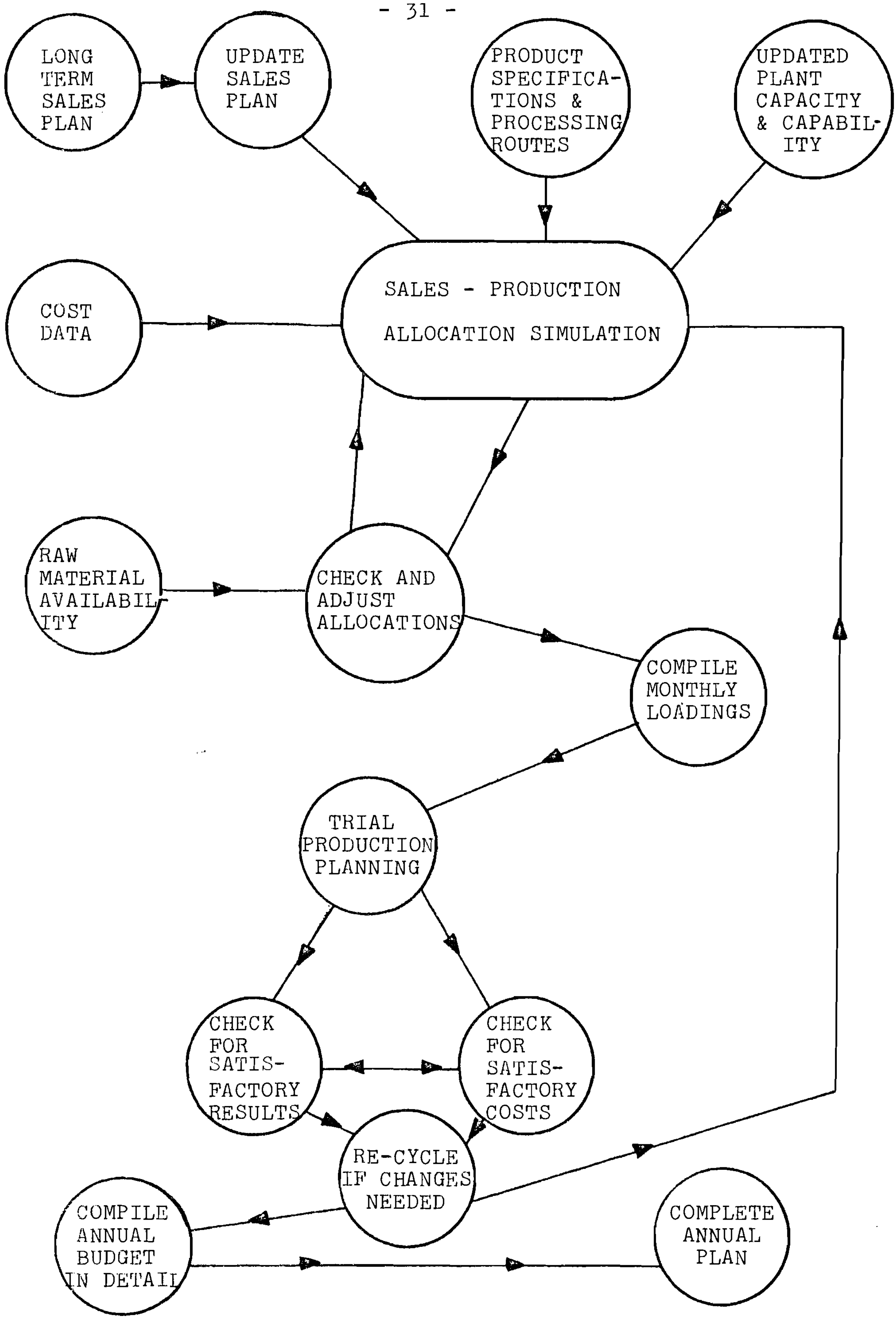


FIG. 2.4 MAIN STAGES OF ANNUAL PLANNING

On the longer time scale models, statistical methods, etc. were used to guide demand forecasts and such aids are even more in evidence on the annual time scale. Detailed analyses of demand by customer, sales outlet, industry, geographical area etc. are compiled using models and the resulting augmentation of estimates provides the basis (often full of contradictions), for manual determination of the sales forecast. The process involves much computer/person interaction and the procedure can cycle several times before the results home in on a state which can be pronounced acceptable.

The sales plan arrived at this stage is still far from being in its final form although major changes are not normally expected.

Sales - Production Allocation Simulation

The next step is to accept the sales plan for the time being, and attempt to calculate how the plan would be loaded on to the company's plants, and how the plants would perform under the assigned loading through computer simulation. The basic idea is to make any mistakes in a medium that does no harm and to learn from such mistakes by the time the plan has to become reality.

The major inputs are the sales plan itself, an up-to-date statement of plant capacities and capabilities, enough detail about product characteristics, intermediate products, yields, processing routes, etc. to enable a carefully considered loading to be meaningful, and cost information which can be used to select minimum cost routes or at least indicate any penalty for taking non-optimum routes. As a generalisation the simulations are not self-optimising but rather work on a heuristic (trial and assessment) basis.

The first stage is usually to load the expected orders onto the most obvious plant, taking into account plant capabilities and costs and other items when significant e.g. works to customer transport costs. Such a process causes no problems initially, i.e. when there is adequate uncommitted capacity on the "favoured" processes. Eventually, of course, the loading become tighter and the difficulty of selecting the "best" allocation increases. Towards the end of the process some positively undesirable allocation will be made and perhaps some orders left unallocated.

A complete process of reviewing, adjusting and re-allocation then commences. In the first instance, the trial allocation will be costed and steps taken to improve any high cost sections. In general, this stage is not automatic and is in the form of man/computer interaction.

Several interesting programs for optimising sub-sections of this allocation procedure are in use. For example, a company with several steelmaking shops of different capabilities and at different locations, faces a specific demand for steel. How best can this demand be allocated to the various shops? This question is answered by such a sub-model and after it has "done its best" the effect on other aspects of production must be reassessed.

A more common form of sub-system optimisation covers the allocation of raw materials, this is mainly achieved by linear programming.

Eventually, the allocation, costings, etc. are deemed to be satisfactory, or at least the best that can be determined. This decision quite naturally is a human judgement.

Trial Monthly Loadings and Production Plans

Following the simulation theme, the outcome of the allocation trials is a production demand that could well arise in practice. How then would it look if followed through?

The first operation is to divide up the annual allocations into monthly allocations, process by process. Assuming a division into months is achieved, perhaps by several iterations, the next step is to hand the 12 monthly demands over to the production planning function for an opinion on feasibility. At the same time, cost accountants liaising with the planners, assess the monthly plans to ensure that they are both workable and economic. Any unacceptable aspects can cause the whole plan to be thrown back to the sales-production allocation simulation.

Annual Budget

Doubtless the above procedure could cycle forever but since it is a manually controlled process, eventually a complete and sensible plan emerges. At this stage in most companies, the plan is presented to a top level management committee whose members are predominately production and technically oriented. Assuming agreement is forthcoming, the final stages in the annual planning procedures are to formalise the decision taken.

The monthly production plans are well developed as a result of the trial planning exercise so it remains to calculate a detailed company budget covering all operations and activities over the 12 month period. Although a lengthy process, it is a fairly straight forward procedure with computer assistance.

Complete Annual Plan

All this work and effort results in a detailed plan for all of the company's functions. A sales plan is ratified, a production plan exists and a budget for all activities has been laid down. In several companies the total is called the "Annual Operations Plan"

Especially in large organisation (a single steel plant may employ 20,000 people) decisions must be made everyday at many levels, and it is impossible to involve everyone who is likely to be affected, in all such detailed decision making. The annual plan is the vehicle by means of which everyone knows of the overall company objectives, especially in the way they are to be interpreted during the given year, and decision makers can in consequence act within the correct limits and in the planned direction. With the budget as a further guide, money can be committed and spent, within the limits of the budget and for specified purposes, without time consuming ad hoc discussions.

Comparison With Longer Term Planning

To reiterate, all plans of 12 months and longer are based on forecasts and estimates but the details and accuracy can be greater over the shorter periods.

Several companies plan long term over 10 years and then annually while others include a 5 year review in between. One company claimed to start with a 5 year horizon only and made a special case out of significant plant developments.

In many instances, different computer programs are used depending on the time scale, due to the different level of detail handled. Some companies, however, by flexible program design, claim to use the same programs over all necessary time scales.

2.6 HALF YEAR, QUARTERLY AND MONTHLY PLANNING

Still operating basically on a forecast demand, the plans laid on an annual basis are reviewed periodically by all companies. The frequency and the extent of such revisions varies a great deal and ad hoc revisions may well take place at any time if some catastrophe hits.

Not all companies review at the 6, 3 and 1 month points but some do. Mostly the same routines and a similar level of detail are used at each review point, compared with annual planning; however the amount of time and effort expended depends on the magnitude of any changes found to be necessary.

Some processes, e.g. section mills and billet mills, can handle only a very limited range of product sizes at any given point in time. This is because each set of rolls is shaped to roll a specific size and changing from one set of rolls to another is a major operation. For such processes, the objective is to group together as many individual order lots as possible so as to enjoy a long production run, lasting say several hours or days. A consequence of this practice is, naturally, that any one particular size and shape may be rolled only once every 6 to 10 weeks, hence any order received in the meanwhile must wait.

One extra task carried out approximately every quarter is to determine the programme of sizes to be rolled (sequence and run duration) over the following 3 to 4 months, based on past demand and the sales forecast. Computer models exist to aid this type of production planning. Usual practice is to advise regular customers of the planned timetable, and where a customer has some flexibility, knowledge of the plan can attract actual orders to the periods wanted.

2.7 THE SCHEDULING PHASE

A sequence of production planning routines has been described which result in a more and more refined production plan as time goes by and as the actual production period approaches.

The plans for each individual process represent the anticipated load of order types and quantities but it remains to be seen what mix of orders actually arrives. The section covering Order Processing contains a description of the stages through which an order must pass through until it is loaded onto the plant. A list or load is built up for each process and for each production time period. Each process has its own inherent cycle length and this is an important factor in deciding the period lengths. In a given works, the planning and scheduling system must cope with several different time scales.

A blast furnace cannot change (e.g. iron analysis, rate of working) very quickly and control systems are designed to result in a steady, consistent production. Most companies calculate a monthly production plan for their blast furnaces.

The sinter plant, similarly, is aiming to supply the blast furnace with a steady consistent material, sinter, and that, together with the coke ovens is planned in harmony with the blast furnace monthly.

Steelmaking, on the other hand, moves much faster, a typical cycle time per furnace is less than one hour. Companies have mostly chosen one week or 10 days as the basic steelmaking production period.

All other processes with a variety of constraints are also planned over periods which are subdivisions of a calendar month. Since the number of weeks in the month is nonuniform, this causes phasing problems which are usually handled by:

a) ignoring the calender month at this stage and defining the year as having 13, 4 week months.

b) splitting each month into 3, 10 day periods. This is imprecise because of February and the 31 day months but, in practice, the odd day causes little trouble.

c) splitting each quarter year into 3 months of 4, 4, and 5 weeks duration. This is a common practice but one suspects it caters more to the needs of accountants than production management.

For each process, there comes a point in time when the detailed sequence of items to be produced in a given time scale must be specified. This is scheduling. Thus, dividing the monthly plan into weekly assignments which estimate the sequence of items to be produced during each week, constitutes a monthly schedule. Similarly, dividing the weekly plan into assignments for each day, composes the weekly schedule and so on. The more detailed schedules give the sequences of separate operations, considering the times required for their fulfillment.

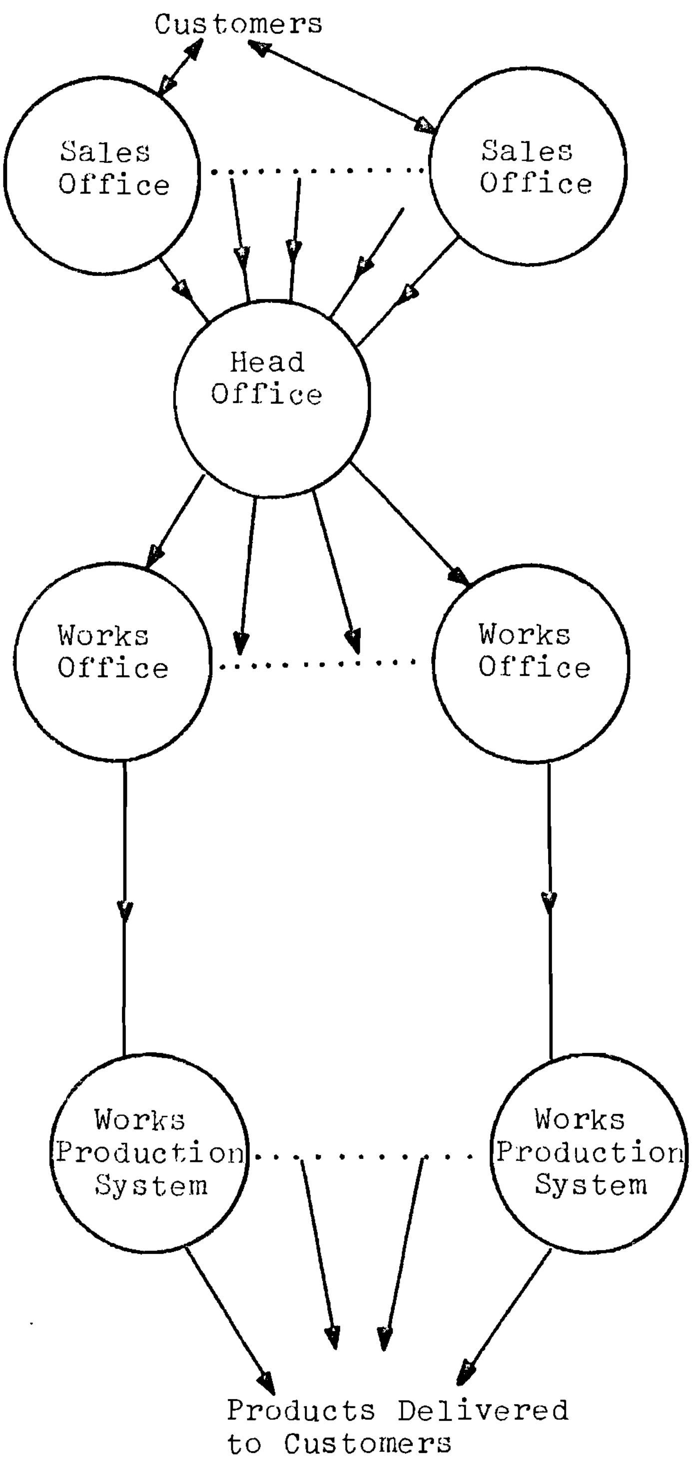
2.8 ORDER ENTRY SYSTEM

Production plans, even quite detailed plans, can be and are, determined without any knowledge of firm orders and based purely on estimation of the expected demand. As has been already mentioned many longer term activities such as building plant and negotiating long term contracts for raw materials must of neccessity be founded on forecasts.

Eventually orders do begin to arrive and it is necessary to examine each order before accepting it and to determine just how the items are to be produced before priming the work's production processes. This operation is called Order Entry and is particularly critical in market orienteted countries. (see Fig. 2.5)

Sales Offices

Customers normally negotiate directly with a sales office, often located well away from the steelwork sites. If some unusual form



Basic Functions

Customer/Company negotiations; manual check of orders; coding.

Detailed check of order, basic determination of how ordered items will be produced; confirm delivery date; allocate to works; send acknowledgement to customer.

Calculate processing details; combine orders into lots; allocate to production periods; adjust to balance loadings; prepare detailed process instructions

Produce products to specification and to time.

FIG. 2.5 ORDER ENTRY

of steel is wanted, there may well be detailed discussions between the technical experts of both the customer and the steel company to decide precisely what type of steel is best suited to the purpose. Most steel companies take a strong paternal interest to ensure that a customer orders a type of steel that properly suits his needs. Some go as far as to guarantee that the delivered product will fulfill its intended purpose.

It follows that, in general, the sales office receives orders for items that are either to standard specifications, repeat orders, or orders for previously discussed new types of product.

The first task of the sales office is to manually check the order for completeness of information and consistency. In many cases the order is transcribed into a standard format with many of the details coded in the process. This stage is largely a manual operation although some mechanical assistance in selecting codes is found in some offices.

Examples exist where a major customer prepares orders in a standard format agreed between customer and steelmaker; this both saves time and each order is likely to be more completely and accurately specified. The "ultimate" also exists where the customer transmits his orders via a computer medium e.g. a magnetic tape file. In such a case, the magnetic tape may be physically transported from customer to steel company or, if the distance is too great, transmitted over telegraph lines.

A customer normally wants to know these things: 1) Is my order acceptable? 2) How much will it cost? 3) When can it be delivered? A sales office can usually answer 1) and 2) without difficulty but 3) can often present problems, especially if the customer is pushing for a very early delivery date.

Practice varies around the world but the most usual solution is for the production planning and scheduling functions to advise the sales offices periodically (daily in some cases) of the standard lead times that can be fulfilled for each product classification. For example, orders for billets may be accepted for delivery in a minimum of 3 weeks hence, and for sheets in a minimum of 6 weeks. There is always some absolute minimum time which is dictated by basic processing times, but the practical delivery time will depend on the number of orders currently awaiting processing. It is common practice for a sales office to be authorised to negotiate and agree on delivery dates based on the guidelines already mentioned and without any reference to the detailed production loading or schedules. The only exceptions are for very special steels which may have a dozen or more critical stages of manufacture, some through processes of strictly limited capacity. In these cases, a trial loading is used to calculate a reasoned delivery date.

For some products it is feasible to provide the sales office with a list of unallocated stocks which could be delivered to a customer without delay. Normally, only common steel grades and product sizes are handled this way.

In markets where the sales office has some flexibility in negotiating a price, it is as well to provide details of standard and marginal costs as a basis for profitability calcualtions. Examples exist where this is taken one further step of sophistication with an indication given to the sales office as to what types of orders to encourage and which to discourage. The classification and ranking of products is based on a comparison of current production loads with the ideal, minimum cost works loading. Such a system is not so crude as to expect the sales office to tell a customer his advance order isn't wanted, it simply sets the minimum acceptable price for "wanted" orders.

How ever the order arrives at the sales office it must, after the checking already mentioned, be sent on to the head office. Naturally the head office may receive orders from several sales offices or agents and may also deal with some customers direct. Tradition influences current practice.

The order information passed from sales office to head office will be in some standard form. In some instances, the details are on paper and sent physically to head office. Where distance is a problem, a facsimile may be sent over a telegraph wire. However, since most advanced systems today employ computers for production planning and scheduling the trend is to introduce a new order into the computer system as early as possible. In consequence, many sales (and even agent) offices have a terminal linked by telegraph to the head office computer and this allows the order details to be typed directly into the computer format. In cases where the terminals are fully on-line, order details can be checked immediately for validity and completeness.

Head Office Order Processing

Assuming that the order details are available at the head office in some computer media, the head office activities are virtually fully performed by computer. Again the order details are checked for completeness and sensibility and the coding carried out at the sales office is validated. There are systems in use which require no further manual operations at the head office except to deal with error, misfits, etc. detected and thrown up during the checking stages.

The first head office task is to build up a basic picture of the processing necessary to successfully produce the ordered item. This involves pulling appropriate details from files containing metallurgical specifications, production routes, etc. The codes already applied by the sales or head office represent the key to locating the correct details. Thus, a full processing specification begins to be built up.

Once it has been decided how an order will be fulfilled the next question is where? and when? "Where?" implies selecting a works or plant which is capable of producting the ordered item; "When?" implies ensuring that the plant loading situation will allow the items to be produced and delivered to time.

The files at the head office will contain details of which plants can make which items and usually some cost information which aids the selection of the most suitable plant (if there is a choice). This selection is a two stage process in most companies. The first stage is an allocation of forecast demand to the various plants within the company. A recalculation may take place annually or quarterly and most companies today use some form of economic model to minimize production and transport costs by a sutable allocation of expected demand.

When it comes to allocating a real order, the second stage, the task requires little effort if the order details conform with the expected demand pattern. Trouble does arise, however, if the actual pattern of demand differs from the expected or if production capacity fails to materialise through breakdown or other problems.

Most order entry systems have a developed model to cope with the situation of finding no available capacity at the "ideal" works. The system attempts to locate alternative suitable capacity which, by definition, will result in more costly (but hopefully still profitable) production. If after attempting to load on several (progressively worse) alternatives, plant capacity still cannot be located, the problem becomes one for manual attention. The alternatives at this point boil down to admitting failure to confirm the requested (and possibly agreed upon) delivery date or to using a higher grade steel which further reduces profitability.

No one cares to admit the fact, but in really tight corners the company may decide its optimum overall strategy is to delay one customer order in favor of a more "important" customer's wishes. This type of situation can only be handled by top management although the computer could be programmed to throw up the hard costs of alternative strategies.

When an order has been successfully allocated to a particular works, it is transmitted, complete with all its detail, to the received orders file of the works level computing system. With many modern systems this transfer is effected via magnetic tape files or by telecommunication lines.

In some of the companies visited, the head office compiles the orders destined for each steel works in the form of a detailed monthly production plan which is transmitted beforehand to the works office.

The final action for the head office level is to produce an acknowledgement to be sent to the customer, confirming the details of the order and the agreed delivery date.

Works Office Order Processing

Accepted orders arrive at the selected works office and represent firm commitments. It is the task of the works planning and control system to organise all works productive facilities so as to satisfy these commitments at minimum cost.

The works level computers will first examine the order details and then estimate the technological routes and instructions for their fulfillment. Then, all orders having similar technological instructions and delivery times are combined in lots and compiled in the works orders file. Each file item specifies the amount of steel required, the processes through which the steel must pass, and the numbers and sizes of all intermediate products. In calculating quantities, account is taken of the yields normally experienced in each successive process. By considering the normal processing time and the known basic schedule requirements for each process (e.g. the cycle of shapes and sizes planned for the section mill, considering the standard time for changing mill rolls), a processing time table can be drawn up specifying dates on which the steel should be scheduled onto each process along the selected technological route, during a given time horizon.

If each component of processing is then added to the load already allocated to each process time period, the order can be said to be loaded onto the plant. In general, the longer the time horizon considered, compared with the cycle time of the production operations, the easier it is to perform the plant loading. Thus, in the simple case, there is enough uncommitted capacity at each process to accommodate all of the orders. Even when this is the case, however, some processes may become unduly loaded with specific product types and some reshuffling should take place in order to balance the plant loadings. This level of readjustment does not normally alter the production date of any specific order item to an extent that jeopardises completion of the due date.

In case where there are alternative technological routes, optimization techniques may be applied to allocate the orders (e.g. two merchant mills of different sizes may be available to roll the sizes and shapes required by a given order but with different production costs).

All has now been done to indicate the load on each process over a scheduling time horizon but not the sequence of processing within that time horizon. That calculation is performed at a time prior to the actual production date which is dictated by the length of the processing cycle and is discussed under "Scheduling".

Before the processing of a new order can be properly called complete, the works level routines compile the detailed processing instructions for every item at every process it will pass through, including transportation moves and sequence changing stock areas. This involves adding to the number, weight and dimensions of each intermediate product already calculated for the loading process, all processing tolerances, temperatures, processing characteristics (e.g. heating cycle coded at the annealing stage), test and quality checks again with limits. All these data are stored on what is usually called the Works Order File.

The order processing procedure, being the main part of works production scheduling, greatly influences the efficiency of the works operation. It is performed as a mutual task of the order processing operator and the computer through a form of interactive dialogue. Thus, in the simple situation where there is enough capacity and no alternative plant loadings have arisen, the operator's role is simply to approve the decision made by the computer (through some heuristic algorithms programmed in the computer). But in the case where there are alternative loadings to be resolved, the final decision is made by operator.

In one of the steel works visited, an order processing system is in use where each order received is compared with the data of previously fulfilled orders. If it is a repeated order, the relevant technical data is taken from the data bank and displayed to the order processing operator. If the operator agrees with this data, the newly received order with its corresponding technological routing and instructions is put into the order file. An entirely new order which does not have a prototype in the data bank is processed in the usual way (with the help of the computer) and after its fulfillment, all of the technical data is stored in the data bank. In this way, the number of"entirely new orders" entering the order processing system may be progressively decreased with time.

"State-of-the-Art"

As written, this has been a description of a typical up-to-date planning and scheduling system. A number of examples were seen in which every stage of order processing is performed automatically by computer routines with the exceptions of the initial manual scouting and coding stage and any decision-making required for the resolving of conflicts. This is not to say such systems automatically cope correctly with every eventuality, they don't. They are programmed to search for expected characteristics and they process the expected correctly, but any incompatible or unrecognised data are rejected. This means the details are printed out for manual attention while being retained on file pending correction.

The combinations of different process specifications are legion and by no means every combination can be held on file. Only practised or expected processing combinations are in fact recorded and the normal procedure for some completely new processing combination is to manually specify the details before the first real order is fed in.

All persons talked with expressed a healthy dissatisfaction with existing systems. This is not to say that the systems are no improvement over comparable manual systems; they most certainly are on the grounds of speed and accuracy alone.

Speed of response is a critical measure of achievement and a few systems have reduced the time from order receipt to formal acknowledgement down to 24 hours. A second measure is the minimum size of customer order that is economically reasonable to manufacture. This minimum may be considerably reduced by an effective order processing system through the combining of similar small orders into lots of adequate size.

The main lack of contentment is centred on the algorithms for allocating orders to works for production loading and balancing. No practical and precise optimising routines are known and so, although "good" answers result, they cannot be called the "best" possible.

Few persons expressed satisfaction with the system for calculating and quoting delivery promises although a highly reliable delivery performance against promises is generally considered to be an extremely important objective. It is simple to have very high success rates, on the few orders one would get, by quoting cautiously long lead times. By quoting overly optimistic delivery times the orders may flood in until customers realise that virtually every promise was broken and so business drops off. The reasoned "optimum" position between these two extremes is not easy to locate and the "correct" answer may change with changing conditions.

2.9. PRODUCTION SCHEDULING

Every process has inherent constraints and requirements. For example, steel type "p" cannot be made in the same furnace immediately after steel type "r" because type "r" contains a high proportion of phosphorous and type "p" needs a very low concentration. Rolling mills nearly all have sequence constraints and since rolls wear with use, their satisfactory life time dictates cycle lengths. Air heating processes take a minimum time, etc.

The operations level, and this includes services, transport, etc. as well as the basic technological processes, need to be told what to do and when. A production schedule must be produced at a time suitable for each process which contains the necessary identification, before and after characteristics, and the processing sequence. In addition test details must be available.

Although, many computer-performed tasks e.g. accounting, invoicing, process control, are accepted as commonplace in today's modern steelworks, the scheduling process has remained a stronghold of human control. It is an ideal stronghold because, although the main rules and objectives are simple, the caveats, special conditions, etc. result in a seemingly unfathomable set of restrictions.

There are, in fact, many scheduling programs found in steel works around the world. This is not to say that they are all used on a regular basis or that their results are implemented blindly without manual scrutiny. A steel process schedule is a very critical stage and production management maintains a constant vigil against anything that might disrupt the smooth, efficient flow of production, or worse, that may damage the equipment.

A sharp distinction between computer and manual scheduling should not be made since all up-to-date systems include routines which sequence production items as preparation for determining the production schedule. The degree of sophistication involved in this programmed sequencing does vary, however. In many cases, the resulting sequence represents a feasible but not particularly optimal schedule. In all cases, manual schedulers review the computer result and either accept or adjust the sequence.

Rescheduling

The system at the operations level implements the schedule, or suitable portions of the schedule, by comparing input identification codes and other data with those indicated on the schedule. Many forms of divergence from the planned schedule may occur due to a) non availability of the expected item, b) process breakdowns or restrictions, c) malprocessing. The operations level will either detect such variances for itself or be informed via manual input. However the variance arises, a situation immediately exists in which implementation has failed in the planned form and some remedial action must be taken. The failures range from simple sequence errors which, provided identity can be maintained, causes little real trouble, through to full process breakdowns.

For malprocessed items, a full spectrum of attitudes was found ranging from :

> a) use of a complex on-line search routine to match the "unwanted" item against the existing list of orders. Thus, if a suitable order is located, the marriage is made and processing continues, perhaps with some changes in detail; a remake order is then raised to cover the "disappointed" order, to b) the complete removal of the offending item to some storage area where it rests until a manual decision is taken about its future. A remake order is also raised.

Various approaches exist which fit somewhere between these two extremes.

In case where the problems are much bigger, for example a steel-making furnace must be shut down, the repercussions are more significant and the consequences more far reaching. The basic philosophy of the planning and scheduling system explains the way out.

Plans are originally made in the expectation that production will proceed with a normal degree of success. That is to say, for example, that 100 tons of steel will result in, say, 85 tons of sound hot rolled coil. The daily loads on each process reflect these plans but detailed scheduling is not finalised until a) the material which is physically ready to be taken through the next process is known and b) the state, condition and capabilities of the process have been assessed.

The scheduling stage accepts the material and equipment as it is and attempts to derive an optimal production sequence within the existing constraints. Thus although these two, material and process, may be not exactly as planned, the best that can be achieved under the experienced constraints will be determined.

2.10 OPERATIONAL LEVEL OF THE INTEGRATED CONTROL SYSTEM

General Considerations

As has been shown earlier, there is an operational level of control between the production scheduling level and the process level which translates the schedule into control actions initiating the various manufacturing operations. This ensures that the quality and yield requirements for prescheduled orders are met.
The operational level of control is sometimes called the coordinational level, or production control. Since the function of this level includes organization of the processes and its goal is to

react operationally to all deviations from the schedule, the term operational level seems appropriate.

A steel works usually has three main production stages: iron making, steel making, and steel rolling. Iron is produced by blast furnaces; steel is made in open hearth furnaces, oxygen converters or electric arc furnaces; steel rolling is carried out on various mills and divided into two parts, primary and secondary rolling.

Fig. 2.6 represents a typical flow of processed material through these stages with the steelmaking facilities represented by oxygen converters, and the primary rolling by a universal slabbing mill. Ore is blended and delivered to the sinter plant (in some cases through an ore enriching plant). Coal, after being crushed and blended in the coal-preparation shop, is delivered to the coke oven plant where the coke is produced. Coke gas, a by-product of the plant, is refined and used as fuel for the different reheating units. Benzol, coke tar and other chemicals obtained as byproducts are shipped to customers.

A steel works usually has several blast furnaces. The main components of the blast furnace charge are sinter and coke delivered from the sinter and coke plants, respectively. The hot iron from the furnaces is delivered in ladles to the steelmaking plant. In a modern steel works, these ladles are of the Torpedo type, which means that mixers are not required.

Several types of technology are used to produce steel from crude iron; the most advanced is the oxygen converter process which permits large amounts of scrap to be used. The large-sized scrap is crushed in the scrap-preparation shop and delivered to the scrap yard in a form suitable for direct use in the converters. After scrap has been charged, the hot metal is poured from a ladle into the converter.

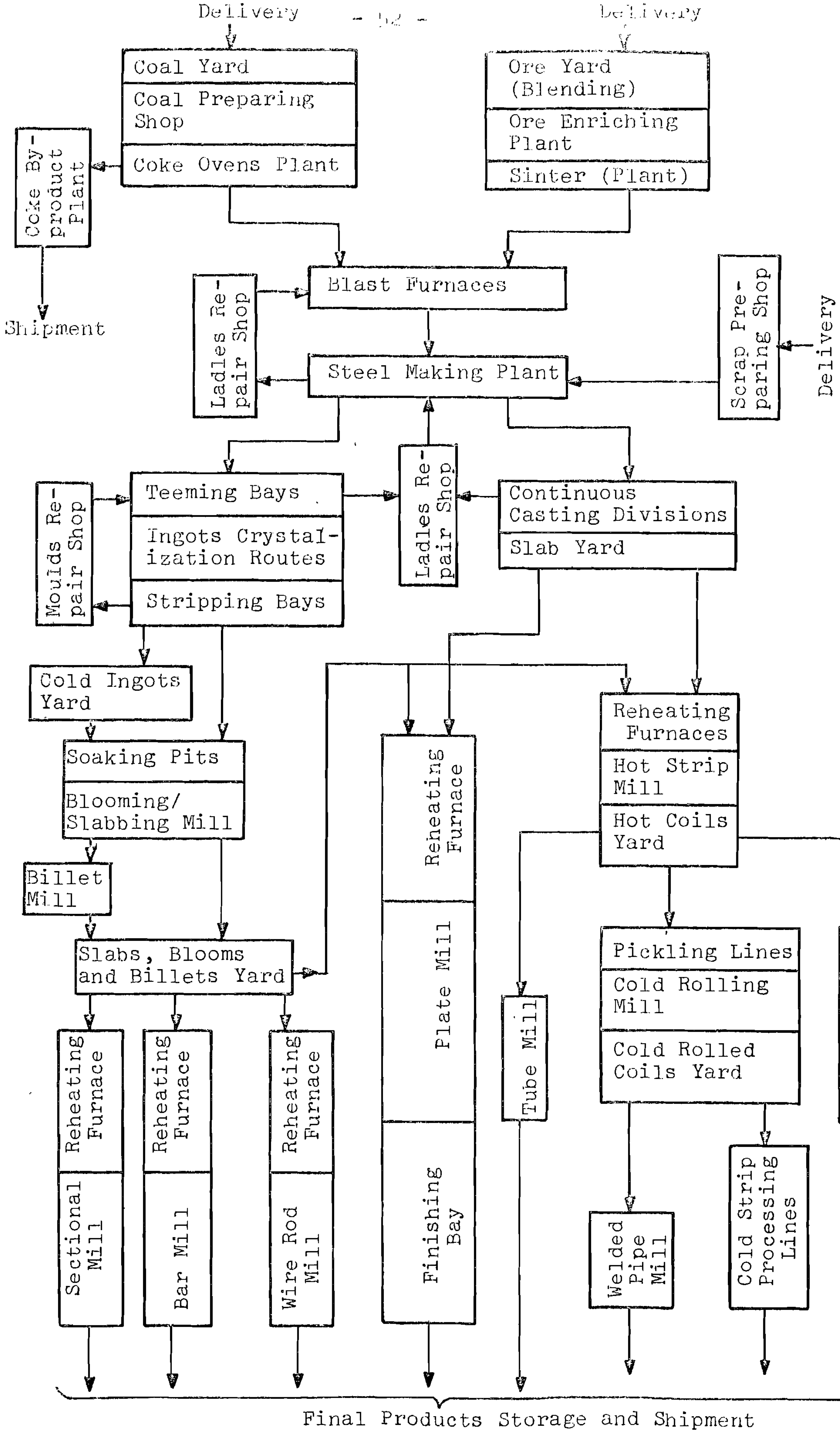


Fig. 2.6 DIAGRAM OF THE STEEL WORKS MATERIAL FLOW

Steel produced at the steelmaking shop and tapped into steel ladles can be sent on to continuous casting machines or poured into ingot moulds at the teeming bays, depending on the technological route established by the production loading procedure. The continuous casting machine can produce slabs and billets of various sizes; for simplicity, Fig. 2.6 shows only the production of slabs.

After the ingots have solidified in the moulds (the duration depends on the grade of steel), they are stripped at the stripping bays and then sent to the soaking pits. When no pits are available for charging the new ingots, or when the steel grade does not match the specifications of the plan, the ingots are sent to the cold ingot stockyard. They are normally charged into the soaking pits at some later time when there is a delay in delivery of new ingots from the stripping bays.

The empty ingot moulds are repaired and stored in the mould repair shop. When needed, they are delivered on a special mould train to the teeming bays. After teeming, empty steel ladles are sent to the repair shop until called for by the steelmaking plant.

The primary rolling stage shown in Fig. 2.6, is performed by a universal slabbing mill which can roll ingots into slabs or blooms. If the mill is rolling blooms, these may be sent directly to the billet mill, the section mill, or the bloom storage yard. Billets from the billet mill (or the billet storage yard) may go to one of several finishing mills, such as the bar mill and the wire-rod mill.

Flat rolling is represented in Fig. 2.6 by the heavy plate mill and the continuous hot stip mill; both can roll slabs produced by the continuous casting or by the slabbing mill. Since, the heavy plate mill will often require slabs of different sizes, these are rolled by the slabbing mill which is capable of easily changing slab size. Both mills have several slab reheating furnaces, and the plate mill has a well developed finishing bay consisting of inspection and shearing lines, and packing and shipping departments. The hot strip mill produces steel strip in the form of coils and there is a coil yard at the end of the production line where the hot coils are kept while cooling.

Usually, most of the hot rolled coils are used as semifinished products for cold rolling. Pickling lines on the entry side of the cold rolling shop remove the scale from the surface of the hot rolled strip by chemical treatment. The rolling facilities of the shop generally consist of tandem-type rolling mills, having four to six stands, one or two temper mills and several single-stand reversing mills for the production of narrow-gauge strip in small quantities. There are also strip heat treatment furnaces of batch or continuous type, shearing lines, and coating, tinning and galvanizing lines. All these facilities are combined in a so-called cold strip processing department.

Often, steel works with hot and cold rolling strip mills have tube and pipe mills of different types which use semifinished products in the form of hot or cold rolled strip. In some cases, there is a cold forming sectional mill producing different sections from the hot rolled strip received from the slitting lines.

Each mill has a roll repair shop (not shown in the figure), where the worn rolls are ground and polished.

As can be seen from Fig. 2.6, the technological processing routes of the steel works increase in number towards the despatch end of the works, thus enlarging the information flow and increasing the complexity of the coordination control problem. The technological route starts to branch at the steelmaking plant, where the operation is of a cycling type and each cycle can correspond to different requirements. Each converter heat can be of different steel grade and assigned to a different technological processing route according to the order requirements.

More technological branches appear at the steel rolling stage according to the different sizes and shapes of the rolled metal. The technological instructions required are precalculated and stored in a data bank from which the operational control system draws information in the form of local control system assignments.

The following descriptions of operational control systems do not relate to any particular steel works; they are prototypes embodying the more advanced parts of various systems. The main aim of the descriptions is to outline the characteristics and capabilities of the operational systems for different stages of the production process.

2.11 IRONMAKING

The ironmaking division includes the raw material yards, coke and sinter plants and blast furnaces. A specific feature of this division is that the operations are continuous and the specifications of its products are generally independent of the orders for final steel products. Thus, the coke plant always produces the same coke, the sinter plant the same sinter and the blast furnaces the same iron. Such bulk type production processes, which operate to a constant technology, are simpler to control since the objective is to stabilize the process and to keep them running continuously on the same technology.

The control of the ore-blending operation consists of programmed switching of the ore conveyer sections and excavating units in accordance with decisions made by the ore yard operator. The operator has all the information concerning the ores stocked in different piles and the transportation operations that are carried out by the conveyers together with the excavating units. Initial information about newly delivered ore is fed into the yard's operational control system manually and all ore movements in the yard are recorded automatically by the weighing sections of the conveyers. On request, the system gives the total amount of ore delivered to the yard and the present ore stock.

The operational control system for a sinter plant has mainly monitoring functions, which assist the sinter plant operator to detect in advance any divergency of the process caused by material shortage or by poorly estimated technological conditions. The system checks the amounts of material in the bunkers, and on the basis of periodic chemical analyses of these materials, calculates the composition of the sinter.

The cyclic operation of the coke ovens includes charging the ovens from the top with raw coal, firing them and discharging the hot coke from the ovens by a special machine. The operation of the discharging machine should be coordinated with the door extractor crane operation that controls the position of these mechanisms. Thus, one of the functions of the coke oven operational control system is the tracking of the discharging machines, door extractor cranes and coke transfer cars. The hot coke discharged into a coke transfer car is taken to the coke quenching tower where program-controlled coke quenching operations take place.

There is a strict sequence in carrying out these operations for each oven; the sequences of the coke oven cycle for a given coke battery is controlled by the operational control system. This system monitors the oven's cycling operations and maintains their proper phasing to satisfy limitations of the discharging and coke quenching equipment.

The blast furnace operational control system, usually considered part of the furnace process control system, consists of several local systems, for example, the burden charging system comprising a fully automated, programmed controlled weighing ore car (or conveyers), skip hoist, large and small bells, distributor and coke weighing gridle.

A second system which can be included in the operational system is the hot blast stove programmed controller, which reverses the stoves from the heating to the cooling phase to obtain hot blast for the furnace. The data-logging system, which can also be considered part of the operational system, calculates the burden.

2.12 STEEL MAKING

Fig. 2.7 shows the main material flow through the oxygen converter plant. On the entry side of the plant there is a hot metal flow, a scrap flow, an additions flow, and an oxygen flow. Hot metal is delivered in ladles from the blast furnaces and weighed before being poured into the converter vessel.

Scrap is delivered from the scrap yard in charging baskets and is also weighed. Additions are stocked in hoppers and delivered by conveyer to the converter weighing bunkers. Oxygen is produced by the oxygen-making shop.

On the exit side of the plant, the figure shows the flow of steel in ladles, which are delivered to the continuous casting department, and the flow of the ingots in moulds, which are delivered to the stripping bay.

Material movements inside the plant are by ladle transfer cars which deliver the ladles to points from which they can be taken by overhead cranes: slag cranes for slag ladles, teeming cranes for steel ladles operating at the teeming bays, and teeming cranes in the continuous casting department.

To organize and control the operation of the steelmaking shop, the position of all the transport units must be monitored, the weight of the material flow measured, and the levels of the material in the hoppers checked. To control the converter process, the temperature must be measured and hot metal and waste gases analysed and measured.

The organization of the production process is a function of the operational control. This control should check the sequence of the individual operations, such as delivery and withdrawal of the ladles for steel and slag to and from the converter, delivery and withdrawal of hot iron ladles, charging hot metal and scrap into the converter, lifting and inclination of the converter vessel,

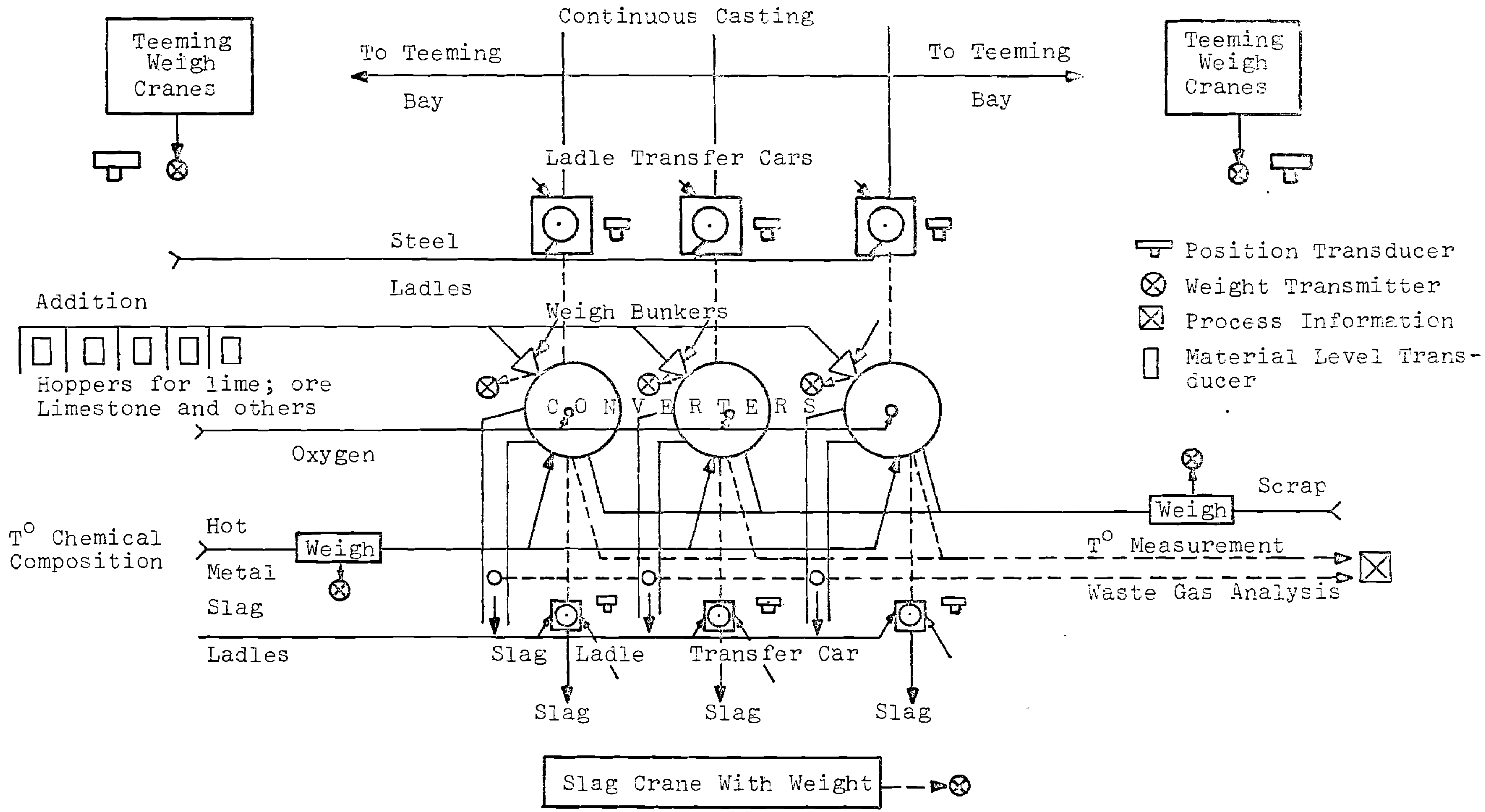


Fig. 2.7 Diagram of the Material Flow Through BOF Plant Location of Transducers and Point of Measurement

and so on. The operating cycle for a two-converter plant is shown in Fig. 2.8. Since the limitations of the transportation and teeming facilities do not permit simultaneous, identical operations, the operating cycles of the two converters must be out of phase by ninety degrees. Ensuring this displacement is another function of the operational control system.
Fig. 2.9 shows the main functions of the operational control system for the steelmaking plant. As was previously mentioned, the goal of this system is to combine the production planning and scheduling system with the local process control systems. Thus, the assignment for the operational control of the steelmaking shop is received from the production planning system in the form of daily plan for steel ingots and for slabs cast in given sizes and grades. This plan gives all the necessary information concerning the required amount of scrap, hot metal, additions, steel and slag ladles, moulds, and so on. The calculated figures are compared with the information which each shift receives from the scrap yard, ladle and mould repair shop, and the shop floor; the operational control system issues requests for scrap to be delivered to the scrap yard, ladles and moulds to the repair shop, etc.

The daily steelmaking plan does not indicate the sequence of heats for different steelgrades to be manufactured by the converters; it provides only the number of heats of each grade to be sent to the continuous casting division and to the teeming bays, with indications of the type of ingots and the slab sizes to be produced.

Because the grade of steel produced by the converter often fails to meet specifications, the detailed schedule is not prepared beforehand by the planning level of the system; rather, the steelmaking plant assignment is given in the form of a shift or daily plan. The scheduling is performed by the operational control system in the light of current events. It includes preparation of schedules for the teeming bays and the continuous casting machine operations.

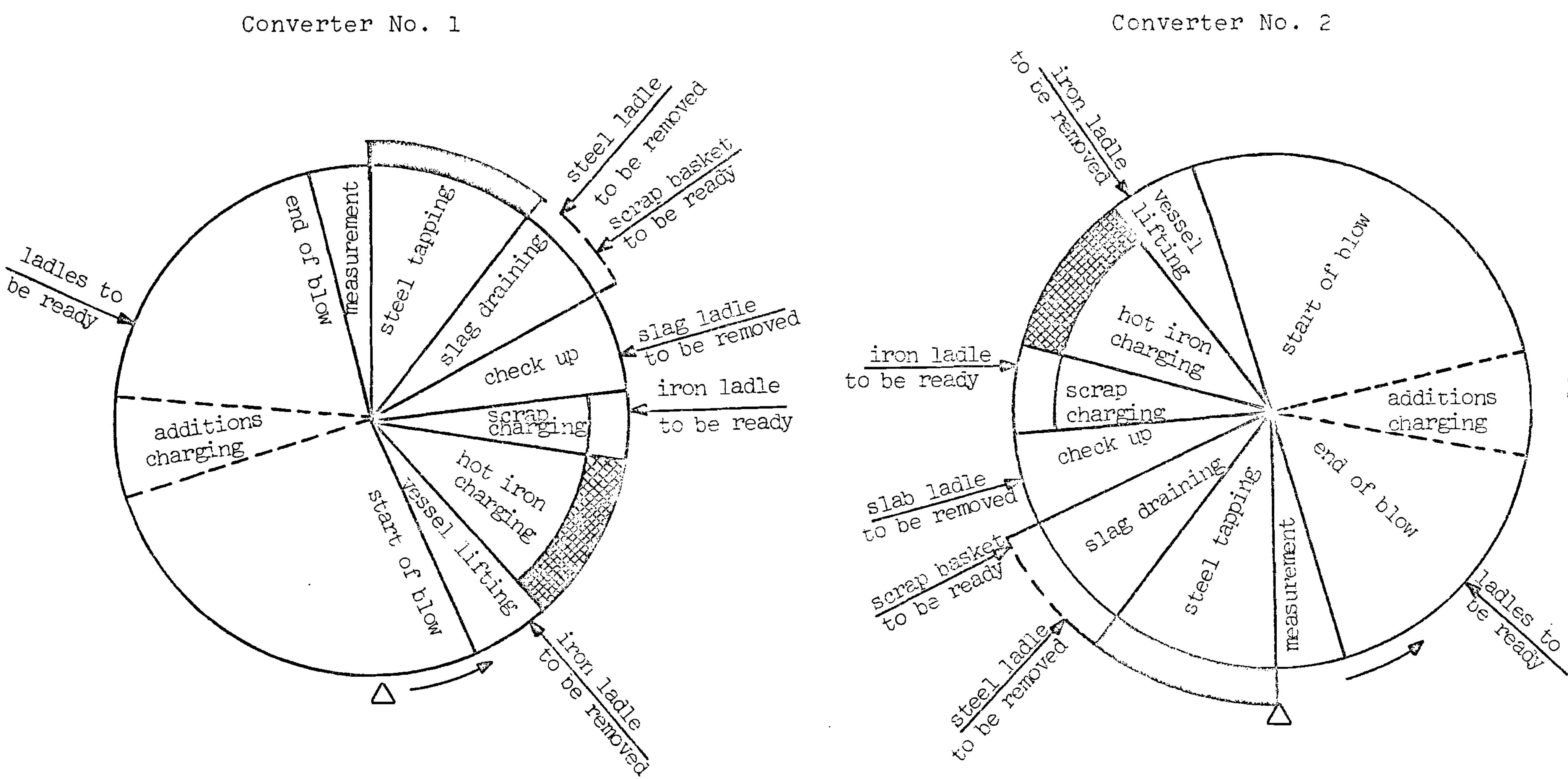


Fig. 2.8 Diagram of two converters operation cycles (displaced by 90°)

Points of the equipment position control and issuing of commands.

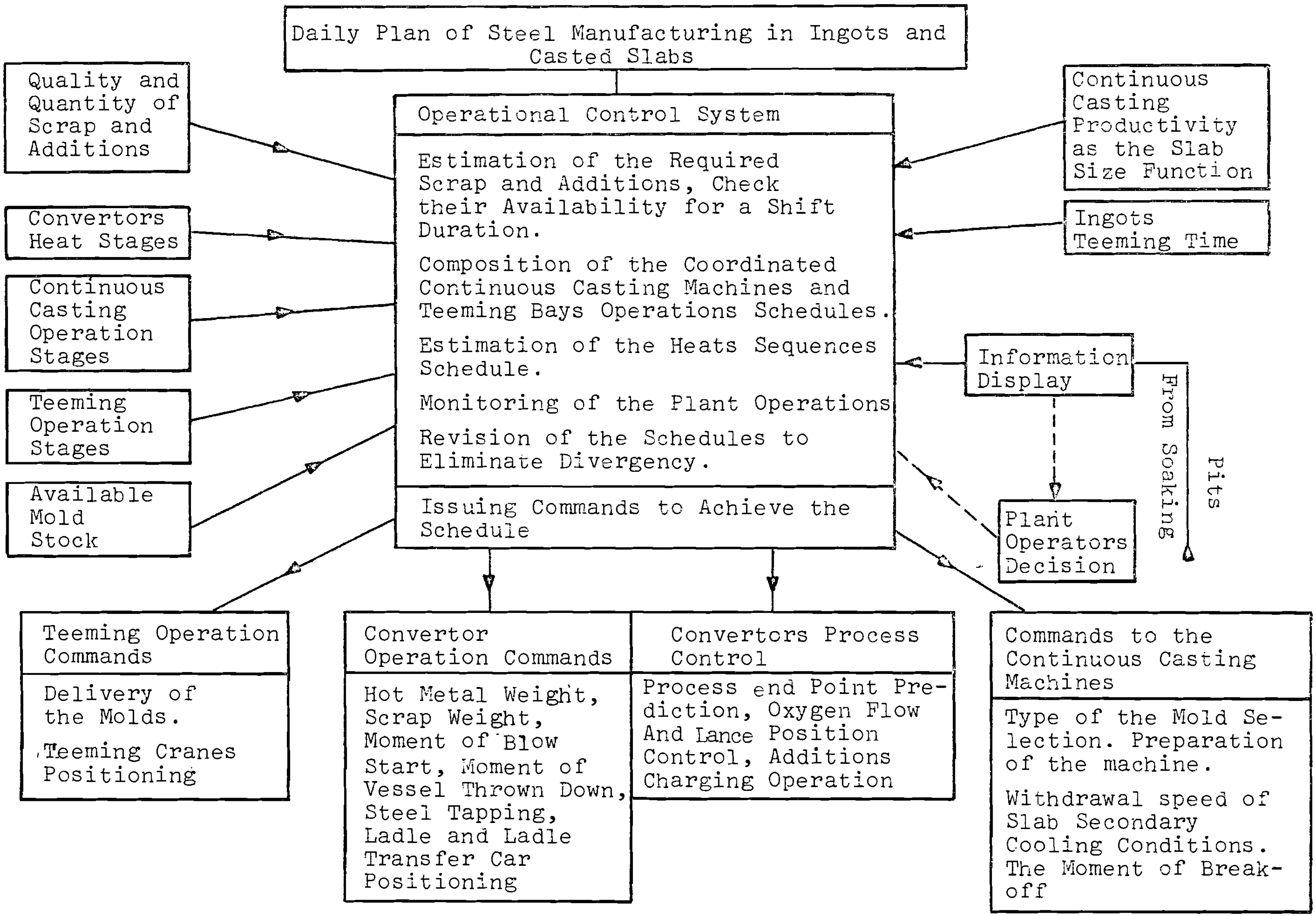


Fig. 2.9 Operational Control of Steelmaking Department

The scheduling of teeming-bay operations should minimize the number of heats sent to the cold ingot stockyard. In other words, this schedule should maintain the condition of the soaking pits such that there are always pits available for charging new ingots arriving from the stripping bays. To calculate such a schedule, the duration of the teeming operations and the track time should be considered, as well as the heating time for ingots in the soaking pits, and the rolling cycle time.

Since there are always some failed heats which are sent to the cold yard and must be repeated, the planning system foresees an average number of such heats and plans their substitutes by charging soaking pits with cold ingots available at the cold yards. Thus, the teeming bay schedule must consider any delay in the ingots' ready time due to cold charging of the soaking pit. This reduces the productivity of the pits considerably since the heating time of cold ingots is much greater than that of hot ingots.

The schedule of continuous casting machine operations should minimize the number of interuptions of the machines since such interruptions require extra operations which lead to an increased average cost of slab production. When compiling the coordinated schedules for teeming and continuous casting operations, it is necessary to consider the fact that the cost of idle time on the blooming mill is higher than on the continuous casting machine, and thus continuation of the blooming mill operations is of higher priority.

Both schedules should ensure that there are no delays in the converters' heating cycles. To achieve this, the withdrawal speed of the cast slabs is varied within permissible limits.

After the coordinated schedules of the teeming bays and continuous casting operation have been determined, the sequence of converter heats of different steel grades is established. In case of divergency from the estimated schedule, the schedule should be revised. It is obvious that the sooner the divergency is revealed, the fewer losses the plant will have. Continuous monitoring of the converters minimizes the delay in detecting errors. As mentioned earlier, this monitoring includes control of the transfer cars and overhead crane position and the readiness of ladles, mould trains and so on. Information about the revealed divergency from the schedule is displayed to the plant operator who decides what action should be taken or how to reschedule the plant operations.

The monitoring of operations is closely connected with the issuing of commands for fulfilling the estimated schedule, thus reducing the probability of divergency. These commands are divided into three groups: converter operation, teeming operation, and continuous casting operation.

The operational control system issues information about the grade of steel to be produced by the converter, and the local process control system calculates the converter charge and the oxygen required. The results of this calculation are sent back to the operational system which determines the set points for the local weighing systems for scrap and hot metal. Static and dynamic models of the process are used to predict the process end point and to estimate the oxygen flow, oxygen lance position and weight and timing of each charge component.

Commands sent to the teeming bay identify the number, type of moulds to be delivered; they also include the commands to crane operators to take a ladle of hot metal to a specified teeming bay.

The operational control system sends instructions to the continuous casting division to prepare a given machine for operation, to install a specified mould size and to establish the required cooling conditions and slab withdrawal speed. The system also establishes the moment when the machine must be prepared for a new operation.

2.13 PRIMARY ROLLING

The teemed ingots solidify in the moulds by natural cooling. For this operation, the mould train is brought to the cooling area where it remains for a time depending on the type of mould and the steel grade. Because the cooling time can vary considerably, the sequence of heats leaving the teeming bay may not be the same as the sequence of heats ready for ingot stripping.

The operational control system for primary rolling Fig. 2.10 modifies the sequence of heats to be delivered to the stripping bays and monitors the movement and position of the ingot trains located in the cooling area. The system issues commands for the delivery of ingot trains to the stripping bays, including commands for ingot stripping. The expected sequence of heats leaving the stripping bays is determined in advance, and the predicted time at which an ingot is ready for charging is compared with the predicted situation at the soaking pits (the next operation in the system). This comparison allows an advance estimate of when cold ingots from the yard can be charged in the pits and which heats should be sent to the cold ingot stockyard. If the heat is not sent to the stockyard, the thermal conditions of the ingots are estimated, based on the time between the teeming and stripping operations, the type of moulds, and the grade of steel. In accordance with the order requirements, the rolling pass schedule and the rolling cycle time are estimated. These data permit calculation of the required discharge times of ingots from the pits.

Monitoring the condition of the ingots in the different pits indentifies which pits are suitable for new ingot charging and establishes the ingot charging operation sequences. After a pit is charged, the computer, having information on the thermal conditions of the charged ingots and the specific characteristics of the pit, predicts the time required for heating (including soaking) the ingots. The predicted ready time for newly charged ingots is compared with that of ingots in other pits; any

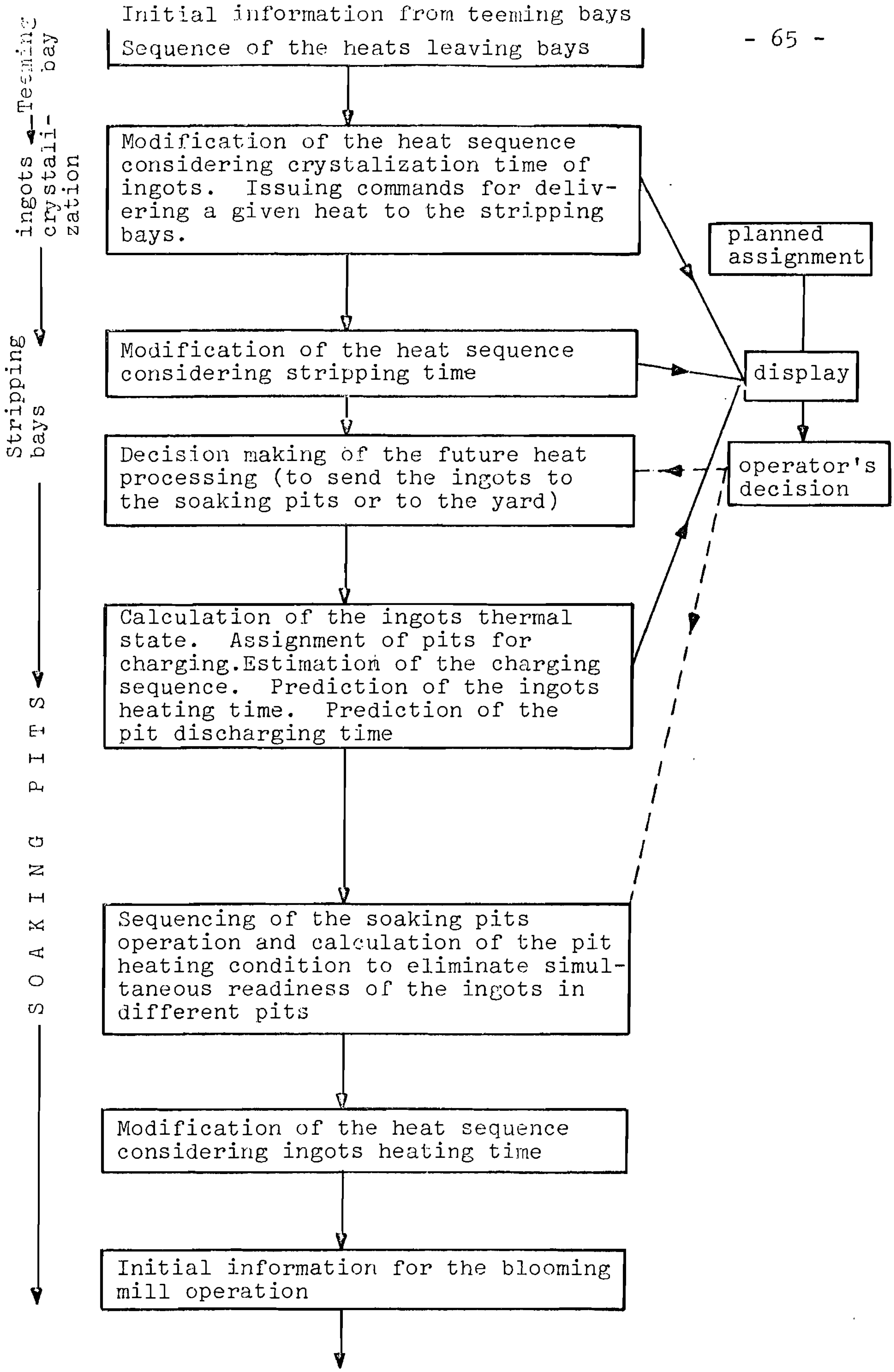


Fig. 2.10 Operational control of the steelmaking - Primary rolling region

coincidence of ready times is avoided by slowing down or speeding up the heating in the pits as necessary, i.e. the ingot ready sequence may be modified by controlling the heating rates.

Thus, the preliminary schedule of teeming operations compiled in advance and based on the standard data for cooling, stripping, heating and rolling operations, is revised in accordance with actual events. These revisions require knowledge not only of the current situation, but also of anticipated changes in the future. To determine the revised schedule, all the available information is displayed to the soaking pit operator who makes the final decision. He then transmits the details of the revision to the planning system which revises the daily production plan at the completion of each shift, thereby compiling an updated assignment for the next shift.

The pit discharging operations are carried out, according to the estimated schedule, by the operational control system which issues appropriate commands to the crab crane operators and to the local system of ingot-buggy position control.

The rolling of each ingot is performed automatically by the local control systems for screw downs, rolling tables and main drive. The operational system (Fig. 2.11) sends commands to the local systems as the rolling process progresses, in accordance with the precalculated distribution of the reduction between passes. Only in cases where the rolling load exceeds the permissible level is on-line recalculation of the reduction distribution necessary. In some cases, instead of on-line calculations, the system has two precalculated reduction distributions corresponding to normal and overload rolling conditions. If the rolling forces are too high, the system switches the reduction schedule to one which calls for more (and hence lighter) passes.

During or after the last pass, the length of the rolled metal is determined and an optimal shearing plan is calculated. The lengths

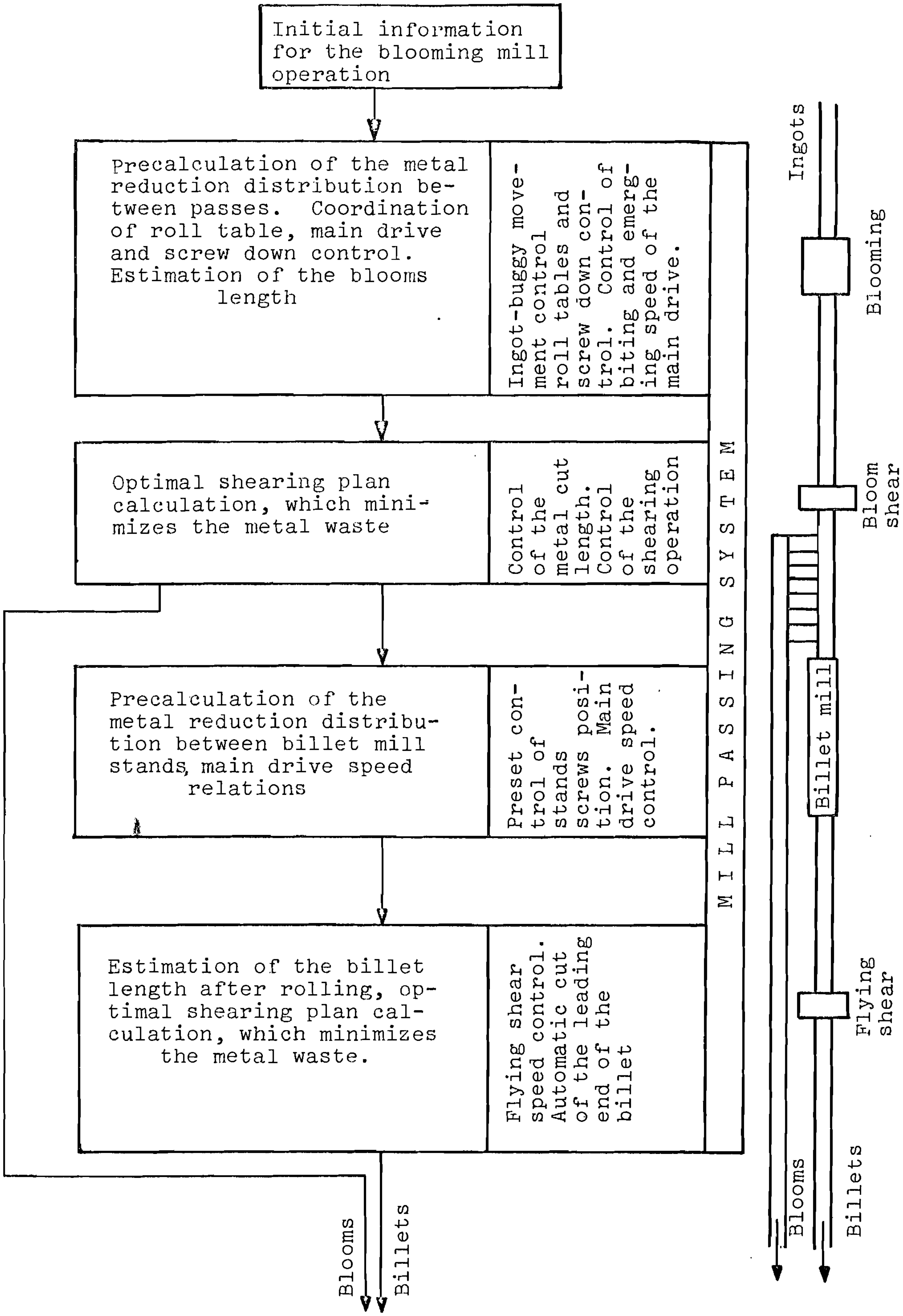


Fig. 2.11 Operational control of primary rolling

of the metal cuts are given to within the permissible tolerance, as instructions to the local control system for the shear and the shear rolling tables.

If the order to which the ingot is assigned requires blooms, the mill passing system issues commands to deliver these to the yard. When an order requires billets, the mill passing system directs blooms to the billet mill.
The setting of this mill is changed by the operational control system after the last billet of a given size is rolled and a new size of billet is to be rolled. This system also gives the assignment to the local system of flying shears control, which measures the total length of metal rolled from one bloom and calculates the optimal shearing plan. All the blooms and billets are automatically marked before entering the yard, and the marking is controlled by commands from the operational control system. In addition to monitoring, sequencing and issuing commands, the operational control system performs data logging and accounting functions; this information is sent to the upper levels of the system.

2.14 SLAB YARD

The semifinished and finished products of the rolling mill are stored in the stock-yards until they are required for the next processing stage or for shipment. Due to the batch type production, the amount of metal stored in the yard can be considerable; to prevent subsequent processing delays, it is essential to have complete information on the location and identity of each metal piece stored in the yard.

One of the most common failures in yard operation is the "loss" of slabs due to incorrect recording of their location in the yard. This is caused by the lack of accurate feedback of the crane operation in transporting slabs to and from the yard. To eliminate the possibility of such failures, the slab yard operational control system shown in Fig. 2.12 has devices for controlling the crane operation and its position.

Only two operations are necessary for automatic control: taking the slab off the yard floor, and discharging the slab onto the floor. To obtain confirmation of correct operation, a logic device can be used which checks the position of the crane hoist and the load on the hook. The crane position measurement can be performed by a non-contact method.

By fixing the crane position when the signal of the slab discharging operation is obtained, the exact location of where the slab is discharged by the crane is determined. The location at which a slab is taken off the floor is fixed in the same way.

Thus, the computer has information about the location of each slab. At the request of the slab yard dispatcher, the information system presents the required information on a display. For instance, the dispatcher can ask where the slabs of some particular order are located, or where all slabs of some grade of steel of a given size are located.

The dispatcher also has the schedules for the rolling mill operations in the form of a time schedule for slabs to be delivered to the mills. On the basis of this information, he decides what assignments should be given to the cranes, and according to these assignments the system issues commands to the crane operators. The commands are transmitted by a telecommunication line to the cranes where they are displayed on the crane operator's screen.

To achieve a fully automated yard for rolled metal, the yard can be equipped with rows of shelves for stocking metal. Stacker cranes run between the rows and fulfill the transportation and loading tasks according to commands received from yard's operations control system. This system has all the information regarding where metal is stored on the shelves and, on request by the yard

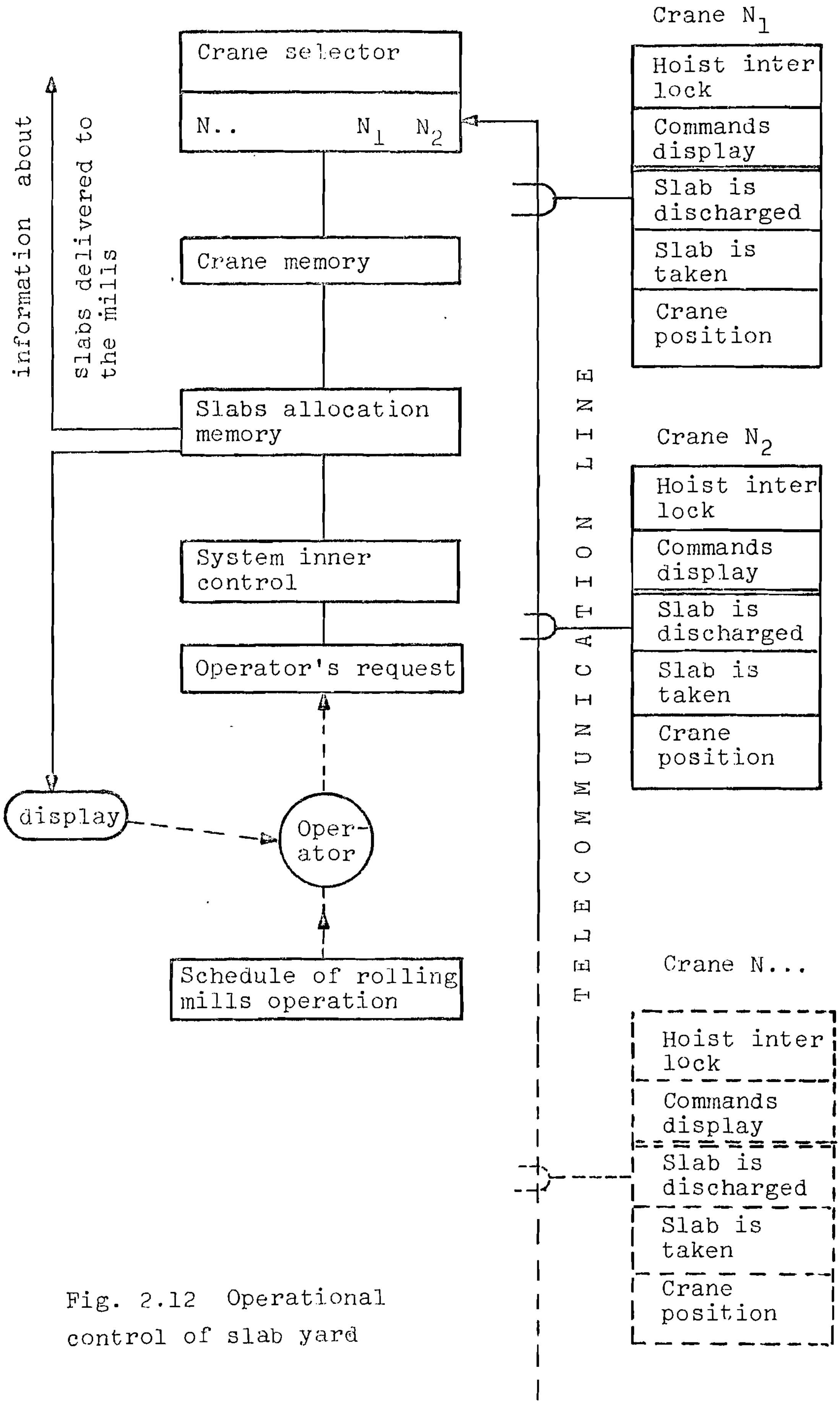


Fig. 2.12 Operational control of slab yard

dispatcher, issues commands to the crane controls so that a required metal stock is retrieved from its storage shelf and delivered to the shipping department, or to the finishing mill entry roll-table, all automatically.

2.15 HEAVY PLATE MILL

To reduce the metal vaste during plate shearing the slab sizes are calculated during the order processing stage according to the specifications of the grouped order. Thus, each slab delivered to the heavy plate reheating furnace has a definite order assignment, and no alternation of this destination is normally permitted since it may cause considerable metal losses in shearing.

The heavy plate mill operation necessitates strict adherence to all the technological instructions selected in advance. Alterations are allowed only during rolling, considering the actual equipment behaviour. For example, the heating program of the furnace should reduce the fuel consumption without affecting the slab's thermal condition; the rolling process operations should ensure that the required plate temperature and dimensions are achieved while minimizing the rolling time cycle. (see Fig. 2.13)

For correct operation of the system, it is essential to identify each slab delivered from the slab yard. This information is supplied by the slab yard operational control system described above. A request to the data bank then provides the metal processing technological instructions for the slab.

The slab tracking system in the furnace provides information on the location of slabs in the furnace, which may be used for optimal slab heating program calculations. After the slab leaves the furnace, its movement through the rolling mill line is tracked by the mill passing system and the shearing line passing system, which operate by means of signals received from the transducers

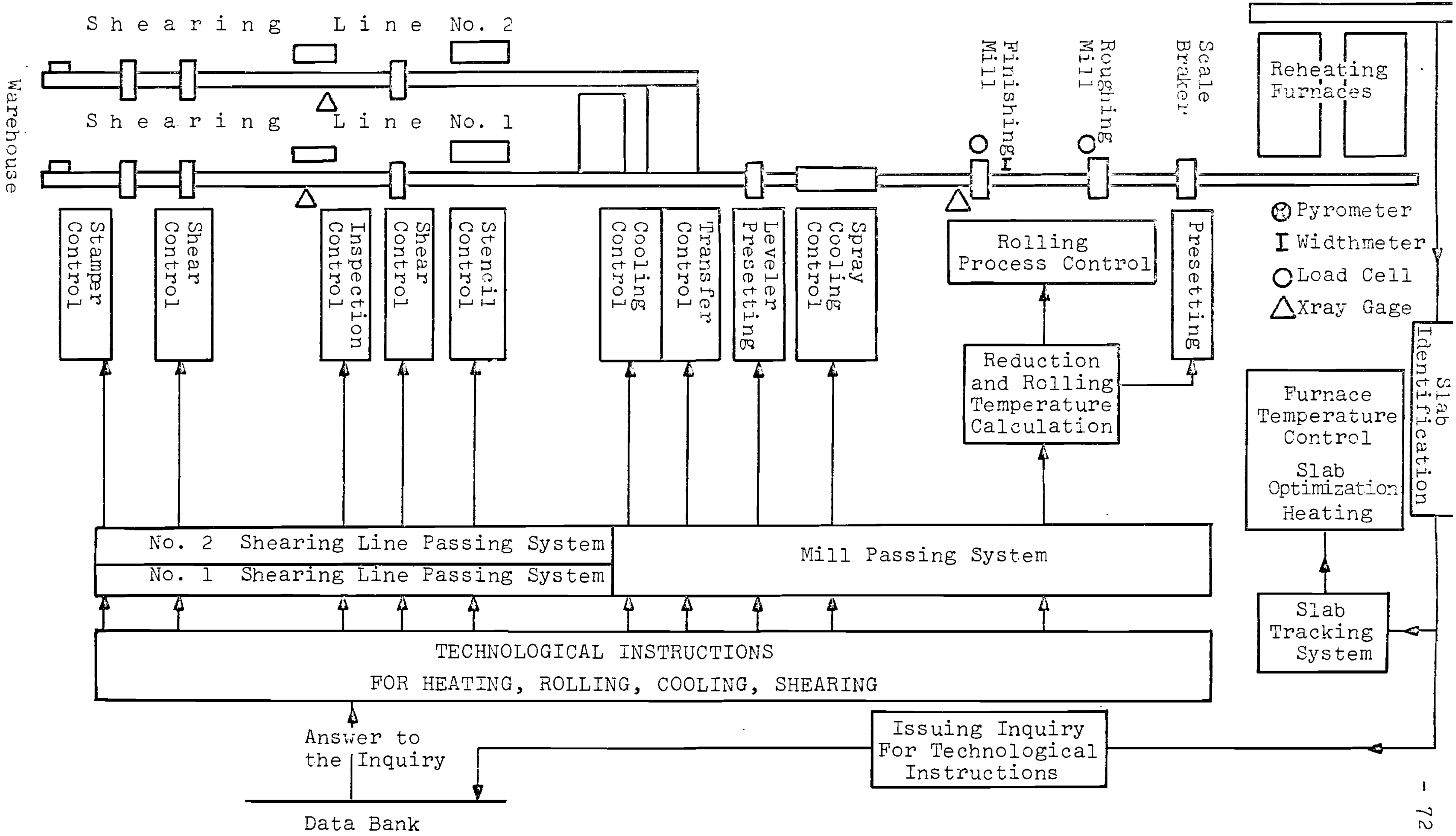


Fig. 2.13 Operational Control System
for Heavy Plate Production Process.

located along these lines. The operational control system translates the technological instructions into assignments to the local control systems. In addition to these functions, the operational system performs data logging and accounting functions, sending the results to the upper level control system.

2.16 HOT STRIP MILL

The daily plan for the hot strip mill is prepared on the basis of the weekly or monthly plan, and during its preparation, limitations on the thickness and width of the strip due to roll wear are taken into account. Two types of roll wear are considered. The wear of the backup rolls spoils the shape of wide strip; hence the strip width should be progressively decreased during the period between backup roll replacements. The wear of the working rolls spoils the shape of thin strip and thus necessitates increasing the strip thickness during the period between working roll changes. The backup rolls are replaced after seven to ten days' operation; the working rolls may be replaced up to twice per shift. Considering these limitations, the daily plan is made up of orders having items of almost the same width but a broad range of thicknesses.

The sequence is determined in such a way that, after each working roll replacement, the rolling should be started again from the widest strip of the smallest thickness and completed with the thickest strip of smallest width. To satisfy these requirements, small order items should be combined and large order items split. These procedures should give rise to an optimal (for a given set of orders) batch of slabs to be rolled in a sequence of increasing thickness, thus ensuring that the maximum total strip length is rolled up to the next working roll change. The fulfillment of this criterion reduces the number of roll changes, thus increasing mill productivity and reducing production costs (changing rolls is expensive). However, as the strip thickness increases, the rolling time decreases; and the furnace discharge frequency is increased, thus there is the possibility that mill production will be limited by furnace capacity.

Reheat furnace capacity depends on the required slab temperature; i.e., the lower the temperature, the higher the capacity obtained. The lower limit on temperature is determined by the mill stand load, and in practice can be used only in the rolling of thick strip which requires less metal reduction. Simultaneously, a decrease in slab temperature allows an increase in rolling speed in order that the final strip temperature be within specified limits. Thus, by proper selection of slab temperature as a function of strip thickness, higher production rates on the hot strip mill can be obtained.

To achieve different slab temperatures in the continuous furnace, it is necessary to charge slabs to the furnace in batches, each of which is heated to a slightly different temperature. Thus, if different slab temperatures are specified, this also affects the slab rolling sequence.

Depending on the mill condition, there is always a possibility that some of the slabs included in the prepared sequence will not be rolled when expected so that their rolling must be transferred to another period. Before each roll change, a revised version of the sequence should therefore be determined. This calculation is done by means of a model which gives the relation between roll wear and strip length to be rolled (for different steel grades and strip dimensions).

After estimation of the slab rolling sequence, the slabs should be delivered from the slab yard to the charging section of the mill. The operational control system for the hot stip mill (Fig. 2.14) issues requests to the slab yard operational control system in the form of a slab delivery schedule. The operational control system, anticipating the slab discharging sequence, determines the order in which each new batch of slabs is to be

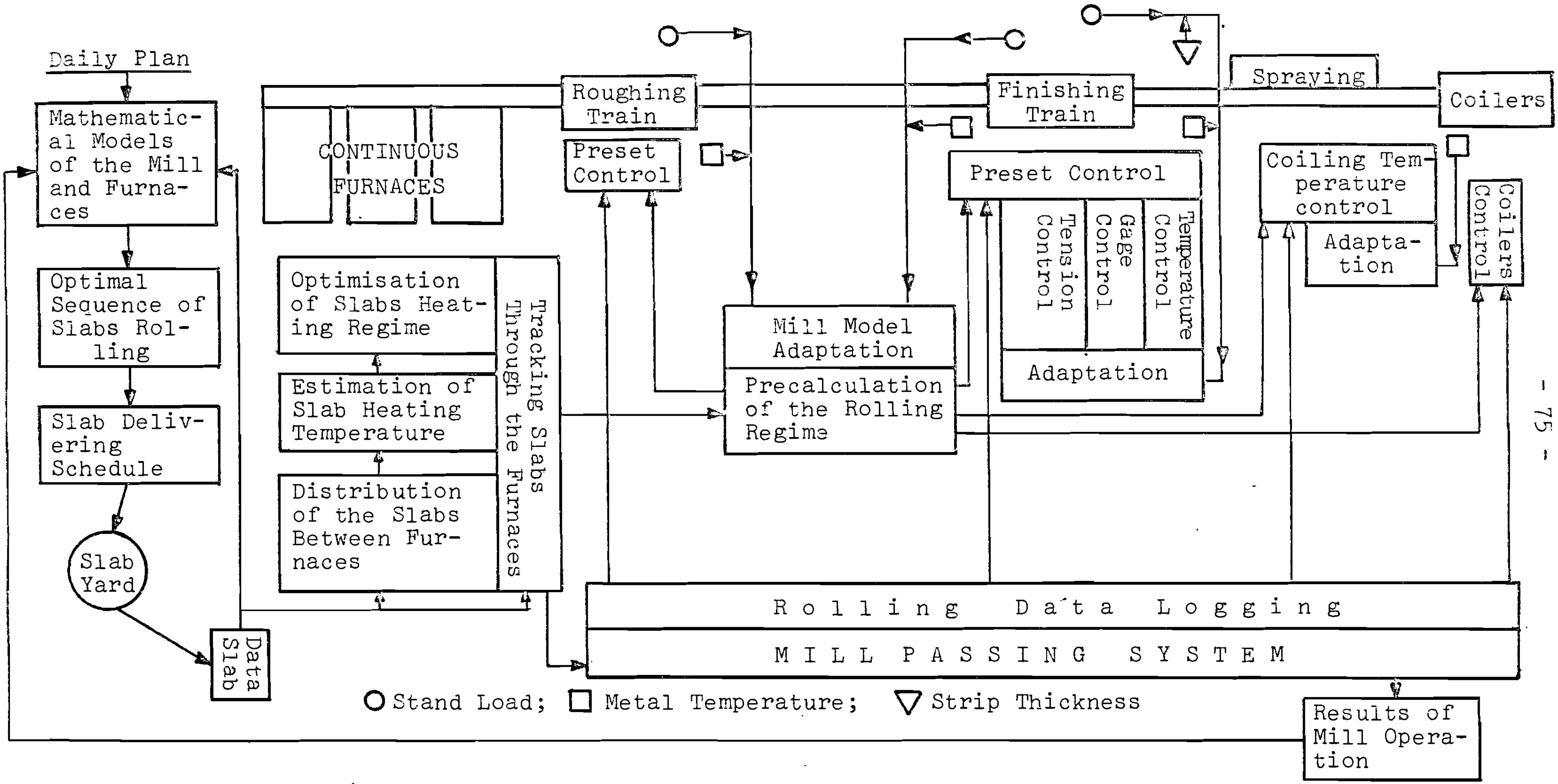


Fig. 2.14 Diagram of Hot Strip Mill Operational Control System

charged into the different furnaces. The system also tracks slabs through the furnaces and sends information on their positions to the furnace heating optimization system which, according to this information, establishes the set points for the temperature controllers.

After a slab has been discharged from the furnace, its movement through the mill line is tracked by the mill system. The signals generated by this system (as the metal passes each stand and points of control between the stands), are used as commands for the local process control systems, e.g. stand screw-down preset control, mill drive speed control, interstand strip tension control, stand gauge control, finishing rolling temperature control, coiling temperature control, and so on.

The set points of these local control systems correspond to the rolling program which can be calculated in advance. The results are stored in the operational control system memory, or can be calculated just before a new slab is rolled. In both cases, the results of the pre-calculation are revised by an adaptation procedure during the rolling of each slab.

By continuously monitoring rolling process performance, the operational control system estimates the quantitative and qualitative results of the mill operation, providing data for each order and each coil; similarly, plant operation data is recorded for each shift, day, and so on.

Coils are taken from the coilers by conveyers and delivered to the hot strip mill coil yard where they are kept for several days for cooling. This yard is capable of stocking several hundred coils and has a special information system similar to that described above for the slab yard. Coils in this yard are transported partly by overhead cranes and partly by electric cars.

2.17 COLD ROLLING DEPARTMENT

As mentioned previously, hot rolled coils pass through the continuously operating pickling lines after cooling, where scale is removed from the surface of the strips by chemical treatment. To ensure continuous strip movement through the line, strip loop accumulators are used at both the start and finish of the rolling line. This allows operators to weld or sew together strips from two different coils without stopping the movement of strip through the baths, and to coil the different strips separately after pickling.

The operational control system tracks the movement of the coils from the coil yard to the entry side of the pickling line and the movement of each strip through the line up to the discharge of the coil from the exit side. By tracking strip movement, the system issues commands to the equipment on the entry side to weld or sew the strips of two coils. On the exit side, commands are issued to stop coiling, cut the strip and start new coiling. Since there is usually more than one pickling line, the system directs the coils delivered from the yard to the appropriate line, considering the pickling processing time.

After pickling, the coils are transported to the cold rolling mill. The productivity of the pickling line increases with strip thickness (since the surface area is less for a given weight coil). On the other hand, the productivity of the rolling mill decreases with decreasing final strip gauge.

Since it is impossible always to have equal productivity of the rolling mill and the pickling lines, there is usually an intermediate coil storage area between them. The daily plan is based on equal loading of both operations; however, to prevent accumulations or shortages of pickled coils during the shift, it is necessary to compose coordinated sequences of the pickling line and rolling mill operations. Thus, one of the functions of the operational control system (Fig. 2.15) is to estimate these two sequences so as to minimize mill idle time caused by a lack of pickled coils.

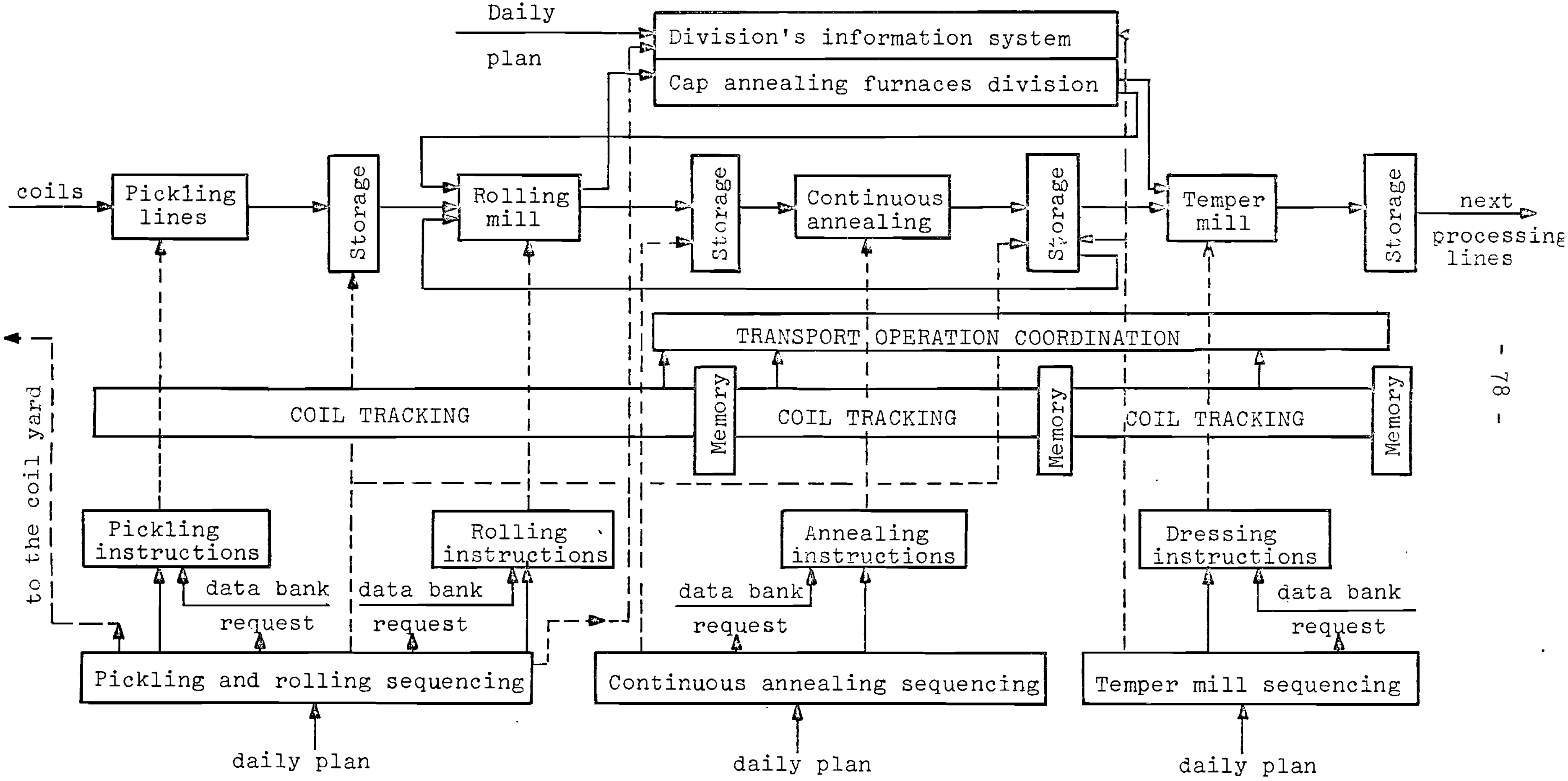


FIG. 2.15 Diagram of cold rolling department material flow and operational control structure

The calculated strip rolling sequence allows pre-estimating the rolling practice for each particular coil. Thus, after completing the rolling of one coil, all the data for mill presetting for the new coil are available. This is achieved by means of the mill mathematical model and can be considered as a function of the local mill preset control system (as shown in Fig. 2.15). Data logging during rolling, records information on rolling mill behavior, which is used for adaptation of the mathematical model of the mill.

After being rolled, the strip goes first through annealing and then through temper mill for "metal dressing" to obtain the required mechanical properties. If the order requires a thinner gauge, the annealed strip is passed on for secondary rerolling.

2.18 ANNEALING

Annealing facilities in the plant can be either continuous type furnaces through which the strip is passed or batch type cap furnaces. The latter operates in a cyclic manner with each cycle taking many hours.

The operational control system for a plant with continuous furnaces tracks coil movement from the rolling mill to the entry side of the furnace. It gives information to the furnace control system, such as what kind of annealing cycle should be performed. The continuous-type furnaces, like the pickling line, operate in a non-stop manner, and the entry and exit sides of the furnace are equipped with loop-type accumulators, shears and joint-type welders.

The operational system, which checks the movement of strip through the furnace, issues commands to the equipment on the entry side to weld the strips of two successive coils, and on the exit side to stop coiling, cut the strip and start a new coiling.

As for the pickling lines and the rolling mill, the daily plan for the annealing furnace does not give the sequence of coils of different orders to be annealed. To compensate for possible imbalance of rolling mill and annealing furnace productivities (over short durations) there is an intermediate rolled coil storage on the furnace entry side. As can be seen from the above, the function of the operational system is to determine the sequence of rolled strip coils to be annealed in the continuous furnace so as to minimize the number of coils in storage and to exclude the possibility of a coil shortage.

The batch-type annealing process using cap furnaces requires the scheduling of their operation over a much longer period than the cycle time, which is much longer than one shift. Usually, the works has both types of annealing facilities, and the furnace type to be used for strip of a particular order is selected beforehand during order processing, where all the technological routes are established. Thus, the coils to be sent to the cap furnaces are known in advance. Since the cap furnace cycle is longer than one day, the planning time interval for this division may be on the order of several days.

The daily plan derived from this several-days' plan, represents the batch of coils to be charged in the furnaces and the batch of coils ready, after annealing, for future processing. This plan considers the number of coils to be rolled after annealing in the continuous and cap furnaces; it is calculated in such a way that the total load is balanced for all the equipment for the day's duration. Thus, the operational control system need only estimate the sequence of the operations for the daily (or shift) plan, but the cap furnace division should have a separate information system for continuous monitoring of annealing process in all of the cap furnaces.

The same problem, namely sequencing for a short time period, is the task of the operational control system for all processing lines located on the technological route following the rolling mill. The coordination of processing for a longer time interval must be tackled by the planning system. Thus, many of the processes in the cold rolling department can be considered as non-interacting during the calculation of sequences based on a day's plan. This means that the operational control system can be split into several parts, each of which can receive assignments from the planning system separately.

However, some coil transport operations are performed by the same cranes and electrocars. To prevent confusion between different operations by the same transportation equipment, the coordination of their operation should be performed by the operational control system. To do this, the system requires information about the location of transport mechanisms and the tasks they carry out, in the same way as in the stock-yard.

The system should know the location of each coil in the storage area. This information can be fed into the system, either manually or automatically, using the principle described earlier for the slab yard, where feedback information is used to check that commands issued by the system are correctly carried out. (For an electrocar powered by accumulators and having a large area of movement, this feedback can be obtained by a special induction system which tracks the movement of each car.)

2.19 OPERATIONAL CONTROL SYSTEM INTERFACES

These examples of the operational control system show that each part of the system can operate separately if the initial information is available, and that this information is just a link between a given system and that of the previous stage. Thus, the primary rolling system receives the initial information from the steelmaking plant; the steelmaking plant receives it from the daily plan assignment, which has a form of daily schedule prepared by the production scheduling system. But the schedule may be revised by the steelmaking operational control system in case of a failed heat, or of changes in the situation in the steel-making shop or the soaking pit division. Rescheduling is done by the operator who receives all the information required for decision-making on a display unit.

The primary rolling operational control system also prepares all the information required for decision-making or redestination of the heat delivered from the steelmaking plant. The scheduling of the soaking pits can be done fully automatically but the operator's confirmation is required.

The slab yard operational control system receives the initial information from the primary rolling system and from the rolling mill operational control system, which estimates the slab delivery schedule (except for the heavy plate mill whose operation is scheduled by the works production planning system).

It can be noted that secondary rolling operations are more independent of previous production stages due to the presence of the yard, which forms a buffer between primary and secondary rolling operations. Interconnection of their operational systems is performed through the production planning system, which prepares coordinated schedules with time horizons of one day or more (depending on the average time required for the hot rolled metal to be ready for the next stage of processing) which minimizes the stock in the yard. The same situation exists in the cold rolling department which is connected with the hot strip mill through the hot coil yard (where the coil cooling time is of the order of several days).

It is interesting to note that the operational control system for the cold rolling department is split into several subsystems of different time scale operation, and interconnected through the daily plan prepared in advance by the production planning system.

Thus, operational control systems are linked through the on-line information flow connected with the material flow, and through the production planning system, when the material processing time is long enough (of shift duration or longer).

Monitoring of the process performance, organization and coordination has a great influence on production efficiency by decreasing the equipment idle time, speeding up the process flow, and decreasing the incidence of failures of production operations. Additionally, by means of achieving a smooth production process flow and by better coordination of the technological conditions, the product quality is further improved over that already obtained through the local process control system. Application of the operational control systems to the semi-finished and finished yards greatly improves the organization of material handling, and thus helps to reduce the stock.

CHAPTER 3. INTERPRETIVE AND GENERALIZED ASPECTS OF THE STATE-OF-THE-ART STUDY.

3.I. MOTIVATION FOR STEEL WORKS COMPUTERIZATION AND INTEGRATION

Every steel producer finds itself in an environment consisting of capital resources, manpower availability, raw material availability, demands for steel products, market situation and geography. Each of these factors influences the type of steelmaking organization required for successful operation, and this in turn affects the type of system for planning, scheduling and control best suited to the company's needs. In many cases, the environment is not constant, e.g. the demands for steel can vary from time to time, and consequently the ideal system must be capable of adapting to the changing circumstances.

Fully computerized works may be more economical than manually operated plants for the following reasons: fewer employees, higher equipment productivity, decrease of inventory stock, improvement of delivery dates, ability to handle small orders, product quality improvement, and so on. These factors are particularly important for the steel manufacturers in a market oriented economy due to the competitive situation. But the additional cost of a fully computerized works is very high and this cost must be considered in the evaluation of alternative systems.

Capital Resources

The amount of capital available to a company is a function of the resources available in the parent country and the business health of the particular company. A restricted availability of capital may have a major influence on systems design and implementation. Thus, it may well be that a fully automated works is more economical than a manually operated plant, but if there is insufficient capital to build such a plant the whole question is academic.

Manpower Availability

Many companies may appear to be moving towards a higher level of automation solely to save manpower. Undoubtedly, this is one motivation in countries where manpower costs are high but it is by no means true universally, nor are costs the only reason for replacing man by machine.

The large new works which can produce IO million tons per annum or more are mostly built in areas where there are insufficient numbers of people, let alone suitably experienced people, to even contemplate staffing such a works for manual operation. The automated works requires far fewer workers skilled in the steelmaking art and the main manpower problem is resolved by hiring young college graduates to operate and to maintain the computerized systems.

Considering steel works of small and medium capacity, these have been in the past predominantly manually controlled. The trend is clearly towards more and more computerization, starting with the control of the technological processes, and extending to computer applications in the field of management information and in operations control. This situation is most typical to companies in the USA and in European countries.

In some cases, companies computerize their plants because they cannot recruit and retain sufficiently highly experienced staff and because performance suffers through the need to continually train new staff. With a computerized plant, the very best practice can be built into computer programs and control systems and a consistently high standard can be maintained.

Raw Material and Fuel Availability

All forms of material and fuel can be provided anywhere, at a price! The situation is likely to be quite different at different works and whatever is costly and/or represents a significant expenditure will attract the attention of efficiency seekers. For example, many companies employ sophisticated selection and transportation cost minimization programs to determine a lowest possible cost solution to the problem of obtaining adequate quantities of suitable ores. There are examples of computer controlled distribution and usage of electricity which results in avoidance of penalty charges (for highly fluctuating loads) while still maintaining high production rates.

Countries, which do not have their own ore and coal must import them, often from great distances, and hence, must compensate these additional expenses by decreasing production costs in order to remain competitive with steel manufacturers in other countries. Thus, a country like Japan, not having its own raw materials for steel production, has developed the most advanced computerized steel plants.

Demand for Steel Products

The manner in which a steel company receives its orders varies a great deal and ranges from a fully planned situation, perhaps over a one to several year period ahead, to a completely free competitive market situation.

In a completely planned situation there is a little need for a rapid response to, for example, quoting competitive delivery times. There must still be an efficient order entry system but speed is not a prime requirement.

For steel manufacturers in a market oriented economy, computerization is needed not only to improve the production efficiency but also to achieve prompt and effective processing of received orders. Thus, the order entry system should be able to respond quickly to enquiries about price, delivery date, etc., otherwise the company is liable to find the order has already been placed and thus lost. That is to say that an offer of price and promised delivery date must be available almost immediately and the probability that the delivery promise will actually be kept, must be very high.

Geography

The locations and distribution of steel works within a company mostly affects communications, both physical movements and information transmissions, and will also have an influence on the level of computerization. The planning and control systems must operate with a speed and accuracy compatible with the company's environment and needs. For example, a company that is physically dispersed, e.g. a head office in the capital and plants in remote industrial areas, must ensure that there is a means of rapid communication between the important offices and functions.

The complications of scheduling product shipments depends on the geographical distribution of customers and the mode of shipment. Thus, if a company delivers most of its products by boat, the system which ensures that there is full boat load scheduled and that items are actually at the dock side at the proper time for loading must work to a higher standard of precision than the delivery system for a company using lorries for delivery by road.

Summary

As can be judged from the above discussion, there are a number of motives for computerization and integration of steel works. No general rule can be suggested for the decision-making concerning the degree of computerization, but the premise is that a company will be encouraged toward increased computerization if a) demand is greater than capacity, in which case automation would increase effective capacity, b) manpower is expensive, and c) it is market oriented, in which case, production efficiency and the speed with which an ordered item moves through the works are important. In general, there is a continuing trend toward more extensive and more sophisticated computerization of the steelmaking system ranging from plant level control through to management information and decision functions.

3.2. PERFORMANCE OF THE PRODUCTION SYSTEM

The performance of the production system is based on four main phases:

1. Estimation of products demand and analysis of the economic situation.
2. Design of the production facilities and the products.
3. Production planning considering the existing plant facilities.
4. Operation of the production processes.

The first phase is characterized by the long-term products demand forecast and is based on detailed investigations of the market situation and its trend. The economic analysis is performed considering the forecast demand, and long-term economic policy of the company is formulated. Final assignments for the production system are then estimated in accordance with this policy.

The first phase is usually of the form of economic planning without detailing the product types.

In socialist countries, having a planned economy, this phase represents a part of the inter-key-industries balance plan which is based on the long-term national economy development plan.

<u>The second phase</u> has as its aim the equalization of production facilities with the demand. It is also characterized by long-term horizons and a high cost of implementation due to the long time required for the design and construction of new production facilities, or for modernization of existing facilities to meet the production assignments.

The design of the products to be manufactured according to the production assignment can also be related to this phase. In most cases, however, the time required for this part of the task is much smaller than that required for the design of new production facilities. In addition, if the products are changed very often, their design is usually performed in line with the planning phase of the production process.

For steel works, the types of the products tend to be stable and during the normal operation of the works, relatively few problems arise concerning new product design. On the other hand, the problems of production facilities design are very complicated and were considered beyond the scope of the present study. Consequently, the problems of this second phase have been excluded from further consideration in the present state-of-the-art review.

<u>The third phase</u>, production planning, is connected with the prediction of future production process flows to meet the demands established by the production assignment. To perform this prediction, the technological routing of the material processing, as well as the technologies of each process along the

route, must be defined. The production plan is then based on considerations of existing equipment capabilities, process time constraints, product delivery dates, production costs and related factors.

The fourth phase, production process operation, can be considered as organization of the processes according to the preselected technological routes, and coordination of the different process operations in order to minimize the effects of various disturbances which may have occurred during the production process flow. The organization of the process refers to presetting the equipment in accordance with the pre-determined technological instructions and initiating the processed material flow through the pre-determined technological routes.

3.3. PRODUCTION PLANNING

Planning Hierarchy

One of the main difficulties in the compiling of production plans is the uncertainty of the prediction process, which increases with increase of the planning horizon. To overcome partly this difficulty, the planning phase is divided into several stages, each with a progressively shorter time horizon, thus forming a planning hierarchy. The main underlying characteristic of this hierarchy is to take into account available data in time to consider several allocative strategies, to update plans on a time scale which reflects both the need to take decisions and the availability of further or more accurate data, to transform plans into working schedules as orders are received and to instruct the plant processes accordingly.

The time scales of the different stages of the hierarchy are estimated, considering not only the timing of decision-making but also the time required to fulfill these decisions (e.g. order raw material and semi-finished products, equipment preparation, labour training, and so on). The planning hierarchies used by different steel producers are very similar, although the level of detail varies between different systems.

There are three main points of divergency among existing systems:

a) the so-called medium term planning is found only in companies who prepare less formal IO-year plans and can be viewed as a refined, more detailed version of the closest 5 years in a IO-year plan.

b) The transition between an annual and a monthly production plan tends, in practice, to be gradual rather than a step function. The points in time at which companies make a formal restatement of the plan varies.

c) The critical process when transforming an allocated production plan into individual process schedules is often considered to be the steelmaking process. Prior processes like the blast furnace tend to work steadily at rates only occasionally changed. The basic steelmaking schedule is usually based on some fraction of a month, ranging from 7 to I4 days, with some plants preferring IO days. The latter is a neater subdivision but, otherwise, no overwhelming evidence was found in favour of a specific period.

Table 3.I gives the main planning time table and time scales. On the annual repetition frequency, the activities are performed in the sequence: long-term, medium-term and annual planning so as to allow each successive planning activity to be a develop-

Table 3.I. PLANNING HIERARCHY

Frequency	Period Covered	Activity	Result
Ad hoc	various	Business strategy	Basic guidelines
Annual	IO-I5 years	Long-term planning	Plant development plans, long-term contracts, financing plans
Annual	5 years	Medium-term planning	Refined plant development plans, marketing strategies and budgets
Annual	I year	Annual planning	Detailed operating plan and budget
Monthly	6,3, and I month	Production planning	Increasingly firm production plans
Daily	up to 3 months	Order entry, allocation to works	Works order file
Daily	up to I4 days (depends on process)	Process scheduling	Sequence of processing instructions
Real time	up to 24 hours	Operations control	Issue of instructions, tracking and receipt of feedback
Real time	up to a few hours (depends on process)	Process control	Direct control of processing
Ad hoc in real time	Immediate	Re-scheduling	Recovery from errors

ment and refinement of the previous one. Thus, the planning process as described is essentially feed forward in nature. There are feedbacks, however, which derive from actual plant capabilities, operating rates, efficiencies, costs, etc. which might quantitatively alter possible production plans. These feedbacks are also manifest through updating of the planning models.

The step by step feed forward approach continues until the point when actual orders arrive. These represent the first real feedback by which the prediction process can be judged, and the plans over time scales of up to one year may well be adjusted in the light of reality.

When actual orders are received, the production assignment is estimated in detail and the preparation procedure for compiling the plan, called "order processing", is carried out. The aim of this procedure is to estimate the technological routes and instructions for the material processing to meet the order requirements (with maximum efficiency) and to perform the necessary production operations.

The second aim of the "order processing" is an estimation of the times required for the orders to be fulfilled through each stage of the technological route. Comparing these times with the equipment availability times, the "plant loading" is performed, which is the basis of the production scheduling. If the manufacturing time required on one of the stages exceeds the available working time, some of the orders should be rejected from the assignment or special measures should be taken (for instance, to postpone equipment repairs, to order semi-finished products from other plants, to prolong the work shift, etc.).

The "plant loading" procedure is achieved by means of the production stages models, which gives the time required by different production stages to manufacture different types of product. The models include allowances for the possibility of non-coordination of separate production operations. The nature of these allowances depends on the scope of the operations considered by the model and on the controllability of the production processes. Thus, by improving the control, the models can reflect these processes more precisely, and the plan compiled by them will be more effective.

A detailed model can perform plant loading with less probability of occurrence of non-coordinated operations and, in effect, the scheduling is reduced to a "job-shop" problem. But increasing the detail of the model makes the problem solution more complicated. Since the presence of disturbances (unpredicted by the model) causes this precise sequence to deviate very quickly from the actual process situation, the degree of detail of the model should be selected considering the plant loading time horizon.

There are other factors that depend on the planning time horizon. Specifically, if the scheduling is treated as an optimization problem (e.g. to maximize mill productivity or process efficiency, to minimize mean inventory levels of semifinished products, etc.), increasing the time horizon tends to increase the degree of optimality of the solution. For example, maximizing performance over one shift may lead to a shortage of resources available for the following shift with a consequent reduction in the overall performance of the process for the two shifts. There is a tradeoff, however, due to the increased divergency between the real and the scheduled process as the horizon increases.

To partly overcome this conflict, several levels of the production scheduling with different time horizons are used, analogously to the planning hierarchy. The production plan is the assignment for the given time duration (year, quarter, month, week, day, etc.) and the production schedule is the division of this assignment into the shorter time intervals. For instance, the monthly plan being divided into weekly intervals provides the basis for a monthly production schedule, the daily plan, being subdivided into shifts and process cycle periods provides the basis for the daily production schedule. With each decrease of the time horizon, a more detailed model is used, thereby, permitting more precise schedules to be obtained.

In addition, the sliding time horizon is used in many scheduling applications (as in the planning process): the scheduling is carried out over a rather long time horizon but when the initial segment interval has passed, the rescheduling is repeated with the same time horizon, but based on the new information obtained up to this moment. This method permits some increase in optimality of the production schedules under the condition of uncertainty concerning future process deflections.

In the case where there are several technological routes that can satisfy the orders requirements (for instance, steelmaking can be performed either in the open hearth furnace or in the oxygen converter; bars can be produced by merchant mills of different types), an optimization problem of the assignment's allocation among these alternative routes can be formulated.

3.4. OPERATIONAL CONTROL

The production operational phase involves the implementation of the production plans and schedules and is carried out by the operational control system. The functions of this system are shown in Fig.3.I. The system works in real-time and receives information directly from the shop floor. The figure also presents some of the functions which belong to the planning phase, but are closely related to the production operational phase (e.g. assignments for the process organizational stage in the form of the technological routes and instructions).

The technological instructions are created on the basis of standard (or nominal) process conditions; the fulfillment of these instructions gives the required process performance only in the case of equivalence of the standard to the actual process conditions. But the real process always deviates from the standard due to the effects of disturbances, thus requiring corrections of the technological instructions according to the observed deflections. Applying these corrections to one stage (or operat-

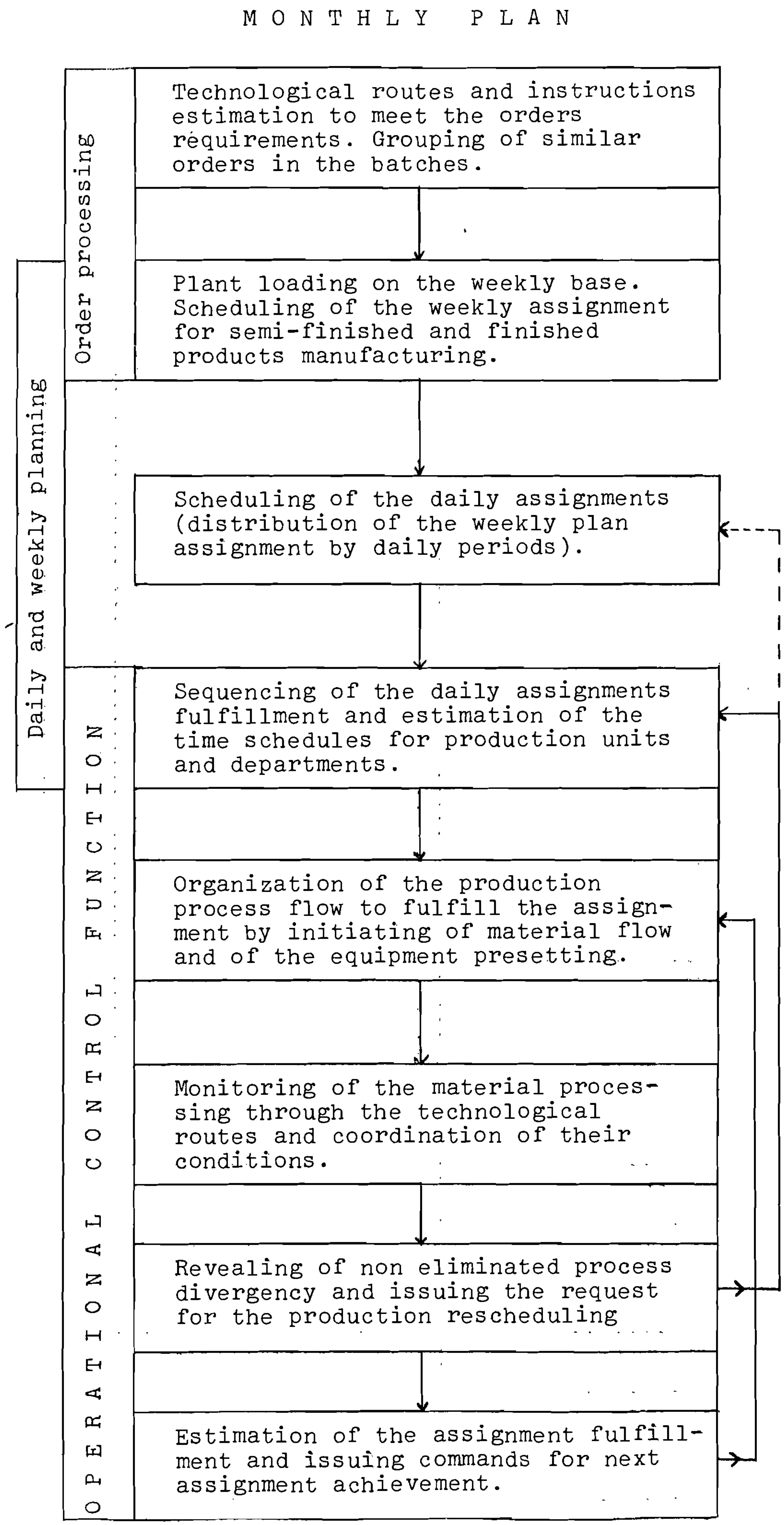


Figure 3.1 The Scope of Operational Control Function

ion) of the production process usually influences the other stages (or operations) as well, thus requiring coordination of the performance of each of these stages.

Depending on the nature of the deflections, the coordination of the production stages can be in the form of an adaptation of the performance model (without changing the process organization) or as a production rescheduling (in some cases with a change of the production plan).

For stable processes which seldom need rescheduling, the production schedule is prepared during the planning phase as indicated above. For instance, in the heavy plate production (described in Chapter 2), the slab sizes are precalculated during the "order processing" stage and each slab has its own destination flow which results in minimum waste of metal in the shearing operation. In the case of a rejected slab, a new planning cycle must be initiated starting from the "order processing" stage, considering the repeat rolling as a new order.

Where the incidence of rejects or production failures occurs rather often, the detailed time scheduling should be performed each time such a failure is revealed. For example, in the steel-making plant, the miscarrying of heats (due to not obtaining the required steel grade) occurs often and, therefore, the detailed scheduling of the primary rolling of ingots is performed for only short time horizon. Since this time period does not usually exceed the normal time duration of the ingot heating cycle, the schedule prepared for this horizon can be revised, as necessary, after each new heat is produced by the plant. Thus, a heat that is produced out of the schedule can often be reassigned by revising the daily (or shift) plan assignments for the rolling operations. In case there is no suitable assignment, the heat is sent to the cold yard. Since the miscarried heat had been destined for some specific order, the heat for the required grade of steel must be rescheduled, and the substituted heat deleted from the assignment.

Process Coordination

The function of process coordination may be explained by the following example given in Chapter 2. A modern hot strip mill is capable of rolling speeds up to 25 meters per second, however, the actual speeds that can be used are much lower because of the limitation imposed by the final rolling temperature which affects strip quality. Thus, the heat losses during rolling of thick strip are much lower than for thin strip, hence, the rolling speed may have to be reduced by a factor of two or three in order to maintain the final strip temperature within the required limits. This has a great influence on the mill production efficiency.

This efficiency can be improved through proper coordination of the temperature control of the slab reheat furnaces and the roll settings on the mill. Specifically, as the required strip thickness increases, slab temperature should be reduced, and the roll settings should be distributed in a way that tends to increase the proportion of metal reduction in the first stands (within allowable loading constraints). This coordination should be done on-line in order to consider the actual condition of the slabs leaving the furnaces.

The result of this coordination greatly depends on the sequencing of the slabs assigned for rolling strips of different thicknesses. Consequently, in defining this sequencing, the special requirements of the coordination feasibility must be considered.

Operational Phase

As can be seen from Fig.3.I, one of the functions performed in the production process operational phase is the organization of the implementation of each item of the schedule. After fulfilling the material processing requirements for a given item in the production schedule, the production process must be reset in accordance with the requirements of the next item of the schedule. A continuous monitoring and accounting of the processed material flows are maintained to establish the moment that the production process switches from one technological instruction and route to the next.

The monitoring also reveals any divergency of the production process from the schedule and thus, may initiate a coordination or a rescheduling of the processing stages. To reveal such divergencies as soon as possible, simulation models are used to provide a fast-time prediction of the process flows. For example, by predicting the ready time of ingots in the soaking pits, the primary rolling operational control system estimates a possible rolling mill idle time or an overheating of ingots. The operational control of the steelmaking plant can minimize converter idle time by predicting in advance the raw material flows and readiness of the auxilliary equipment (teeming cranes, moulds, ladles, and so on).

3.5. DESIGN AND IMPLEMENTATION OF THE INTEGRATED SYSTEMS CONTROL

Integrated systems control of steelmaking covers a broad scope of functions of very different natures and requirements. To create a process control system for a production facility usually requires a deep knowledge of the underlying technology and these systems are often designed by the manufacturer of the technological equipment together with the manufacturer of the control equipment.

The development of planning system should involve a specialist familiar with the capabilities of the technological equipment and with the various possible routings for the material processing. He need not necessarily be deeply acquainted with the processes themselves, but should have a good knowledge of the specific features for a given plant and experience of its general environment.

To design an operational control system for different production stages, it is necessary to be a specialist in the production process organization with a good knowledge of all possible situations which might occur during plant operations as well as the ways of decision-making to improve the situation. His knowledge of the process control should be rather good, particularly, with respect to the restrictions and limits of the process performance.

The differencies in the approaches to the above mentioned problems and the frequent underestimation of the interface problems are often reasons for failure of the integrated system design. This is particularly true in the case of computerization of existing plants due to some conservatism on the part of the plant's staff accustomed to the previous control methods and strategy. There are fewer such probelms for a new plant, but other difficulties may arise, e.g. the lack of experience in solving some of the managerial problems.

When a system for a new plant is under design, it is very helpful that the construction stage and the operational stage are achieved in several steps. For instance, during the first step, only the blast furnace is put into operation. Then the steelmaking plant is erected and the next part of the system is put into operation, and so on. Thus, long time intervals are available for the revisions of the previously designed parts of the integrated system.

It is interesting to note that even after the entire system has been in successful operation for several years, there are always modernizations and improvements of the system's functions that can be incorporated. To accommodate these modifications, the ability to extend the hardware capability should be foreseen at the initial design stage. The decision is often taken to rent rather than purchase the computer in order to provide flexibility in this regard.

The existing and successfully operated integrated control systems have been designed and implemented, in their main parts, by the steel works' staff, rather than by instrumentation or computer manufacturing companies. These companies can supply the hardware and software for the local process control systems and the hardware and computer internal software selected by the designers of the integrated system. However, the latter have to develop all the algorithms and the necessary programming for the computers, and to determine how to structure and organize the system (e.g. how to divide the tasks between man and computer).

3.6. RESULTING EFFICIENCY OF THE COMPUTERIZATION

Depending on the time horizon considered, the planning stages are performed by the company head office or by the works within the company. Usually, long and medium-term planning include an annual planning review performed by the head office, since this concerns the allocation of company limited resources (such as investments, raw material, fuel, etc.). Note that the same considerations arise in socialist countries where the steel works belong to the ministry.

To solve the resources allocational problem without considering how these resources will be used, e.g. without consideration of the production assignment allocation, has no sense. Thus, the company head office prepares the production assignments for each steel works in a way that will be most effective with respect to overall company objectives, e.g. to maximize company profits.

The production planning performed by the works usually has a time horizon of not more than a month, and the criteria for this planning are quality improvement and minimization of production costs.

Thus, in the scope of the company there is a form of centralization which is very close to the centralization of the planning in the socialist countries.

There is also a very strict centralization of the control at the steel works level. The whole production planning procedure, for a month time horizon or less, including order processing and scheduling, is performed in a centralized manner, eliminating the necessity to have separate small production planning departments on the shop level. In addition, this planning with the help of computers require only a few people. Combining the planning-scheduling procedure with the operational control means that only shift teams need to be on the shop floors, with considerable reduction of the steel works' staff.

The total reduction of the number of steel works' employees achieved through a computerized and integrated control system, results in very high productivity levels. Thus, in some Japanese steel works productivity figures of 750 tons steel annually per employee are reported, almost 2,5 times that for works in Europe and the USA.

In addition to the manpower reduction, the integrated system provides increased flexibility of operations and responsiveness, e.g. permitting the handling of small orders, reduction of delivery time, decrease of stock of semifinished and finished products, reduction of material waste, improvement of product quality and increasing generally the productivity.

CHAPTER 4. CONCEPTS AND ANALYTICAL TOOLS

This chapter presents some concepts and analytical tools which have application to the design of integrated systems control of industrial systems. The material of this chapter serves to provide the background for interpretation of the current state-of-the-art of integrated steel works presented in the preceding two chapters. It also provides the basis for a conceptual framework upon which experiences in the steel industry may be generalized to serve a broad class of industrial production systems.

We adopt, for convenience, the term *control* to mean generically all aspects of control and decision-making that are applied to the system operating in real-time, e.g. planning, scheduling, operatons control, process control. The common characteristic of the control function, in the sense employed here, is the basing of actions, responses, decisions, etc. on information describing the state of the system (and its environment) interpreted through the medium of appropriate models relevant to system performance. By the same token, we will use the label *controller* to denote the means or agent by which the control/decision-making functions are carried out.

4.1 BASIC ELEMENTS OF THE SYSTEM

With respect to decision-making and control, we distinguish five basic elements of the system, identified as:

- Plant
- Environment
- Performance Evaluation
- Controller
- Information Processor

The articulation of these elements is shown conceptually as Fig. 4.1.

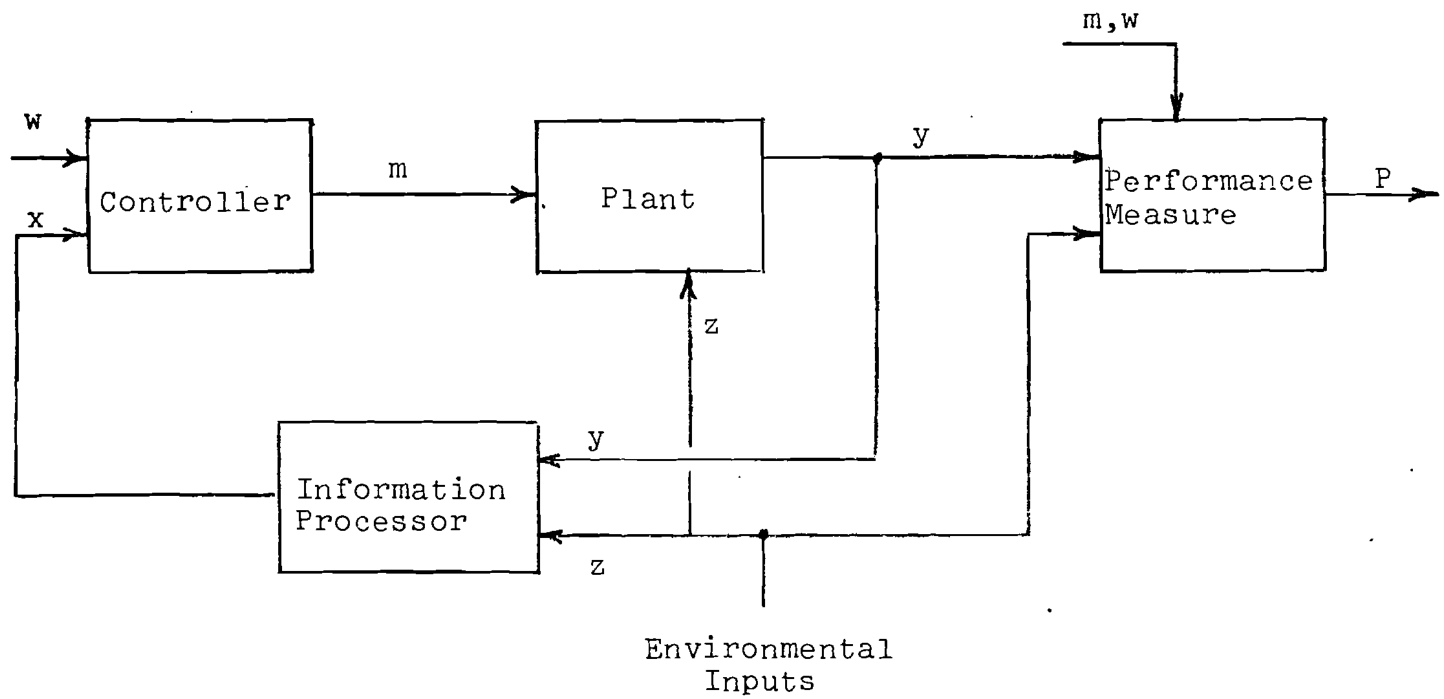


Figure 4.1. Block Diagram of Basic System

Plant

The term *plant* is used here to denote the controlled system or means of production. It may refer variously to a processing unit, a mill, a works or even the company, depending on the level of control being considered.

We assume that the plant is governed by causal relationships, i.e. its behavior, relevant to our control objectives, may be described(in principle) by a set of input-output relationships. We assume further, that some of the plant inputs are free to be selected by a decision-maker or controller so as to influence the plant's behavior in a desired direction. Thus, we may classify the variables associated with the plant as follows:

a)*disturbance inputs* - these are inputs which represent the effects of interactions of the plant with other plant units and/or with the environment, e.g. changes in ore composition, changes in ambient temperature, receipt of a new order, etc. In general, a disturbance change causes the system to deviate from desired or predicted behavior and hence motivates control action. We also recognize a special class of disturbances called *contingency occurrences*. These refer to events that occur essentially at discrete points in time, e.g. disruption of flow of a raw material through strike action, breakdown of a piece of equipment, receipt of a high priority rush order, failure of the product to meet the order specification. Often, a contingency event signals that the system is no longer operating according to assumptions implied by the current control model and that, as a result, it is necessary to modify the structure of the system, go into a new control mode, or develop some other non-normal response.

b) *controlled inputs* - these are the results of the decision-making process carried out by the computer/controller (may also be referred to as decision variables). There are two modes:

(i) programmed mode where the controlled inputs are established in advance based on given demands on the system or requirements of plant performance,

(ii) compensation mode where the controlled inputs are determined so as to compensate for the effects of disturbances.

The controlled inputs either directly or indirectly modify the the relationships among the plant variables, e.g. by changing the energy or material balance in the system. Their determination may be based on

(i) measurement of the disturbance input and prediction of its ultimate effect on the plant (feedforward action) or

(ii) measurement of the effect of the disturbance on the plant outputs directly (feedback action), or more generally,

(iii) a combination of both.

c) *outputs* - these are the variables of the plant which

(i) are functionally dependent on the designated input variables, and

(ii) are relevant with respect to the performance measure on which control of the plant is based.

d) *state variables* - in essence, these are variables associated with the memory characteristics of the plant. In the case of deterministic, dynamic systems, the state vector compacts the relevant past history of the plant, such that, knowing the inputs to the plant over a given time interval, the outputs are uniquely determined over that same period. More generally, the state vector may identify the status of energy/material storages in the system, the current mode of operating units, and other factors which are necessary to the identification of the appropriate input-output relationships (models) currently applicable.

Thus, we imply a plant model of the general form

$$y = g(m,z,s) \qquad (1)$$

where y, m, z, s denote vectors of output variables, controlled inputs, disturbance inputs and state variables, respectively. Here g(•) denotes a vector of functional relationships which may be expressed as - algebraic functions, integral equations, graphs, tabulated data -as appropriate to the application. The variables may be continuous or discrete functions of time; they may be real-valued, integer-valued (e.g. quantized data) or Boolean-valued.

Environment

The plant is a subsystem of a larger system which we term the environment, i.e. all aspects of the external world that interact with and affect the operations and performance of the plant. There are a large number and variety of such interactions; the major one for our consideration is the market as it reflects the demands for different types of products, the costs and availability of raw materials, etc. Other linkages of the environment to the plant include economic and financial conditions, labor supply, weather, quality of raw materials, etc.

The interactions are of two basic types:

a) inputs to the plant which change its state or affect its performance. These we have referred to as disturbance inputs

b) inputs that affect the objectives or constraints to be applied by the controller acting on the plant, e.g. order specifications.

In general, the objectives which should be achieved by the plant during future operations are estimated through an analysis of the environment and a forecasting of its demand. The demand is typically a time-varying function which, depending on the forecast horizon, can be divided into two parts, a deterministic part which represents the average trend of the demand over time, and a stochastic part which represents the unpredicted disturbances superimposed on this trend.

Performance Evaluation

In the design of the decision-making/control system, it is necessary to have defined the criteria for measuring and evaluating plant performance in order that appropriate references or targets for control may be established. At the technological level, we may consider objectives of:

a) maximizing production efficiency
b) minimizing operating costs
c) maximizing probability of maintaining the plant in a feasible or acceptable operating regime
d) minimizing the likelihood of failure of the system to perform to standards, e.g. failure to satisfy product specifications or environmental constraints.

In practice, the performance criteria used in formulating the decision-making and control algorithms for real-time application are generally simplifications of the above, reflecting the dominant factors entering into the performance measure. Thus, the control associated with a particular unit may act to maximize product yield, throughput rate, or thermal efficiency, or to minimize the consumption of a costly resource, the frequency of quality rejects, or deviations from standards. This point will be referred to again in the discussion of the multilayer, control hierarchy.

At the economic level, objectives for decision-making may include maximizing profit, return on investment and related indices. Again, the practical criteria will generally be based on approximations and simplifications which are motivated by computational requirements, the form and accuracy of the models used, the nature of the information required and the reliability of the data available.

We assume that the performance may be expressed explicitly (or perhaps only implicitly) as a function of the system input and output variables, i.e.

$$P = \bar{f}(m,y,z,w) \qquad (2)$$

where m,y,z are defined in (1)[1]; w denotes the vector of external inputs affecting performance, e.g. economic factors, product/order specifications, government constraints, etc. Since the system may exhibit significant dynamics (memory effects), the performance measure should represent an integration of plant behavior over a time period which is large with respect to the effective time lag of the system response[2]. Thus, there will be random components of the variables represented in (2) and we imply by the notation $\bar{f}(\cdot)$ that a suitable averaging is carried out over the relevant time horizon.

Controller

If we didn't consider the problem of realization, we would ideally like to determine the control algorithm so as to achieve an optimal performance: i.e.

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1. Numerals in parentheses denote equation number referenced in the text.

2. Eq. (2) then implies that the arguments of $\bar{f}(\cdot)$ are the complete time functions over the interval of integration, e.g. m implies $m_{[t_o,t_1]}$, etc., where $[t_o,t_1]$ denotes the time interval over which the performance is evaluated.

$$\max_{m \in M} \bar{f}(m,y,z,w)$$

where $M = \{m | y=g(m,z,s),\ h(m,y,z,w) \geq 0\}$ (3)

Here $g(\cdot)$ denotes the set of input-output relationships for the plant and $h(\cdot)$ denotes the set of inequality constraints applicable to the system. Of course, practical considerations (e.g. complexity of the model, cost of implementation) dictate a suboptimal approach to (3) (which sometimes degenerates to the problem of just finding a feasible solution!).

The inequality constraints play a very important role in defining the region of feasible or acceptable plant operation. The constraints may characterize actual technological limits imposed by the equipment or by the nature of the production process, e.g. capacity limit of a machine, melting temperature of the steel. Constraints are also imposed to ensure the safety of operating personnel or of the security of the production means e.g. temperature limits imposed on a furnace in order to avoid too rapid deterioration of the refractory lining. Finally, we impose constraints to ensure that various quality requirements are met, e.g. product specifications, effluent discharge pollution standards, etc. An example is the "coffin rule" constraint used in rolling to ensure that, in carrying out the rolling operation (optimally perhaps, according to a locally defined criterion), surface quality of the strip product is not impaired.

The result of carrying out the maximization operation of (3) implies a relationship of the form

$$m = m(\overset{*}{y},\overset{*}{z},w) \qquad (4)$$

Where y^*, z^* denote vectors composed of those components of y and z, respectively, that are measured and whose values are transmitted to the controller.

The contribution of y^* to the control function represents a *feedback* compensation, i.e. a control response to the effects of prior inputs to the plant; the contributions of z^* and w represent *feedforward* actions, i.e. compensations anticipating the effects of current system inputs on subsequent plant performance.

Note that the realization of (4) may take a variety of forms. Indeed, from the standpoint of plant performance, it is immaterial how the transformations from input information to output decisions/control actions are carried out (i.e., whether by algebraic solution of a set of equations, by hill climbing on a fast-time simulation, or simply by table look-up) except as the method might affect the accuracy, the cost or the speed with which the controller outputs its results. By the same token, the control functions may be performed by man, by machine (computer) or by an intersection of both.

Control Period

The control function (4) is not carried out continuously but rather at discrete points in time. There are several factors which influence the mean period between successive control actions:

a) the effective time lag for response of the system
b) the mean time between significant changes in disturbance inputs.
c) the time required for obtaining and processing the data on which the control is based
d) the time required by the computer (or human decision-maker) to determine the necessary control action (this time may be greatly affected by cost considerations).

e) the minimum time interval over which performance evaluation is meaningful.

Thus, there are two alternative policies for initiating control action:

a) Periodic policy - the control action is carried out at uniform time increments independent of whether or not a significant disturbance change has occurred. This is based on an implied assumption that the average cost of controlling with the given period is lower than the cost that would be incurred by testing first to determine if an action should be initiated. Typical examples of a periodic policy are the monthly plan, the weekly schedule, etc.

b) On-demand policy - the control action is carried out only in response to an initiating signal or "trigger". Control actions may be initiated by a signal announcing that

i) a batch operation is ready for a new cycle,
ii) a significant disturbance change has occurred since the last control action,
iii) a contingency event has occurred requiring an immediate response, or
iv) some maximum time interval has elapsed since the last control action.

Examples of an on-demand policy are the reschedule of a mill instigated by a cobble, the revision of a monthly plan caused by an unexpected major equipment breakdown, the start of a new BOF cycle.

In general, we see both types of policy operating in the steel production system. For example, a periodic policy may govern the normal events and operating requirements of a given plant with an on-demand policy superimposed to take care of abnormal events, contingency occurrences, etc.

Information Processor

As noted above, the underlying assumption in the achievement of integrated control is that the controller acts on the basis of (real-time) information concerning the state of the plant, external inputs, etc. We may distinguish several major functions of the information system:

a) the gathering of data and its distribution to points of usage (including sensors, data input devices, transmission links, data banks, etc.).
b) the reduction (interpretation) of raw data into the form required by the decision-making/control function, e.g. (i) data smoothing, (ii) noise filtering, (iii) prediction and extrapolation, (iv) inference of the value of a variable from indirect measurements, etc.
c) the monitoring of system status for contingency events to determine whether diagnostic and/or corrective responses are to be initiated.
d) presentation of information for the people interfacing the system, e.g. monitoring and control actions by operating personnel, decision-making by management, diagnostics for maintenance and corrective actions, record keeping, etc.

4.2 MULTILAYER FUNCTIONAL HIERARCHY

The problems of realization and implementation of an integrated control according to (3) are generally formidable because of the complexity of the system, the variety of constraints to be satisfied, time-varying behavior, etc. The multilayer, functional hierarchy of Fig. 4.2 provides a rational and sys-

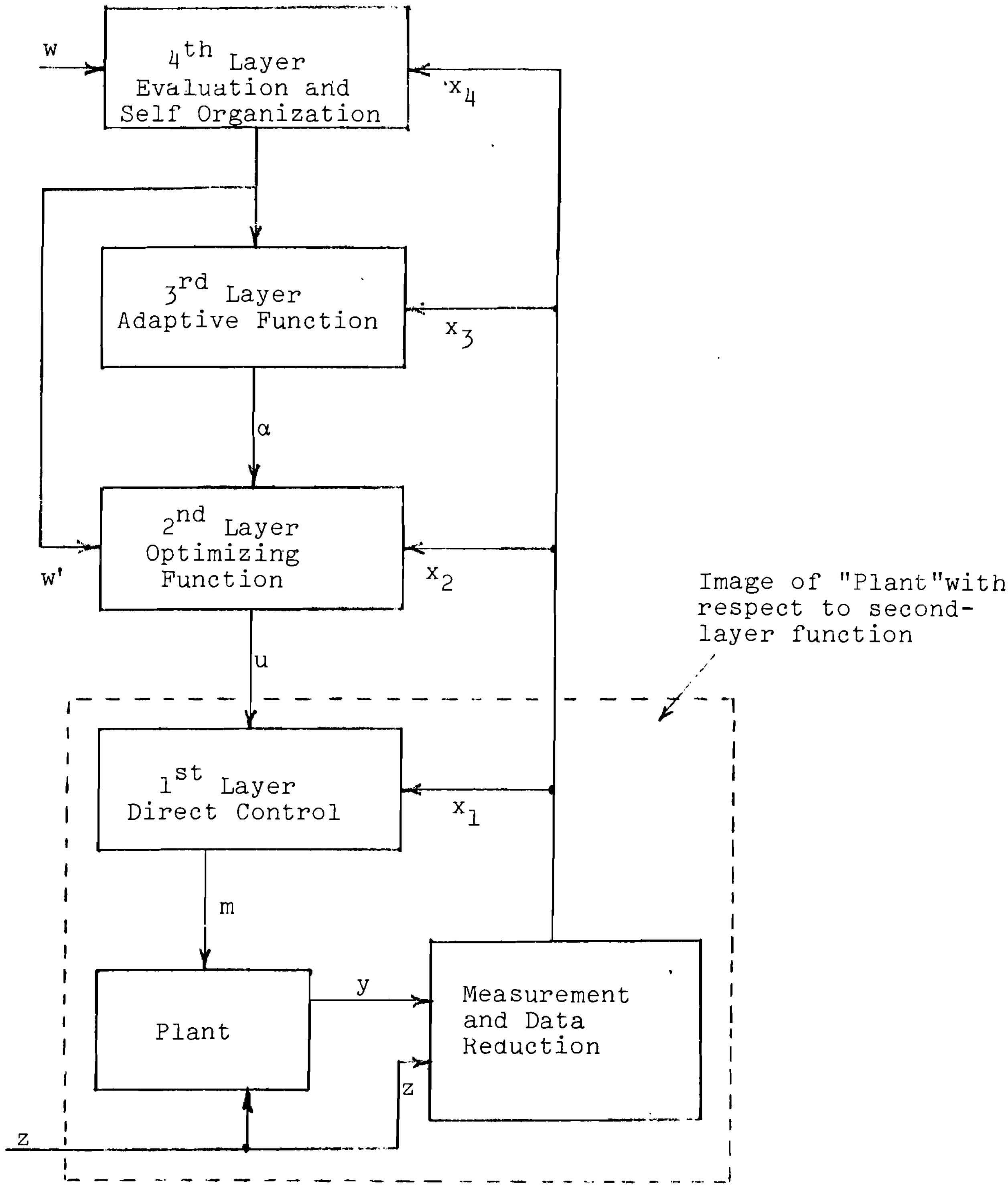

Fig. 4.2 Functional Multilayer Hierarchy

tematic procedure for resolving these problems. In effect, the overall problem is replaced by a set of subproblems which are more amenable to resolution than the original problem. Essentially the problem statement of (3) is modified to

$$\max_{u \in U} \quad P'(u,y',z',w') \tag{5}$$

where $U = \{u \mid y' = G(u,z',\alpha), \;\; H(u,y',z',w') \geq 0\}$

The resulting decision-making/control algorithm is then of the form

$$u = u(x_2, w', \alpha) \tag{6}$$

where $$x_2 = \phi(y^*, z^*, \beta) \tag{7}$$

The following explanatory remarks are in order:

1) The plant is described by the approximate model

$$y' = G(u,z',\alpha) \tag{8}$$

where y',z' are vectors formed by the components of y and z, respectively, that are relevant to the second-layer (optimizing control) problem. The functions G are simplified approximations to the actual plant relationships(1) with the parameter vector, α , properly chosen to give a good representation. Note that (8) characterizes the input-output model of the combined system consisting of the plant, direct controllers and measuring elements as seen by the second layer function (represented by the dotted block in Fig. 4.2). The problem is further simplified by assuming negligible dynamics in the plant model so that G may be represented by static (e.g.

algebraic functions, as noted in Remark 3) below. Any state dependent features of the model are assumed to be imbedded in the parameter vector[1].

2) The vector x_2 characterizes the information from the plant used by the second-layer controller in generating its output u. Eq. (7) represents a data processing function (e.g. prediction, averaging, aggregating) based on the measured components of y and z, denoted by y^* and z^*, respectively. The function ϕ may have a (adjustable) parameter vector β, e.g. based on estimated statistical properties of z, which may be adapted to reflect changing conditions. In general, we assume x_2 to be of a lower dimension than the information vector implied in the algorithm (4).

3) The first-layer (direct control) function plays the role of implementing the decisions of the second-layer function, expressed as the vector $u = (u_y, u_m)$, where u_y denotes a vector of set-points for y which, through feedbacks (and feedforward mechanisms) determines a subset of the components of m; the remaining components of m are determined directly by u_m. This implies the first-layer relationship (see Fig. 4.3).

$$m = m(x_1, u) \qquad (9)$$

where x_1 denotes the information used in implementing the direct control function.

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1. Of course, where the dynamic or memory aspects of the control problem are significant, then (8) can be formulated as a dynamic model, e.g.

$$y' = G(u, z'; s, \alpha) \qquad (8')$$

where s denotes the initial state and y', u and z' denote time functions (or sequences) over a finite interval.

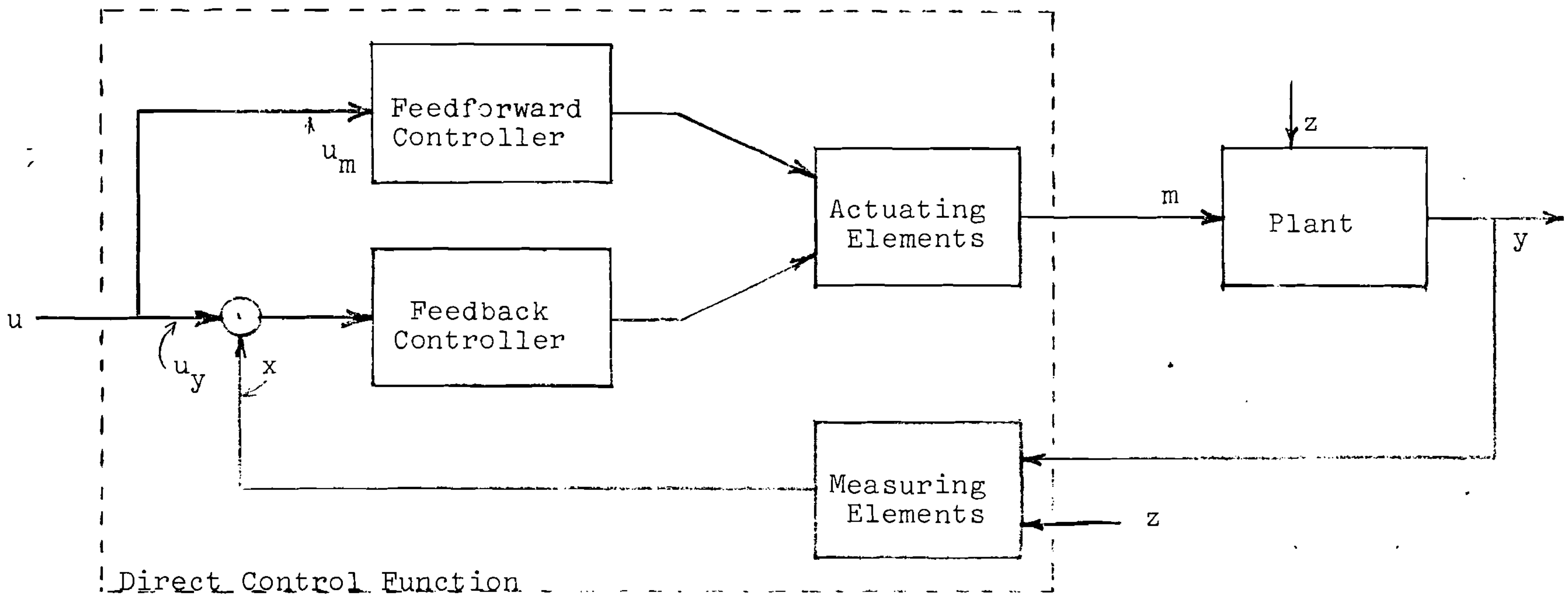


Fig. 4.3 Implementation of the Direct Control Function

There are two useful consequences of (9):

a) various disturbance inputs may be suppressed with respect to the second-layer problem, e.g. by specifying furnace temperature as the decision variable rather than, say heat input rate, we remove the need for explicit consideration (in the optimization) of the many disturbance variables that may effect the thermal equilibrium and heat transfer relationship of the plant; and

b) the dynamic aspects of the control problem may be effectively "absorbed" at the first layer so that static models can be used at the higher layers to good approximation.

4) The vector function H often includes, besides those constraints necessary to ensure safe and feasible operation of the physical system, various artificial constraints whose primary function is to maintain the system within the limited region of operating space for which the approximate model is valid (and hence useful). It is assumed, of course, that the imposition of such constraints will not result in any significant diminishing of the attainable performance. An example of this is the placing of bounds on the maximum rate of change of temperature in the final zone of a reheat furnace to ensure that the assumption of slab homogeneity on which subsequent slab rolling models are based, are reasonably valid.

5) The decision algorithm may be based on (i) an explicit (mathematical) model e.g. a set of input-output relationships for the subsystem from which the algorithm is derived via an optimization procedure, or (ii) an implicit model, e.g. a decision (look-up) table based on empirical rules. In either case, the algorithm is based on some simplified, approximate image of the physical system which is valid only in the neighborhood of a given "state" or set of circumstances. As these change with time, it is necessary to update the algorithm either directly by adjusting some of its parameters or indirectly via the parameters of the

underlying model. The updating is carried out by the third-layer adaptive function in response to current experience with the operating system as conveyed through the information set x_3. This means that we can eliminate from the problem formulation (5) those factors or disturbance inputs which tend to change infrequently relative to the period of control action (e.g. fouling of a heat transfer surface, seasonal variations in cooling water temperature), since they may be compensated through the adaptive functions.

6) The external (economic) factors contained in w are now inputted via a fourth-layer (evaluation and self-organization) function and are transmitted to the second-layer model via the vector w. Changes in w may influence the weighting of terms in P' or some of the bounds imbedded in H. More generally, the evaluation of performance (through the information set x_4) may lead to modifications in the structure of the control system, e.g. in the constraint set U. Finally, we note that contingency events may also lead to changes in system relationships or objective function (manifest as changes in U and/or P'), e.g. the shift from normal operation of a mill to an emergency mode following a cobble or breakdown.

7) The underlying principles of the multilayer functional hierarchy apply equally well to control of continuous, semicontinuous and batch processes. In the continuous case, the plant model may be described by algebraic equations; in the batch case, differential or difference equations may characterize the plant.[1]

1. This, of course, requires a modification of the relationships implied by (5) to reflect the dynamics of the change of state. This is a straight forward extension of the static formulation presented here and will not be further elaborated in this discussion.

A case in point is the example of a heating furnace. The second layer function may determine trajectories of furnace temperature (as the control input) and slab temperature (as the state vector) so that a specified final temperature of the slab is achieved with minimum fuel consumption. The trajectories may be computed prior to the start of each new batch of slabs, with inputs based on measured initial slab temperature, estimated thermal coefficients, etc. The first layer has the problem of implementation. There are a variety of disturbances that cause the actual trajectories to deviate from the computed optimal (reference) paths (e.g. changes in heat transfer properties from those predicted, errors in the model used, etc.). One form that the first-layer control may take (to compensate for the disturbances) is to minimize a weighted mean square deviation of the actual trajectories from their reference paths, applying optimal control theory (linear model, quadratic criterion). It is clear, in this application, that the third-layer adaptive function may update the parameters of the (nonlinear) second-layer model, as well as perhaps the weighting of coefficients of the quadratic criterion used at the first layer (assuming the coefficients for the linearized model are evaluated at the second layer along with the reference trajectories). The fourth-layer functions will be concerned with the same overall considerations as discussed previously.

8) There are a large variety of ancillary tasks normally carried out in conjunction with the control functions identified in the multilayer hierarchy. These might be looked upon as "enabling" functions that are deemed necessary or useful to the pursuit of the overall system goals. Indeed, the provision for such tasks is often a very significant factor in determining hardware and software requirements in computer control applications. Among such ancillary functions we include:

(i) data gathering (filtering, smoothing, data reduction),

(ii) record keeping (for plant operator, production control, management information, accounting, etc.),

(iii) inventory maintenance (e.g. keeping track of goods in process),

(iv) sequencing of operations (e.g. startup/shutdown operations).

The essential feature of these functions is that they are routine, repetitive and open-loop, hence can be handled by stored programs and fixed hardware. Considerations of decision-making and control may come into the picture at the higher layers, however, with respect to modifying the procedures, operating sequences, etc., based on evaluation of performance or in response to contingency occurrences.

4.3 MULTILEVEL CONTROL HIERARCHY

We consider again the optimization problem (5) reformulated[1] for convenience as follows:

$$\max_{u \in U(z)} f(u,y,z) \qquad (10)$$

where $U(z) = \{u | y = g(u,z),\ h(u,y,z) \geq 0\}$

where f is the measure of overall performance (objective function), u is the vector of decision variables (controller outputs), y is the vector of plant outputs, z is the vector of disturbance inputs, U(z) denotes the feasiblity set (conditional on z), g and h denote vectors of equality and inequality constraints, respectively.

We assume that the problem (10) has a solution, $u^o(z)$; however, despite the simplifications introduced into the model via the

1. Besides slight changes in notation, we have suppressed the dependence of the functions on w and α (i.e. assumed these are fixed over the time horizon of the optimization problem).

multilayer approach, the solution is still too difficult or too costly to obtain directly in a form suitable for on-line implementation (limiting factors may include excessive computation time, inadequate storage capacity of the available computer, etc.). The multilevel approach, where applicable, provides a means of circumventing the difficulty of decomposing the overall problem into a number of simpler and more easily solved sub problems. Thus, in application to the problem (5), we assume that the functions are separable in the sense that we can decompose the overall problem into N sub-problems as follows:

i^{th} subproblem:

$$\max_{u_i \varepsilon U_i} \quad f_i(u_i, y_i, q_i, z_i) \qquad i = 1,2,\ldots N$$

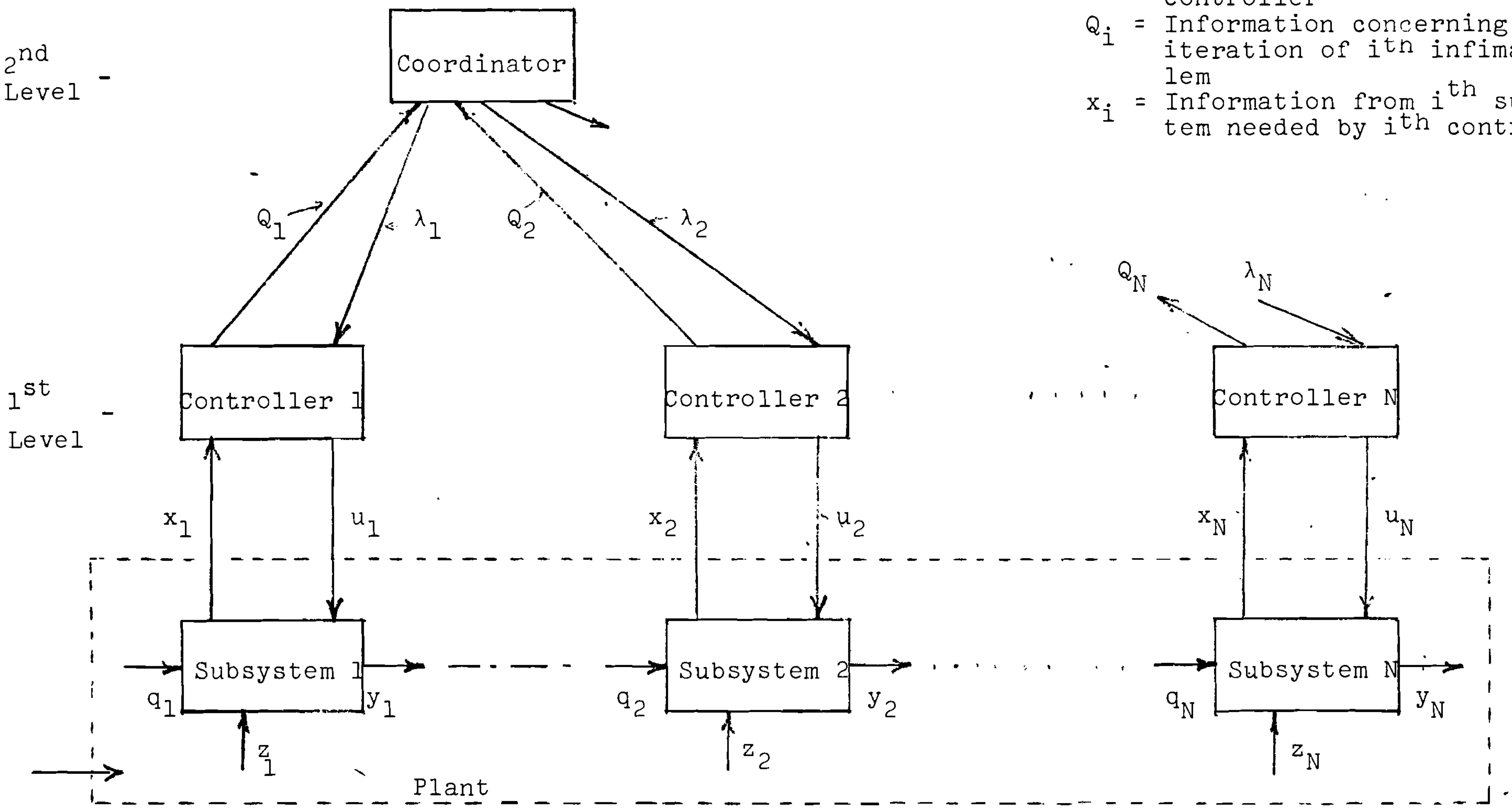
$$\text{where } U_i = \{u_i \mid y_i = g_i(u_i, q_i, z_i),\ h_i(u_i, q_i, z_i) \geq 0\}, \tag{11}$$

subject to the interaction constraints,

$$q_i = \sum_{j=1}^{N} T_{ij} y_j \qquad i = 1,2,\ldots N \tag{12}$$

The variables are identified with reference to Fig.4.4. Except for the q_i, the notation follows that of (10) with the modification that the subscript i particularizes the vectors and functions to the i^{th} subsystem[1]. The vector q_i denotes the inputs to subsystem i which result from interactions with other subsystems. It is assumed that these interaction inputs can be

1. Note that whereas the u_i, y_i, q_i are assumed to be disjoint subsets of u, y, and q, respectively, it is not necessary to impose such a restriction on the z_i, i.e. a disturbance input may affect one or more subsystems.



Legend for Symbols not Defined in Text

λ_i = Coordination input for the i^{th} controller

Q_i = Information concerning current iteration of i^{th} infimal problem

x_i = Information from i^{th} subsystem needed by i^{th} controller.

Fig. 4.4 Multilevel Hierarchical Structure expressed in the form of (12) where the T_{ij} are matrices of zeros and ones which couple the components of q_i with the appropriate components of y_j, $j \neq i$. It is assumed further that,

$$f(u,y,z) = \sum_{i=1}^{N} f_i(u_i,y_i,q_i,z_i) \qquad (13)$$

when q_i is given by (12), and that a solution satisfying the constraint sets U_i, i=1,2,...N, simultaneous with the interaction constraints (12) will also satisfy the overall constraint set U (in problem (10)).

In the multilevel hierarchy, the subsystem problems (11) are solved at the first level of control. These solutions have no meaning however, unless the interaction constraints (12) are simultaneously satisfied. This is the coordination problem that is solved at the second level of the hierarchy.

There are a variety of coordination schemes that have been proposed, e.g. price adjustment coordination (interaction balance), primal coordination (interaction prediction), penalty function methods, etc.[1] These are all similar in the sense that they serve to motivate an iterative procedure for solution of an optimization problem wherein a set of local subproblems are solved at the first level in terms of a set of parameters specified by the second level. The methods may differ, however, in their applicability to a specific problem, in the computation requirements, convergence speed, sensitivity to model error, incorporation on-line, and other considerations.

1. Some of the references that might be cited are: Mesarovic, M.D., Macko, D., Takahara, Y., Theory of Hierarchical Multilevel Systems, Academic Press, New York, 1970

Wismer, D.A., ed., Optimization Methods for Large-Scale Systems, McGraw Hill, New York, 1971

Himmelblau D.M., ed., Decomposition of Large Scale Problems, North Holland, Amsterdam, 1973.

The price adjustment method is based on the Lagrangian formulation of the overall problem. Thus, the Lagrangian function based on (12), (13) is given by

$$L = \sum_{i=1}^{N} f_i(u_i,y_i,q_i,z_i) + \sum_{i=1}^{N} \lambda_i(q_i - \sum_{j=1}^{N} T_{ij} y_j) \qquad (14)$$

Defining,

$$L_i = f_i(u_i,y_i,q_i,z_i) + \lambda_i q_i - y_i \sum_{j=1}^{N} \lambda_j T_{ji} \qquad (15)$$

we have

$$\sum_{i=1}^{N} L_i = L \qquad (16)$$

and hence we may express the first-level problems as

$$\max_{u_i,q_i} L_i(u_i,y_i,q_i,z_i,\lambda), \qquad i = 1,2,\ldots N$$

$$\text{subject to } y_i = g_i(u_i,q_i,z_i), \quad h_i(u_i,q_i,z_i) \geq 0 \qquad (17)$$

where $\lambda = (\lambda_1,\lambda_2 \ldots \lambda_N)$.

The solution of the N first-level problems for given values of z (based on current measurements on the system) and λ (given by the second-level coordinator) yields u_i^*, q_i^*, y_i^* for $i = i,2,\ldots N$. Using these values at the second level,

$$\max_{\lambda \varepsilon D} \sum_{i=1}^{N} L_i(u_i^*, y_i^*, q_i^*, z_i, \lambda) \tag{18}$$

where D is the permissable set of λ values for which there exist solutions to the first-level problems. The resulting λ is then fed into the first-level controllers and the procedure is iterated until convergence to a constant (non-zero)λ value is attained. Achievement of this result implies that the interaction constraints (12) are satisfied and that optimum to the overall problem has been obtained.[1]

In the <u>primal coordination method</u>, the interaction variables are set by the second-level controller so that the first-level problems reduce to

$$\max_{u_i \varepsilon U_i} f_i(u_i, y_i, q_i^*, z_i), \qquad i = 1,2,\ldots,N$$

where

$$U_i = \{u_i | y_i = g_i(u_i, q_i^*, z_i),\ h_i(u_i, q_i^*, z_i) \geq 0,\ q_i^* = \sum_{j=1}^{N} T_{ij} y_j\} \tag{19}$$

with $\{q^*\}$ given by the second-level coordinator. The first-level solutions are denoted by the set $\{u_i^*\}$ and are transmitted to the second level which solves the coordination problem,

$$\max_{q \varepsilon Q} \sum_{i=1}^{N} f_i(u_i^*, y_i, q_i, z_i)$$

where

$$Q = \{q = (q_1, , q_N) \mid q_i = \sum_{j=1}^{N} T_{ij} g_j(u_i^*, q_i, z_i),\ h_i(u_i^*, q_i, z_i) \geq 0\} \tag{20}$$

1. Actually, some further conditions may be necessary, see Mesarovic et al previously cited.

The procedure is iterated until convergence is reached.

On-line control application

As far as the plant is concerned, it is only the final result of the iterative process that is important, i.e. the functional relationship $u^o(z)$ that is established. Thus, the entire multilevel structure is internal to the computational block generating the optimum control. However, in the on-line application, the computation depends on the current value of z and this changes with time. Thus, much of the advantage of decomposition may be lost if the iterative process of coordination has to be repeated with every change in disturbance level.

If the system is decomposed along lines of weak interaction and if the coordination scheme is selected so that intermediate results are always plant feasible, then the multilevel structure provides the basis for a decentralized control wherein:

a) the first level controllers compensate for local effects of the disturbances e.g. maintain local performance close to the optimum while ensuring that local constraints are not violated;

b) the second-level controller compensates for the mean effect of overall variations in the interaction variables.

The desired result is a significant reduction in the cost of achieving control through reductions in the required frequency of second-level action and in the data transmission requirements.

Weak interaction linkages are readily motivated in industrial systems because the plants are composed typically of interconnections of semi-independent processing units. The interaction may be further weakened by design: e.g.

(i) use of buffer storage between units,
(ii) decoupling control of key interaction variables,
(iii) output control of preceding unit.

We remark that the measures taken to decouple the subsystems are not without cost (both capital and operating) and that there are economic tradeoffs to be exploited via the multilevel hierarchy, e.g. increasing the degrees of freedom by relaxing the coupling constraints - at the expense of more frequent coordination at the second level.

Consider the primal coordination method and assume that the first level controllers operate with period T_1 and the second-level controller operates with period $T_2, T_2 > T_1$. Say the integration problem (19), (20) is solved at time kT_2 based on a predicted mean value of z appropriate for the interval $[kT_2,(k+1)T_2]$. This yields a solution for the interaction variables denoted by $q(kT_2)$. The first-level controllers then solve (19) conditional on $q_i = q_i(kT_2)$, i = 1,2,.., N, until the time $(k+1)T_2$ when the values of q_i are updated.

We note that there is a loss of some degrees of freedom in the above procedure since, in effect, a subset of the control vector u must be assigned the task of maintaining the interaction variables at the values specified by the coordinator. This leads to a degradation of performance relative to what would be attained if the coordination were carried out every time first-level action was required. Thus, denoting the (suboptimal) performance value at time $t \varepsilon [kT_2,(k+1)T_2]$ by $f^*(z(t), q(kT_2))$, where T_1 is assumed consistent with the bandwidth characteristics of z, we may write

$$J(T_2) = E\left[\frac{1}{T_2}\int_{kT_2}^{(k+1)T_2}\left(\frac{\partial f^*}{\partial q}(z(t),q(kT_2)) \cdot \quad q(t)-q(kT_2)\right)\right] dt \qquad (21)$$

where E denotes expectation with respect to the distribution on z(t); J is an approximation to the performance degradation. Note that q(t) denotes the value of the vector of interaction variables determined by second-level action based on z(t).

In principle, the period T_2 may be determined so that the average degradation is acceptably small, i.e. consistent with the incremental cost of carrying out second-level control action. We note further, that there is usually some flexibility in the choice of interaction variables, i.e. variables to be updated by the second-level controller. Thus, by defining the subsystem problems according to weak interaction linkages, we tend to increase the allowable period T_2 for which the degradation is within acceptable limits.

An aspect of the multilevel control application that has particular relevance to industrial systems control is the problem of allocation, by the second-level coordinator, of a finite resource among the first-level units, e.g. allocation of investment capital among different works, allocation of steel to the needs of different mills in the works, etc. In this case, the constraint set for the i^{th} subsystem may be modified to

$$h_i(u_i, q_i, z_i) \geq \beta_i \tag{22}$$

where β_i represents the local resource allocation (or target) determined by the coordination according to overall objectives and constraints. Again, there are benefits due to simplifying the subsystem problems, reduced frequency of computation of the integrated problem, reduced sensitivity of the overall performance to uncertainties in the system inputs, etc.

Applications

There are a variety of applications of the multilevel concept in steel making; indeed, industrial systems have tended to evolve along well-defined hierarchical structures based on the characteristics of the technological processes involved and on the management organization. For example, in the steel industry, we have a hierarchy of decision-making and control defined according to the following levels[1]:

- Company Level
- Product Division Level
- Works Level
- Mill Level
- Production Unit Level
- Machine Level
- Operations/Process Control Level

In general, each level serves as coordinator to resolve conflicting needs and goals among the infimal units at the level below. The coordination methods used in practice tend to be informal and ad hoc; it is expected that, as the degree of computerization and integration of the system increases, the need for more formal structuring and definition of tasks will be felt and the developments of multilevel theory will play an increasingly important role.

Two examples of multilevel coordination are cited:

a) The temperature of slabs leaving the Reheat Furnace for the Hot Strip Mill may serve as a coordination variable with respect to the objective of maximizing operating efficiency of the Furnace Rolling Mill subsystem. Thus,the slab temperature affects the maximum throughput rate of the furnace as well as the fuel consumption. On the other hand, the slab temperature affects the power required in the rolling and also the finishing temperature of the strip (and indirectly, the production rate of the mill). There is an optimum slab temperature with respect to overall performance of the mill (depending on slab dimensions, strip specifications, grade of steel, etc.). Thus, determination of this temperature is a task for the

1. This structure is fairly typical although there are some variations in practice among countries and companies.

second-level controller that is coordinating the first-level controllers applied to the furnace and rolling mill subsystems, respectively. The first-level controllers act to maintain optimum performance of their respective subsystems conditioned on the specified slab temperature constraint.

b) Under circumstances of limited steel producing capacity relative to demand, it is necessary to allocate the heats to each mill. The supremal unit determines the allocation in order to maximize overall performance (e.g. profit); the infimal units operate to minimize costs subject to constraints of order due dates, specifications, etc. Feedback of infimal performances, constraint violations, etc. provide the supremal with inputs on the basis of which the allocation rule may be improved.

We make two final remarks:

a) The multilevel structure extends in an obvious fashion to a hierarchy of three or more levels with each supremal unit coordinating the actions of a group of infimal units according to the same principles as described above. Indeed, as illustrated in Fig.4.5, the structure of units infimal to a given controller in the hierarchy may be collapsed to a single subsystem so that each supremal unit "sees" only a single level structure beneath it.

b) There is a strong compatiblity between the hierarchical control approach and the use of minicomputers in dedicated tasks which are coordinated through integrated systems control.

4.4 TEMPORAL MULTILAYER CONTROL HIERARCHY

Each controller or decision-making function at a given level of the multilevel hierarchy described in the previous section normally represents a number of distinct control actions or decision functions. These may be classified according to relative time scale or period of control action, motivating a hierarchical structure which we label as the *Temporal Multilayer Control Hierarchy*.

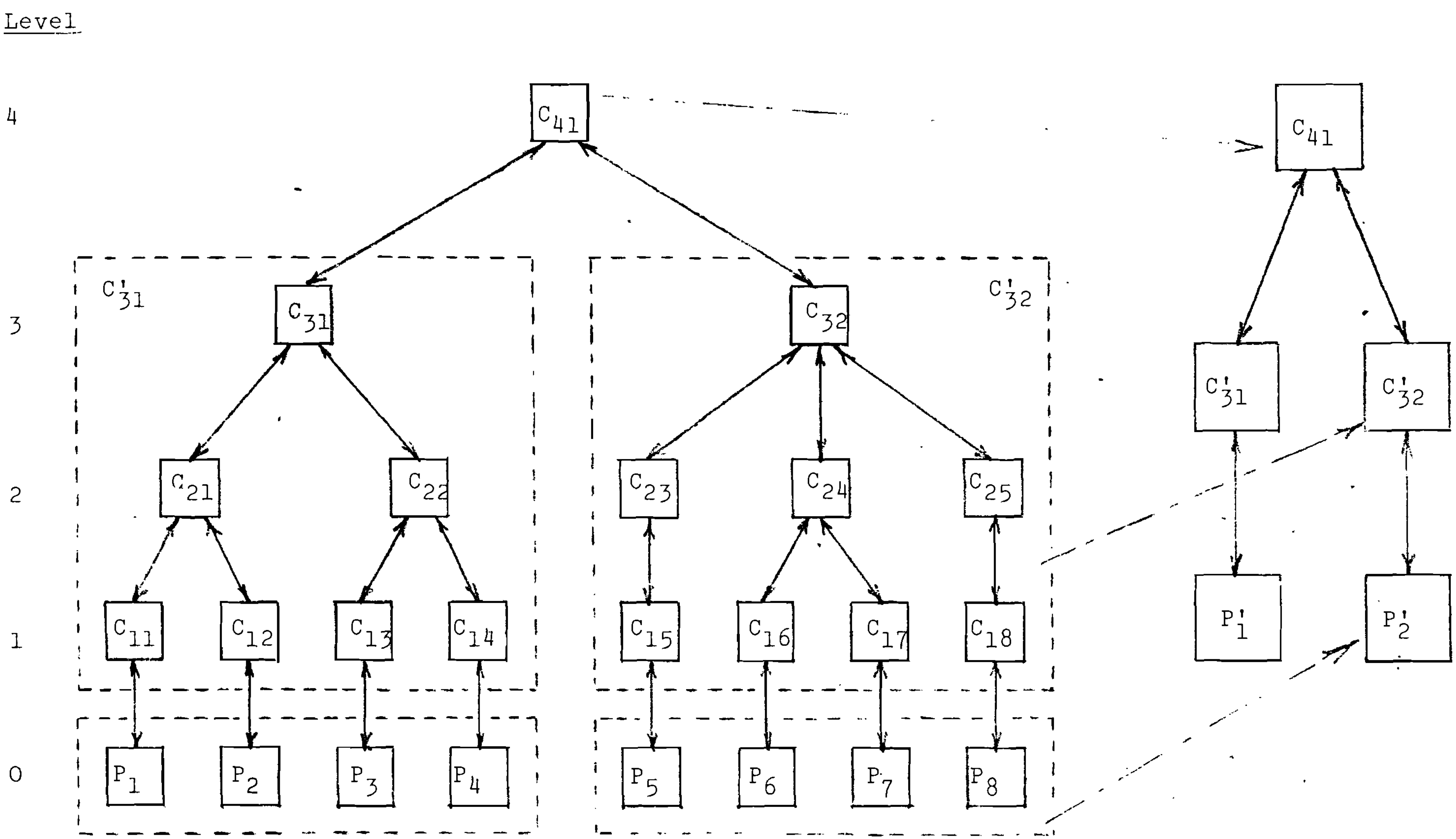


Fig. 4.5 Collapse of 4 Level Hierarchy to Equivalent Two Level Structure

The temporal multilayer structure serves to partition the control problem into disjoint subproblems based on the different time scales relevant to the associated action functions. These time scales reflect such factors as:

a) the minimum time period required for obtaining the necessary information, e.g. the determination of statistical parameters require sufficiently long data records to be meaningful; the composition of a heat is available only after completion of the steelmaking cycle.

b) the minimum time period for the system to respond to prior actions, e.g. dominant time constant for a continuous process, the construction time for a new plant or equipment installation.

c) time-varying characteristics of the disturbance inputs as displayed by bandwidth properties, mean time between discrete changes in input conditions, etc. (e.g. seasonal/diurnal changes in cooling water temperature, mean time between receipt of an order requiring special processing).

d) minimum time horizon for which the solution to the control problem has meaning

e) cost-benefit tradeoff considerations.

Fig. 4.6 illustrates the basic structure. Three levels of the multilevel hierarchy are represented with the controller C_{ij} expanded to show the multilayer structure. We adopt the following notation:

C_{ij} denotes the j^{th} controller at the i^{th} level

$I(C_{ij})$ denotes the index set of controllers infimal to C_{ij}

$$I(C_{ij}) = \{k | C_{i-1,k} \text{ is infimal to } C_{ij}\}$$

$S(C_{ij})$ denotes the index set of controllers supremal to C_{ij}

$$S(C_{ij}) = \{k | C_{i+1,k} \text{ is supremal to } C_{ij}\}$$

Remarks:

a) The above definitions imply that a controller has direct influence only on controllers at the next lower level, i.e. the control outputs of C_{ij} apply only to $C_{i-1,k}$, $k \varepsilon I(C_{ij})$.

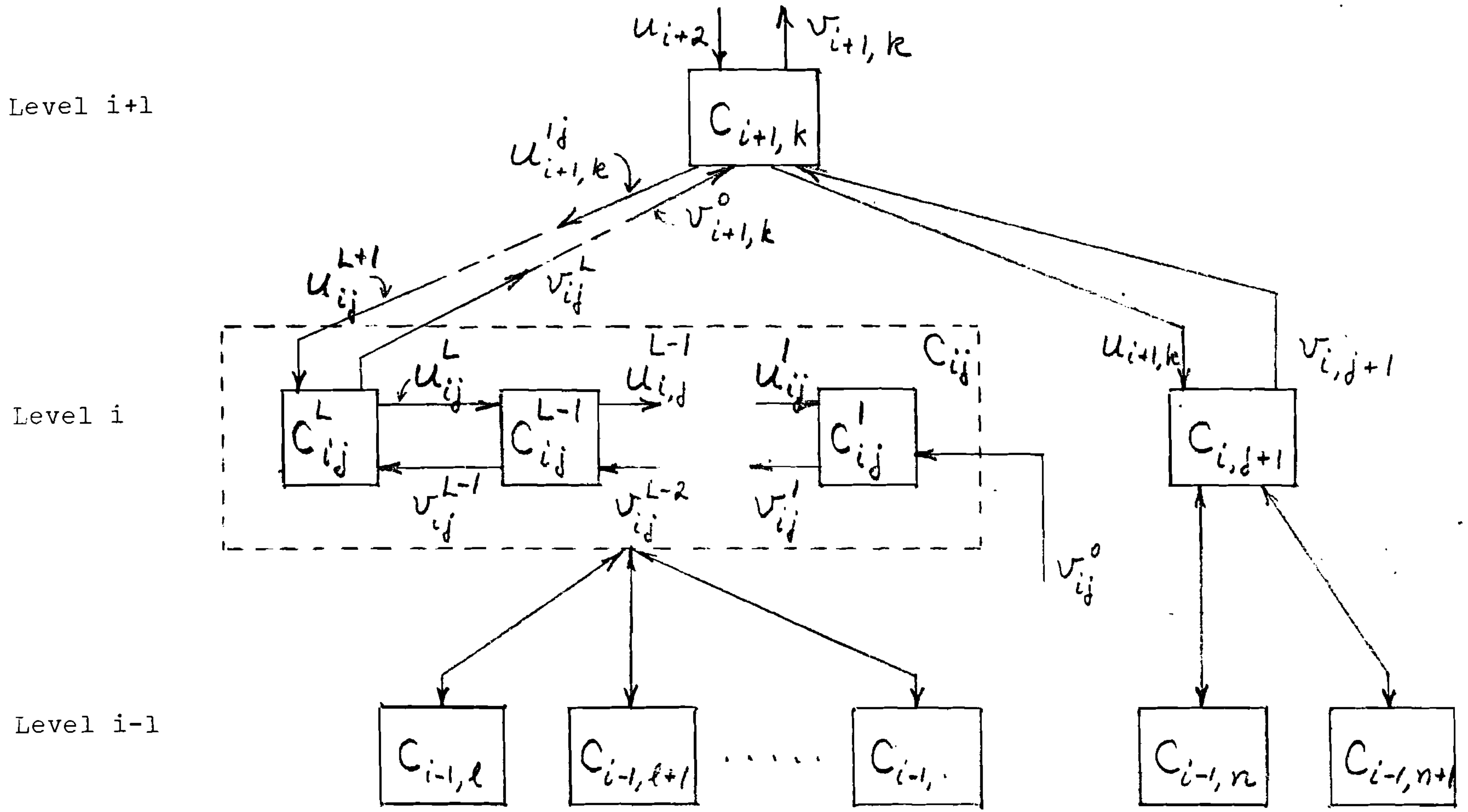


Fig. 4.6 Temporal Multilayer Hierarchy

This restriction is consistent with the notion of C_{ij} acting as coordinator for a set of (conflicting) infimal units.

b) The set $S(C_{ij})$ is assumed to have only a single element. This feature avoids ambiguity and possible conflict in the specification of goals and constraints applied to C_{ij}.

We assume that the control tasks of C_{ij} are themselves composed of sets of subtasks which are carried out by controllers C_{ij}^k, $k = 1,2,\ldots L_{ij}$ organized according to a temporal multilayer hierarchy, where

C_{ij}^k = k^{th} control layer of C_{ij}

L_{ij} = total number of layers in C_{ij}

The controller C_{ij}^k generates the transformation,

$$u_{ij}^k = F_{ij}^k(u_{ij}^{k+1}, \; x_{ij}^k, \; \alpha_{ij}^k) \qquad (23)$$

where the index notation particularizes the variables to the k^{th} layer of the j^{th} controller on the i^{th} level. The variables are defined as follows (the subscripts i j are deleted here for convenience).

u^k = set of control actions(decisions) generated by C_{ij}^k
u^{k+1} = control actions of the supremal unit, C_{ij}^{k+1}
α^k = set of parameters associated with the algorithm or decision model
x^k = information set particularized for the k^{th} layer decision process

The information set is composed of inputs v^{k-1} and θ^k, where

v^{k-1} = information from the infimal unit C_{ij}^{k-1} which is relevant to the k^{th} layer function

θ^k = information describing the state of the plant and relevant external factors.

We note that action at the k^{th} layer depends on the prior decision at the (k+1)th layer. There is also interaction in the other direction; it is assumed, however, that the coupling is weak so that the k^{th} layer decision-making may proceed on the basis of averaged or aggregated properties of the lower layer actions (as communicated via x^k).

We adopt the following convention with respect to the linkages of C_{ij} with its supremal unit at the (i+1) level and its infimal units at the (i-1) level:

$$u_{ij}^{L+1} = u_{i+1,k}^{1j} \qquad k \varepsilon\ S(C_{ij}),\ L = L_{ij}$$

$$u_{ij}^{1l} = u_{i-1,l}^{L+1} \qquad l \varepsilon\ I(C_{ij}),\ L = L_{i-1,l}$$

Similarly, we have

$$v_{ij}^{L} = v_{i+1,k}^{oj} \qquad k \varepsilon\ S(C_{ij}),\ L = L_{ij}$$

$$v_{ij}^{ol} = v_{i-1,l}^{L} \qquad l \varepsilon\ I(C_{ij}),\ L = L_{i-1,l}$$

The controller C_{ij}^k outputs an action every T_{ij}^k units of time[1]. We assume the following ordering holds:

$$T_{ij}^{k} > T_{ij}^{k-1} \qquad k = 1,2,\ldots L_{ij}$$

$$T_{i+1,j}^{1} \geq T_{ij}^{L} \qquad \forall\ i,j$$

This ordering assures that the period of control action of any infimal unit does not exceed that of its supremal.

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1. This implies a periodic control policy. In the case of an on-demand policy, T^k denotes the mean period of k^{th} layer action.

We denote the k^{th} layer control action at time nT^k by $u^k(nT^k)$, $n = 1,2,\ldots$ (we again suppress the subscripts i,j for convenience and initialize the start of the sequence to time zero). It is assumed that this control action remains in effect over the period T^k, i.e.

$$u^k(t) = u^k(nT^k), \quad t\varepsilon\ (nT^k,(n+1)T^k] \qquad (24)$$

The k^{th} layer control action is determined with reference to a decision horizon T^k. We assume that, in general[1].

$$\tau^k \geq T^k$$

When $\tau^k = T^k$, we have tne standard formulation of the stationary horizon problem. When $\tau^k > T^k$ and, more particularly, when $\tau^k = rT^k$, $r > 1$, then the problem is of the moving horizon type. Viewed as a control problem, τ^k is irrelevant (except as it affects the optimizing procedure) and T^k is the significant parameter. Thus, every T^k units of time, the controls are updated based on the current information set.

An important contribution of the multilayer hierarchy is in reducing the effects of uncertainties in the decision-making process through feedback. Consider, for example, the decision problem to be solved at time t_o which requires that the average performance over the interval $[t_o, t_o + \tau]$ be maximized subject to constraints on the total amount of resources available. The difficulty is that the system is subject to various disturbances about which we have only limited information (e.g. knowledge of z(t) and an estimate of the statistical properties of z(t) over the interval of interest. The problem is compounded by the fact that the plant model may be very complex and only an approximation of the real system.

1.In the case of a static (non dynamic) system, we imply $\tau^k = T^k$ since this is the interval over which the disturbance inputs are extrapolated (e.g. as step or ramp changes).

The multilayer concept provides a means of handling this problem by expanding the original problem into a set of subproblems each with horizon τ' where $\tau = q\tau'$ $q > 1$. The subproblem is solved for the interval $[t_o, t_o + \tau']$ conditioned on an allocation A_1 of the resource and on information about the disturbance, e.g. $z(t_o)$ and the statistics of $z(t)$ over the interval $[t_o, t_o + \tau']$. At time $t_o + \tau'$, the subproblem is solved again but now for the interval $[t_1, t_1 + \tau']$. Now the resource allocation is A_2 and the disturbance is described by $z(t_1)$ and the statistics over $[t_1, t_1 + \tau']$. This leads to a recurrence procedure, with the k^{th} subproblem solved on the basis of A_k, $z(t_k)$ and the statistics of $z(t)$ over $[t_k, t_k + \tau']$, $t_k = t_o + k\tau'$.

The supremal problem is then formulated as: determine the allocations $A_1, A_2, \ldots A_n$ so that (i) their sum equals the total resource availablity, and (ii) that the overall objective is maximized.

It is obvious that the above technique may be applied, in turn, to the subproblem with decision horizon τ', yielding a concatenation of new subproblems of horizon τ'', where $\tau' = q'\tau''$. In principle, we can have a nesting of L such layers, i.e. an L-layer temporal hierarchy.

The practical manifestation of the above approach is in the form of the planning/scheduling hierarchy where we have typically: long range plan (10 years), annual plan, monthly plan, etc.

The following benefits accrue to the above approach:

a) A rational basis is provided for aggregating the variables, permitting simplification of the complex initial formulation of the problem.

b) The effects of uncertainty are reduced because the subproblems (at the lower layer) are solved based on a prediction of the disturbance input over a shorter horizon.

c) The necessary detail required for handling local constraints and locally dominant factors are retained in the infimal controllers

d) There is a natural mechanism for the introduction of feedback of experience in both plant operation subject to the prior control and in the prediction of the disturbance inputs over the horizon period.

While the temporal multilayer hierarchy is imbedded within each component of the multilevel hierarchy, we have, in similar manner, the elements of the functional multilayer hierarchy replicated in each component of the temporal multilayer hierarchy. This is shown in Fig. 4.7 which represents a detailing of the C_{ij} block in Fig. 4.6. Note that the subscripts i,j denoting the j^{th} controller at the i^{th} level are again omitted for convenience.

The control function C_{ij} is decomposed into L_{ij} component functions C_{ij}^{k}, $k = 1,2,..,L_{ij}$. Each layer articulates with the neighboring layer according to the scheme described above, with controls proceeding from the higher to the lower layers and with information flowing in the opposite direction.

Associated with C_{ij} is a Local Data Base which stores all relevant data on the basis of which the tasks of C_{ij} and all its component parts can be carried out. Thus, each layer controller and its associated adaptive function access the data base for the currently applicable data required for their respective tasks.

There are three additional components of the C_{ij} block:

1. Information Processor - The raw data from the plant and environment must be processed to extract the essential information relevant to the decision function. Processing includes: (i) smoothing (to filter out random noise), (ii) extrapolation based on present and past data values to predict (forecast) values that reflect appropriate averaging over the time horizon for the decision function, (iii) aggregating to reduce volume of information flow and to simplify algorithms.

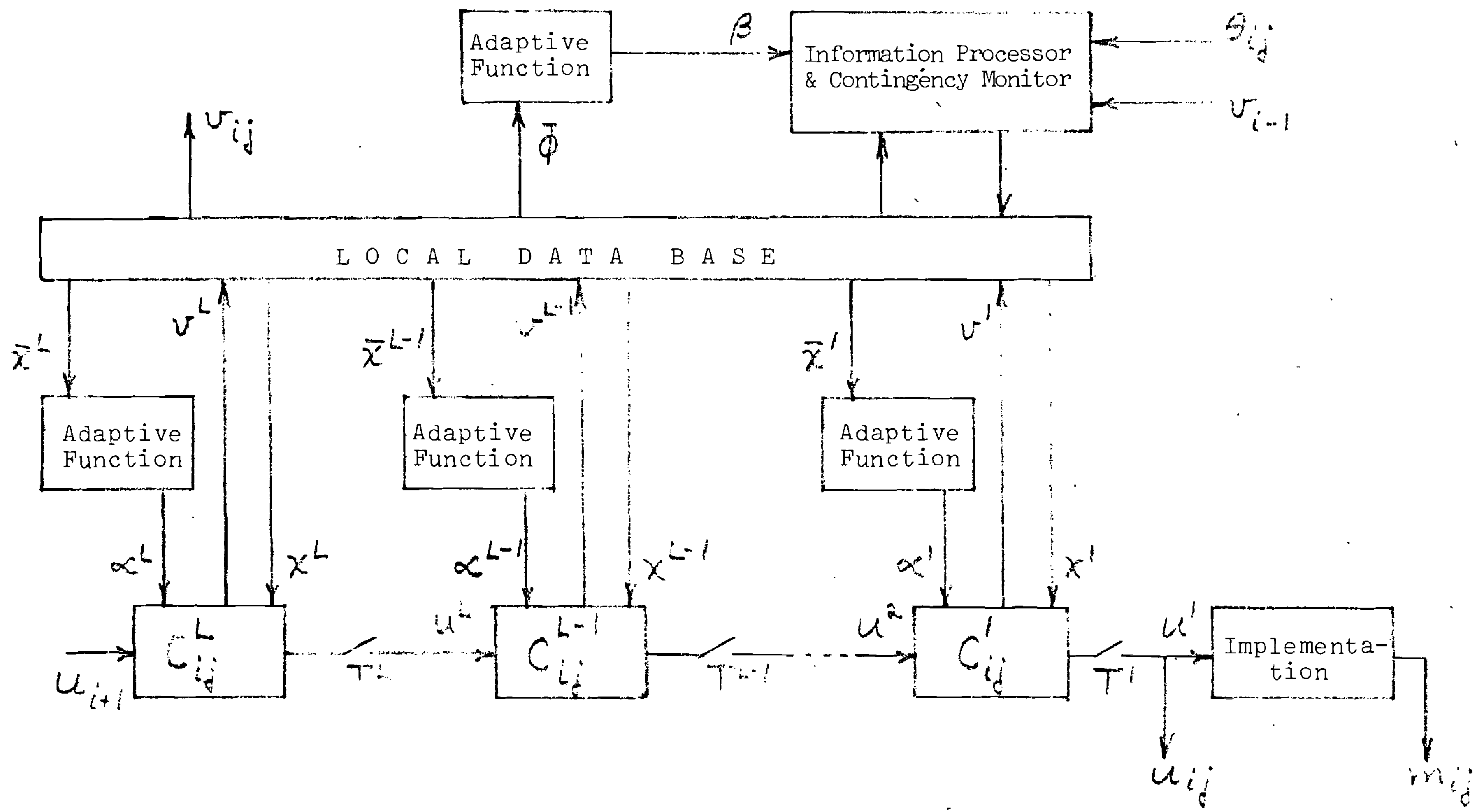

Figure 4.7 Expansion of C_{ij} into L-Layer Temporal Hierarchy.

The data processing function is based on a model (again either explicit of implicit). In general, the model is to be updated periodically or on demand in order to reflect current conditions concerning the statistical properties of the signal, e.g. its mean and variance values.

An important additional feature of the Information Processor is the monitoring of contingency events which may require a response on the part of C_{ij}. The occurrence of such an event triggers first an assessment of the nature and seriousness of the contingency and hence whether any corrective action should be initiated, e.g. an on-demand control response on the part of C_{ij}, a modification of the control algorithm, or even a change in operating mode (e.g. change from normal operation to a shutdown procedure).

2. Adaptive Function - Generally, the model on which C^k is based only approximately describes the system, hence there is need to periodically update the parameters α^k. This is provided by the adaptive function which determines a new α^k every $\bar{T}^k$ units of time based on aggregated information $\bar{x}^k$ relevant to the local control problem. It is assumed that $\bar{T}^k > T^k$, i.e. adaptation is based on the evaluation of averaged behavior of the system under the control action C^k.

It is natural to incorporate contingency control also within the adaptive function, i.e., responses to contingency events that require change of control objective or mode, change of control algorithm, etc.

3. Implementation Function - The output generated by C_{ij} is normally composed of three parts. We have already referred to two of these parts: (a) the vector v_{ij} which is transmitted to controllers at the i+1 level that have use for the information, and (b) the vector u_{ij} which provides the local objectives and constraints to the controllers infimal to C_{ij}. The third part

of the output of C_{ij} is the vector m_{ij} which is generated by the implementation function associated with C_{ij}. This output defines those decisions of C_{ij} that are to be directly implemented on the operating system.

As an example of the Implementation Function, we may consider the Annual Plan carried out at the divisional level. The Plan determines production targets for the various works under its jurisdiction. A related task is the placing of contracts for raw materials needed to satisfy these production goals. This latter task may be carried out by a purchasing department within the division, which then serves the role of the implementation function with respect to this task. Note that the purchase commitments then impose constraints on the infimal control units which are communicated via the control u_{ij}.

There are three conditions implicit in the given structure.

a) The action vector m_{ij} is derived from the decision vector u^1_{ij} which is applied to the infimal units. It is assumed, therefore, that the consequences of such actions are communicated to the infimals via the targets, constraints, etc. imbedded in u_{ij}.

b) The intermediate decisions of the various layer of C_{ij} are outputted only via the lowest layer unit, C_{ij}. This provides the mechanism for updating at the highest frequency associated with C_{ij}, all of the decisions of C_{ij} that are transmitted to the infimal controllers.

   We may consider, by way of example, the case of C_{ij} composed of two layers C^2_{ij} and C^1_{ij} corresponding to the annual planning and the monthly planning functions, respectivley.

The annual plan may be determined once a year, but updated (in part) every month. Thus, what is necessary to transmit to the infimal units are the monthly plan and the monthly update of the annual plan.

c) The vector u_{ij} is ultimately implemented via the set of action outputs generated by the controllers from the i^{th} to the first level which form an infimal chain induced by C_{ij}, i.e. via the sets of vectors m_{ij}, m_{i-1,j_1}, ... $m_{1,j_{i-1}}$, where

$$j_{R+1} \quad \varepsilon \; I(C_{i-k,j_k}), \quad k = 0,1,2,..,i-1$$

We note that the system represented in Figures 4.6 and 4.7 attempts to combine into a single integrated structure the three major features of the hierarchical approach presented in this chapter: the functional control hierarchy, the multilevel coordintion hierarchy and the temporal multilayer hierarchy.

The focus is on the information processing, decision-making and control functions that have to be carried out in order to achieve an integrated production system. We have not made explicit provisions for the many ancillary functions that are a normal and essential part of any computerized system, assuming that these may be incorporated into appropriate units within the functions defined or appended as separate units.

In any event, the results represent a generalization of concept and approach which is meant to serve only as a guideline, Thus, it is taken for granted that, in each particular design application, there will be reasons to deviate from the guideline - and this is a characteristic part of the design process.

Illustrative Example

Chapters 2 and 3 provide a number of examples which may be used to illustrate the hierarchical structures described in this section, e.g. the order entry system, the organization of planning and scheduling functions according to time scale, the coordination of interacting production units, etc. Specifically, we consider a small part of the production planning and order entry system described previously to show the application, in very general terms, of the concepts and notation presented here.

For the purpose of notation, let us make the following identifications:

Level 7: Company[1]
Level 6: Product Divisions
Level 5: Works
Level 4: Shops/Mills
Level 3: Production Units

We consider Product Division A; Works numbered 1,2,3,... within Division A; and Shops/Mills labeled a,b,c,... associated with Works no.1. Thus, C_{6A} denotes the controller for Product Division A (at the 6^{th} level); C_{51}, C_{52},... denote the controllers infimal to C_{6A}; C_{4a}, C_{4b},... denote the controllers infimal to C_{51}, etc.

Among the tasks of C_{6A} are a) to allocate production among the works in the division based on forecasts of product demand, b) to distribute received orders to the works. The input from the company level, u^4_{6A}, defines[2] production goals and constraints for the division. Inputs from the infimal units (works level), v_{5i}, i = 1,2,... include information concerning the current state of each works, productivity levels (e.g. mill performance); etc. The inputs θ_{6A} may include order information, new trends in product demand, economic factors.

1. In accordance with the organization outlined in Section 4.3 where seven levels are identified.

2. Refer to the preceding section for identification of the notation used.

We may further divide C_{6A} into three temporal layers as follows:

C_{6A}^3: Responsible for annual plan at the division level.

τ_{6A}^3 = 1 year; T_{6A}^3 = 3 months

u_{6A}^3 = production allocation over the period of the year

x_{6A}^3 = experience over the past quarter in meeting the production plan, changes in demand forecast

C_{6A}^2: Responsible for quarterly plan

τ_{6A}^2 = 3 months; T_{6A}^2 = 1 month

u_{6A}^2 = production allocation for the quarter

x_{6A}^2 = experience over the past month in meeting the plan,

C_{6A}^1: Responsible for monthly plan

τ_{6A}^1 = 1 month; T_{6A}^1 = 1 week (or less)

$u_{6A}^1 = (u_{6A}^{11}, u_{6A}^{12}, \ldots)$, where u_{6A}^{1i} denotes the allocation of received orders to i^{th} works of Division A to be processed during current month.

x_{6A}^1 = information of order received (specifications, due dates, etc.), current state of works (back-log, slab inventory, etc.), mill performance.

In addition to $u_{6A}(= u_{6A}^1)$, the outputs of C_{6A} include:

m_{6A} = various actions required in securing supplies of of the required raw materials, etc.

v_{6A} = information transmitted to company level concerning performance of the division, e.g. aggregated production capabilities.

The data processing function may include the averaging of production figures, trend analyses on market demand, order projections, etc. A sudden and significant change in any of the input factors may trigger an "on-demand" reassessment of the plan in order to accomodate the new circumstances (e.g. major unscheduled shut-down of a facility, labor strike, severe quality control problem). Alternately, the plan may be only modified in an ad hoc fashion to resolve a current problem pending reassessment at the regular period.

The adaptation function is incorporated in the following ways:

a) Models used for determining production capacities, track times, performance standards, etc. are reviewed annually and updated according to

(i) evaluation of previous year's results, and
(ii) known changes in equipment, operating practice or other relevant conditions.

b) Models used for prediction of aggregated values (i.e. based on probability distribution models of product mix, equipment break-downs, quality rejects, etc.) may also be updated annually based on observations of the previous period plus consideration of any tangible factors expected to affect the distributions.

At the works level, the tasks of say, C_{51} are to transform the current monthly plan (defined by u^{11}_{6A}) into, successively, monthly and weekly production plans for Works no.1, leading to the preparation of the weekly schedule. Thus, the control function C_{51} may be considered in three layers: C^3_{51}, C^2_{51}, C^1_{51} corresponding to the monthly plan, weekly plan and weekly schedule, respectively.

In general, C_{51} is responsible for coordinating the conflicting requirements of the various shops and mills in the works. One element of this coordination is the grouping and sequencing of orders to maximize overall productivity of the works.

The control output of C_{51}, denoted by $u_{51} = u^1_{51} = (u^{1a}_{51}, u^{1b}_{51}, \ldots)$ where u^{ij}_{51} denotes the subvector of u^1_{51} that is directed to the j^{th} shop (or mill). Thus, u^{1a}_{51} may denote the schedule of heats required of the oxygen converters, u_{51}^{1c} may refer to the set of orders to be processed by the Hot Strip Mill during the current period, etc.

Looking at the next lower level, C_{4a}, C_{4b}, C_{4c}... denote the control systems for the various shops and mills in Works no.1. Each of these controllers may be expanded into two or more temporal layers, depending on the nature of the decision-making and control functions. In general, each controller will have responsibility for coordinating the activities of its infimal operational and process control functions, e.g. C_{4c} would have among its tasks the coordination of the Reheat Furnace schedule and operations with the Rolling Mill schedule and operations - through the selection of the rolling sequence, the slab temperature leaving the furnace, etc.

Finally, we may identify for each of the controllers in the hierarchy the functions and operations that correspond to the various components of the functional control hierarchy e.g. Information Processing, Implementation and Adaptation.

4.5 Review of Hierarchical Control Concepts and Approach

The purpose of this section is to relate to some of the antecedents of the hierarchical approach described in this chapter and to identify some alternative hierarchical structures that have been advanced. This review represents only a small sampling of developments in the field and is not meant to be complete. Selected references are identified by superscript and listed at the end of this section.

Most of the underlying concepts and some of the terminology presented here have their origins in the pioneering work of Mesarovic and his group[1,2] which develops a conceptual and analytical foundation for hierarchical structures and multilevel coordination theory. Many of our modifications were prompted by pragmatic aspects of the application of the theory to industrial systems, e.g. more explicit concern for on-line implementation and the effects of disturbance inputs, focus on achieving feasible, suboptimal performance objectives as opposed to a "mathematical" optimum, etc.

The bulk of the literature in the field is oriented to decomposition and multilevel coordination theory and its application to optimization and mathematical programming problems of various kinds. There are a very large number of references on the subject; we cite here only three books representative of the work in this area.[3,4,5] The application to scheduling problems have particular relevance to steel mill operations and some of the coordination tasks defined for the production control system may well make use of these techniques.

A closely related area of application of coordination theory is in handling the dual problem of optimization and identification (e.g. of parameters of the model). We cite again only one of several references in this area[6] and note that this problem, too, is relevant to our field of study, e.g. with respect to adaptation of models and some prediction algorithms.

The essential features of the functional multilayer hierarchy were first described by Lefkowitz[7]. Applications of the hierarchical structure to control of process systems are discussed further by Findeisen[8].

Extension of the multilayer concept to discrete manufacturing type systems is presented by Lefkowitz and Schoeffler[9]. This work motivated some modifications in the conceptual structure of the multilayer control system; specifically, making more explicit the role of a common data base, information processing function, and the provisions for contingency event monitoring and control.

An immediate precursor to the formulation of the temporal multilayer hierarchy is the work of Donoghue.[10] The basic contribution here was the organization of the decision-making and control functions according to the relative time scales of the required actions. Important extensions to the concepts and structuring of the temporal hierarchy were made by Cheliustkin,[11] particularly with respect to its association with the planning and scheduling functions of the steel production system and also with respect to the consideration of model aggregation relative to the hierarchy.

Williams has provided major inputs to the field of hierarchical control as applied to industrial systems.[12] He is presently directing a large research project at Purdue University, in joint collaboration with the major U.S. steel producing companies, on "Systems Engineering of Hierarchy Computer Control Systems for Large Steel Manufacturing Complexes".[13]

In his general formulation of the hierarchy, four levels are distinguished:

Level 1: Specialized Dedicated Digital Control
Level 2: Direct Digital Control
Level 3: Supervisory Control
Level 4: Management Information

This structure is similar, in part, to the functional hierarchy shown in Fig. 4.3; with, however, a stronger orientation to the technological level of control and to the practical aspects of digital computer implementation. An extension of this general formulation leads to a structuring of the overall plant production control system as shown in Fig. 4.8 (taken from Reference 13), which is being considered in the current Purdue study.

There are some strong similarities with the conceptual formulation of the hierarchy that we've presented here. There are also differences e.g. the Purdue version of the control hierarchy has more detail with respect to the technological level of control, and is more oriented to the practical aspects of implementation of the system through digital computer hardware and software. There is also more explicit concern with the communications aspects of the problem and man-machine interfaces.

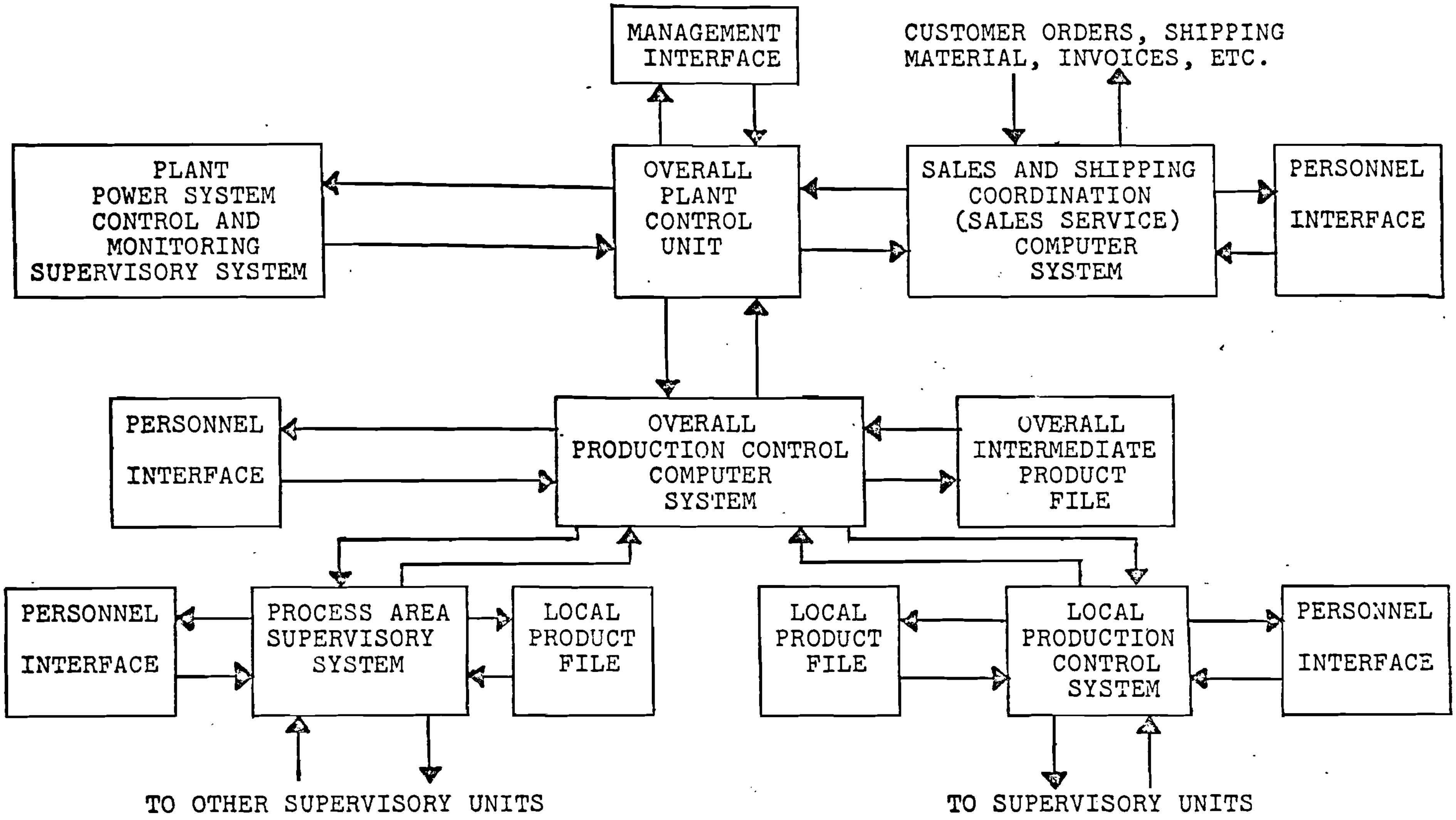

FIGURE 4.8

OVERALL PLANT PRODUCTION CONTROL SYSTEM

Another variant of the control hierarchy is presented by Bernard[14]. The structure is formulated in two dimensions. In one dimension are the classification of functions according to Measurement, Control and Communications. In the other dimension, five levels of the hierarchy are defined for each of the function categories. These levels are, in turn, organized into three groups as follows:

- Emergency Operation: Safety control, emergency manual control, indicators and alarms, diagnostic aids.
- Process Operations Enforcement: Direct and inferred measurements of process variables, conventional and advanced control, operations monitoring and evaluation.
- Operations Scheduling: Plant and process optimization, multiplant coordination, process supervision and accounting.

Again there are general similarities in terms of the various functions to be performed, but with significant differences in the organization of the hierarchy and in the relative detail given to the different functions.

Examples of Hierarchical Control Structures in Steel Industry

The concept of a hierarchical control structure found early motivation in the steel industry, starting with the application of digital computers to implement various operational control and process control functions in the Hot Strip Mill[15] (e.g. at the Spencer Works of the British Steel Corp). This led quickly to considerations of integrated plant control based on a four-level control hierarchy comprising planning, scheduling, production control and process control functions, along with a variety of ancillary tasks related to record-keeping, operator communications, accounting, etc.

The approach, considerably developed and expanded upon, has found manifestation in the new, modern steel works of Japanese steel companies. A specific example is the computerized system installed at the Kimitsu Works of Nippon Steel Company[16]. The part of the system dealing with steelmaking, slabbing and strip products is shown in Fig. 4.9 (much of the detail has been omitted for purposes of clarity). There are almost replicate structures to that shown in the figure for the plate mill, section and wire rod mill and the pipe and tube mill - and these too have been omitted to simplify the diagram.

The system is organized in four levels, as follows:

A Level: Order processing, 10-day production schedule, material requisitioning, order status, shipping, various reports.

B Level: Data gathering, daily and shift schedules, allocation of semiproducts to customers orders.

C Level: Preparation and display of work instructions, data gathering, reports.

D Level: Operations control, process control

Computing facilities for the A, B, and C levels are located in the Works Computing Center; the D level computers are located on the mill floor. The order entry system is located at the Head Office which communicates order tapes for each products group to the appropriate order processing system of the A level.

We make the following general observations:

a) The system is very hardware oriented; specifically, each block(or group of blocks at the A and B levels) denotes the functions carried out by a separate computer. There is an ordering with respect to the size and number of computers

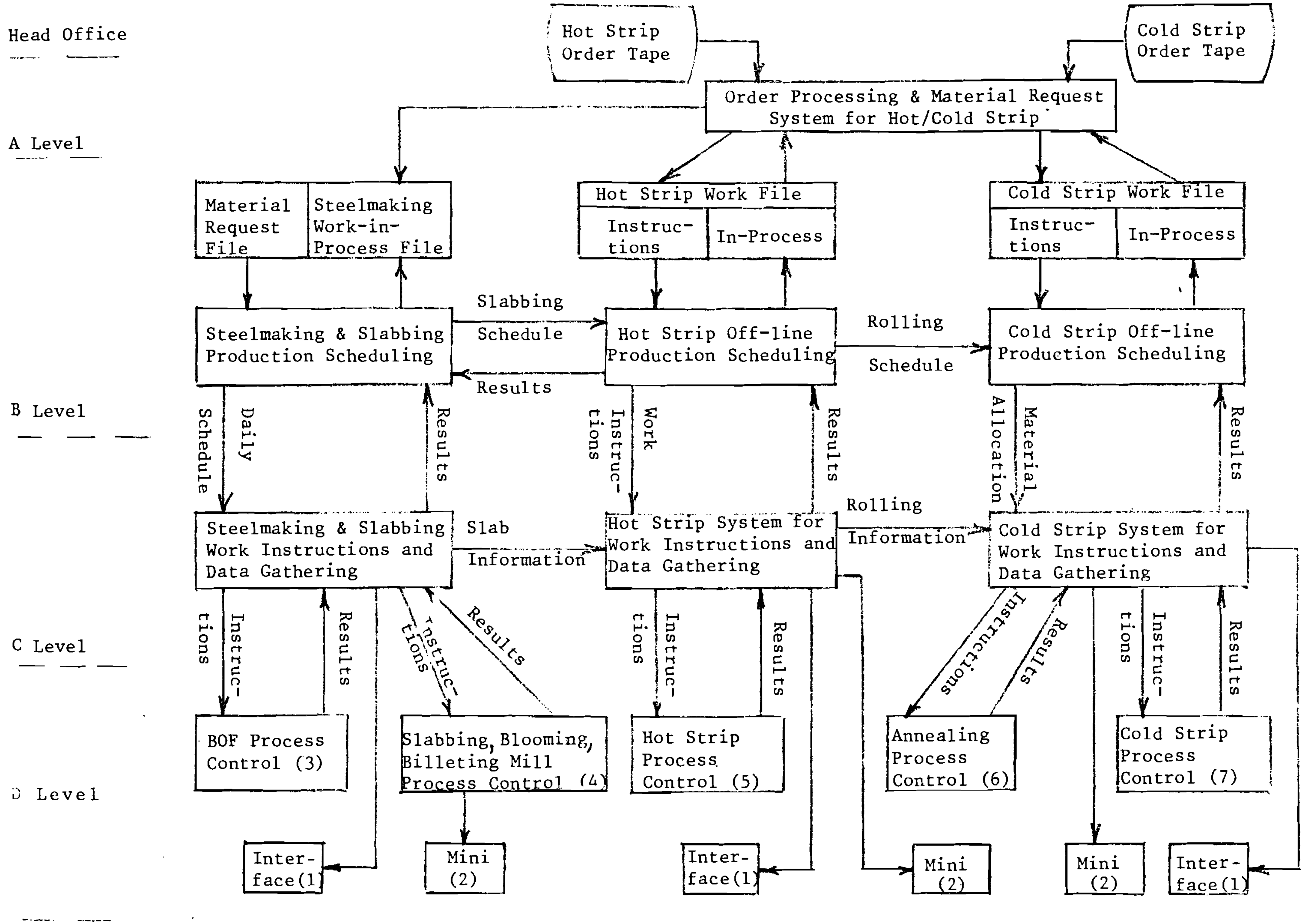

Figure 4.9 Computer Control System at Kimitsu Works (Partial)

<u>Legend for Figure 4.9</u>

(1) Man-Machine Interface: includes keyboard, printer, display panel, auto I/O signal, etc.

(2) Minicomputer: Positioning control
Sequence Control

(3) BOF Control: End-Point Control
Charge calculations
Operating instructions
Production control information
Technical report

(4) Slabbing, Blooming, Billeting Mill Control:
Scheduling
Combustion control
Mill setting and sequence control
Production control information

(5) Hot Strip Mill Control:
Reheat furnace control
Mill pacing
Mill setting
Adaptive control
Spray control
Coiler setup
Technical report

(6) Annealing Process Control:
Combustion control
Timing control
Production control information
Technical report

(7) Cold Strip Mill Control: Mill setup
Adaptive control
Tension control
Automatic sequence control
Technical report

employed at each level; i.e. there tends to be fewer separate computers but of progressively larger size as we proceed up the hierarchy. Indeed, at the lowest level, there are a number of minicomputers assigned to dedicated, special purpose tasks.

We note that, in distinction to this direct association of level with the computer configuration, the consideration of hardware has not been a dominant factor in the hierarchical structures developed in this chapter, and does not appear explicitly in their formulations.

b) The information flows follow the general pattern of the hierarchy described in this chapter: decisions and control actions proceed from supremal to infimal control units, with information feedback on the results of prior actions going in the reverse direction. There are also horizontal channels of information flow whereby interacting units at the same level receive information on the decisions of other units that affect its own decision-making. For example, the Hot Strip Mill Production Scheduler receives information from the Steelmaking Shop on the slabbing schedule; it, in turn, sends back information concerning its results with previous slabs as they may affect future schedules of the Steelmaking Shop.

c) The man-machine interfaces are a very explicit and important part of the Kimitsu system. This again reflects the hardware orientation; in our formulation of the system, the operator-computer communications requirements are implied thorugh the information processing functions.

d) Other aspects of our structure, e.g. considerations for the effects of disturbances and contingency events, coordinating control of interacting production units, and an ordering of decision-making according to time scale (temporal hierarchy), are not explicitly shown on the diagram; however, most of these would seem to be integral to the functions provided.

e) Adaptive control functions are explicitly denoted among the D level computers, but not at the higher levels. It is known, however, that the models and algorithms programmed into the scheduling and planning functions are updated periodically or on demand.

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CHAPTER 5. CONCLUSIONS

The integration of the planning, scheduling, production and process control functions greatly influence the efficiency of the steel works by increasing yield, reducing equipment idle time, decreasing the stock and labour requirements, improving product quality and decreasing the production lag time. The main part of the increase in efficiency is achieved through the computerized systems for order processing, loading, and scheduling of the plants, and through the operational control systems. The long-term, medium-term and annual planning functions performed by the head office influence the general economic position of the company through proper allocation of resources and orders among the steel works. However, these planning functions have only an indirect influence on equipment productivity and idle time, and order delivery lag time.

The integrated control systems approach, in spite of its contributions to improved efficiency and works productivity, is not broadly applied in the steel industry around the world. The only fully integrated systems (at the works level) are found in Japan; in other countries, the level of integration is much lower. This may be attributed to economic factors, prevailing attitudes toward computerization, resistance to any changes from traditional practices of decision-making and control, availability of manpower and resources, and various other factors which have already been discussed in this report.

In a number of steel works, process control systems have been implemented without consideration of the computerization and integration of the production control, scheduling and planning functions. This can be explained, on the one hand, by the complexity of the integration problem, and on the other by the lack of general concepts and effective methodology for the design of integrated control systems.

Those developing the computerized control system are often thoroughly versed in their field of specialty but may have limited familiarity with the characteristics and requirements of other specialty areas that must be considered in the design and use of an integrated system. Thus, to develop a process control system, a detailed knowledge of the technology is required; these systems are usually designed by the manufacturer of the technological equipment, often in collaboration with an instrument company. In developing managerial systems, specialists in management, organization, and planning are required who have a thorough understanding of the specific features of a given plant, and experience of its general environment. What is typically lacking are people with cross-disciplinary expertise who can inter-relate and coordinate the various disparate components of the overall production system. This situation is reflected in the observation made earlier that all existing systems of an integrated type were designed and implemented by the steel works staff, and that there are no engineering companies advertising their ability to build such systems at the present time.

The situation can be improved by formulating general concepts and guidelines for structuring the system and by developing systems methodology and engineering design methods to achieve an effective and useful integrated systems control.

Some concepts and analytical tools described in the report relate to the multilevel or multilayer hierarchical structuring of the system. We consider this as a first very important step in developing a general methodology for integrated control system design. The hierarchical approach provides the basic framework within which the large, complex systems control problem can be decomposed and the subsequent subproblem solutions integrated to achieve the desired result.

This theoretical development is still incomplete, however, and there remain a great many unsolved problems. Many of these relate to definition of the hierarchical structure and to construction of the mathematical models, considering different time scales. One problem related to the temporal multilayer hierarchy is the uncertainty of the available information as a function of time. The longer the time period the higher the uncertainty of the information we have. But, considering limited resources, the "optimality" of the plan increases with increasing planning time horizon. Thus, the solution can be found by trade-off between "plan optimality" and information uncertainty. A problem closely related to the above is the defining of the time horizon for production process evaluation. Over a long time horizon, some of the disturbances influencing the process being averaged may have zero means, although over a shorter time horizon their time varying behaviour may have very significant effect on the process performance.

Different time horizons for planning and control problem solution require constructing mathematical models with different time scales, thus having different variables and structures. How to construct these models, and how the inputs and outputs of models with different time scales should be interfaced, are also unsolved problems. To solve the problem for one time horizon can require its decomposition, e.g. constructing a set of interrelated models, which should also be interconnected somehow with models for other time horizons.

The time scaling and decomposition of models is a problem not only for planning but for operational control, since different production operations have different time responses and different cycling times.

The control actions and decision-making established by problem solutions having different time horizons should be considered. Methods of doing this for models with different time scales should be found, as should be a method of adaptating interconnected models with different time scales.

Of great importance is the problem of determining planning standards. Standards should be established in accordance with results previously obtained. If the standards are too rigid, there is always a possibility of failure in realizing the plan. If they are too "soft", the capability of the equipment will not be fully used, resulting in decreasing production efficiency.

Standards should take into account the probability of some non-coordination in production operation performance, e.g. due to the influence of uncompensated disturbances. The standards should have built-in allowance, which in their turn should be estimated by analyzing the real process performance. Since the implementation of computerized control and decision-making systems reduces the frequency of non-coordination, the magnitude of the allowance can be decreased, thus improving the planning result.

The algorithms used to solve order processing, loading, scheduling and operational control problems tend to be of a heuristic nature, and in many cases reflect the methods used by traditional "manual" control. It seems obvious that as these algorithms are replaced by algorithms based on optimization techniques, the resulting performance attained by the system should improve. Hence, there is an incentire to develop more generally effective optimization routines, particularly, for real-time computer applications.

This review does not include problems of selecting hardware, nor those of communications and information processing based on this hardware. These problems require special study which was felt to be outside the scope of the present project activity. Thus, we thought it necessary to investigate the problems of functional structuring and its general concepts before attempting to resolve questions of software and hardware structures.

As was already mentioned, the present form of this review is a draft, to be supplemented during the conference. This applies particularly to this chapter which we hope will be fully revised during the discussion. One outcome of the latter should be a proposal for the organization of future investigations in the field of integrated systems control. Because of the very limited resources that IIASA can devote to such studies, there is little possibility for practical results without the active collaboration of research groups from the various member countries. IIASA can then serve as a catalyst, initiating and coordinating international activity in this field, organizing workshops for discussion and exchange of information, publications of results, and planning of future activities.

APPENDIX I VISIT TO STEEL COMPANIES AND INSTITUTIONS

The members of the Integrated Industrial Systems Project organized visits to steel works and research institutes in various countries in order to obtain information for the state-of-the-art review.

There were a number of factors that influenced our selection of places to visit. First, we wanted to visit works that provided examples of advanced practice in various aspects of computerization and integrated systems control, i.e. companies that were at the "leading edge" with respect to systems integration. Second, we wanted the survey to be representative in the sense that it reflected responses from some small steel producers as well as the world leaders, nationalized as well as privately owned companies, and systems operating under planned as well as market-oriented economies Finally, we included in our itinerary, visits that were prompted by expressions of interest in our project efforts.

In order to make the visits more productive, we prepared a list of questions which were sent to the companies in advance of our visits. In this way, people in the various steel works were prepared to discuss the specific problems of our interest.

In addition to the steelworks, we visited several institutes dealing with research and design of computerized systems for the steel industry. Additional information was obtained by discussing different topics with the specialists from these institutes. This increased the scope of the state-of-the-art review.

On the whole, we visited 35 enterprises and research institutes in 11 countries. These are listed on the following pages.

List of Steel Companies and Organizations Visited

Austria

Vöest Alpine - Linz Works
Montanistische Hochschule (Leoben)

Australia

The Broken Hill Proprietary Co. Ltd.,

Bulgaria

Kremnikovici Works
Institute CNJKA

CSSR

SONP - Kladno Works
VSZ Kosice Works
NHKg - Ostrawa Works
Institute INORGA - Praha

GDR

Bergakademie (Freiberg)

FRG

August-Thyssen Hütte A.G.
Duisburg Works
Fr. Krupp Bochum Works
Betriebsforschungsinstitute BDEh (Düsseldorf)
Siemens Head Office - München

Japan

Kawasaki Steel Corporation
Mizushima Works
Kobe Steel
Kakogawa Works
Nippon Kokan
Fukuyama Works

Japan cont-

Nippon Steel Corporation
Kimizu Works
Sumitomo Metal Industries
Kashima Works
Japan Iron and Steel Federation (Head Office)

Netherlands

Estel Hoogovens Works

USA

Bethlehem Steel Co. - Bethlehem, Pa.
United States Steel Corp. - Pittsburg, Pa.
Republic Steel Corp. - Cleveland, Ohio
Inland Steel Corp. - Chicago, Ill.
Purdue University - Lafayette, Indiana

United Kingdom

British Steel Corp. Headquarters - Birmingham
Rotherham Works
Scunthorpe Works
Lancashire Works

USSR

Cherepovetz Works
Novo-Lipezk Works
Institute CNIICA, Moscow
Institute for Control Sciences, Moscow
Institute TNIISA, Tbilisi

APPENDIX 2. AN INTRODUCTION TO STEELMAKING

Introduction

The modern way of life, as we know it today, would be quite impossible without the availability of steel. Virtually everything that one does from the moment one wakes in a morning until going to sleep at night involves either something itself made of steel of something which was fashioned using steel tools. This dependence on steel is more extensive and has more important consequences than first thoughts tend to suggest. One can grow food using a wooden plough pulled by horses and harvest the crops by hand but such methods are so inefficient that almost the entire population would have to work on the land. Fuel, especially oil, would not be available without steel; transport, i.e. cars, trains, and planes all rely on steel; recreation, health care, etc. utilize steel in many forms. Some countries produce almost one ton of steel a year per head of population.

Realization of this modern dependence on steel begins to explain why so many countries insist on having their own steelmaking capabilities. Even though it is not always the most economic solution, it is a strategic decision. It was once said that a country could claim to have arrived in modern times when it had a flag, a football team, an airline and a steel works!

Types of Steel

This is not intended to be a comprehensive and detailed catalogue of the thousands of steel types that exist today but rather a review of some major groups. Not surprisingly, the end use of a steel product dictates the steel's characteristics.

In use, a piece of steel is either supporting something, protecting something or attacking something. In any of these roles the steel may have to combat forces which try to stretch, twist, bend, compress, melt, corrode, or erode it, and if all these fail, mother nature will try to turn it back to its original form through rusting.

A steel maker is well aware of all these demands and has developed steels with special characteristics. Some can stand compression with minimum give and no permanent deformation, some have a strong resistance to being stretched, some are intended for use in the form of thin sheets and they must be resistant to tearing or bursting. Other sheets are springy and are used for clock springs or car suspensions. In the cases where steel is used as a cutting tool, it must be capable of being sharpened to a keen edge but it must also be hard enough to withstand being blunted in use.

There are many classes of steel known as "alloy steels" because they contain a proportion of one or more other elements. The added elements each contributes to the final steel characteristics. The most famous alloy is so-called stainless steel. For this nickel and chromium are added and the result is a steel which sometimes does in fact stain but does not rust. With this property it is well suited to use as cooking and eating utensils and for medical instruments.

Other usages for special alloy steels include the ability to stand up to very high or very low temperatures, to contain dangerous substances without seepage and to provide a given standard of strength with minimum weight.

The final property of a given steel is influenced by several factors. Obviously, the chenical analysis is of fundamental importance but physical deformation during processing also plays its part. As an extreme example, steel of a given analysis will exhibit different final characteristics depending on whether the required physical shape is achieved by pouring the steel in a molten state into a shaped mould or by hammering it out of a suitably sized block.

All steel is heated to a red-hot state at several stages in its manufacture, the temperatures reached and the rate at which the steel is allowed to cool, all influence the final characteristics.

The scope of this paper will not allow a detailed description of the intricates of making the full range of possible steel types but must concentrate on a few more basic forms. Hopefully, however, the impression will not be created that steel making is simple and straight forward.

Many attempts are made to develop other materials which can replace steel, and plastics and aluminum are strong competitors for some less demanding uses. It is expected, however, that for the foreseeable future, steel will continue to be the lowest cost material providing strength with minimum bulk and weight.

A Short History of Steel

Ancient man passed through the stone and bronze ages into the Iron Age about I500 B.C. Needless to say, opinions vary considerably over this date. Early practices for extracting the metal iron from iron ores were crude but temperatures of up to I200^{o}C were obtained in stone furnaces and a material known as "sponge iron" was produced. This was heated and beaten repeatedly to remove non-metallic impurities and the end result was good enough to sharpen for an axe head or sword.

Next, methods of heating improved and liquid iron was produced which could be poured into moulds to produce useable shapes. Early examples of the use of "cast iron" are church bells and cannon balls.

It was always possible to pour all the liquid iron into a shaped mould and so a practice of making "pigs" began. A pig is a solid piece of iron of no very precise shape which can be re-melted when needed. The curious name derives from the method of casting the surplus iron by pouring it into channels formed in sand (the form seemed to resemble suckling pigs). Today there is a modern equivalent of the process and people still talk of pigs and pig iron.

The exact changing point between iron and steel is not very clear. Right at the start of the Iron Age, materials were made which could be called steel but this was often by accident. The first processes designed specifically to make steel from iron were developed in the late 1850s and derivations of their principles take us into modern history.

Today the world's steel industries represent big business and current capacity is around seven hundred million tons per year. The main steelmaking processes are the Oxygen Converter, or LD (for Linz and Donanwitz, the homes of the originator) about 40%, Open Hearth (about 25%), and the Electric Furnace (about 15%). These processes are described later in more detail.

Thus, steelmaking has grown from a small experimental activity to the modern steel plant which may cost over US $ 1,000 million. It is controlled by a most complex, computer based system which is as sophisticated as any found in modern industry. A modern works is like a town in itself with up to 30.000 people and up-to-date facilities for training, recreation and health treatment, including perhaps an operating theatre.

The Fundamentals of Steelmaking

Steel is primarily made up of iron, the percentage varies depending on the characteristics demanded, but it is frequently 90% or more. Iron ore occurs in large quantities in various parts of the world, today's important sources include Australia, Asia, Africa, Scandinavia, and North and South America. Much of the ore is in the form of an oxide of iron but the iron also occurs in useful quantities in combination with a range of other elements.

The next largest component of steel is carbon, although often only 0,05 to I%. As will be shown shortly, the processes of obtaining iron from iron ore involves burning coke and that provides more than enough carbon for the steel maker's needs. Except in special alloy steels, all other components are needed in very small percentages.

To make steel (see Fig.A.I), the first task is to make iron and the universal method is by melting the iron ore with coke in a Blast Furnace. A very high temperature is needed for this operation and the end results is Crude Iron. Steel can be thought of as impure iron although the "impurities" must be carefully controlled. However, crude iron is even more impure and consequently a refining stage is needed before steel is obtained.

The refining stage is called Steelmaking and there are several major processes in use today. During steelmaking, the unwanted components of crude iron are removed and any special ingredients added. There is still some question as to whether the process is an art or a science, but undoubtedly it is becoming more and more of a science each day. It remains a critical process since it is not at all easy to control the low level elements and they play such an important role in determining the final steel characteristics. Thus, the fact must be faced that the steel does not always turn out to be precisely as required.

Steel is molten when it is poured from the steelmaking furnace and is allowed to cool in a moulded shape, typically a meter square and two meters tall. From now on the steel may be heated to a red-hot state several times in its processing but it remains in a solid form.

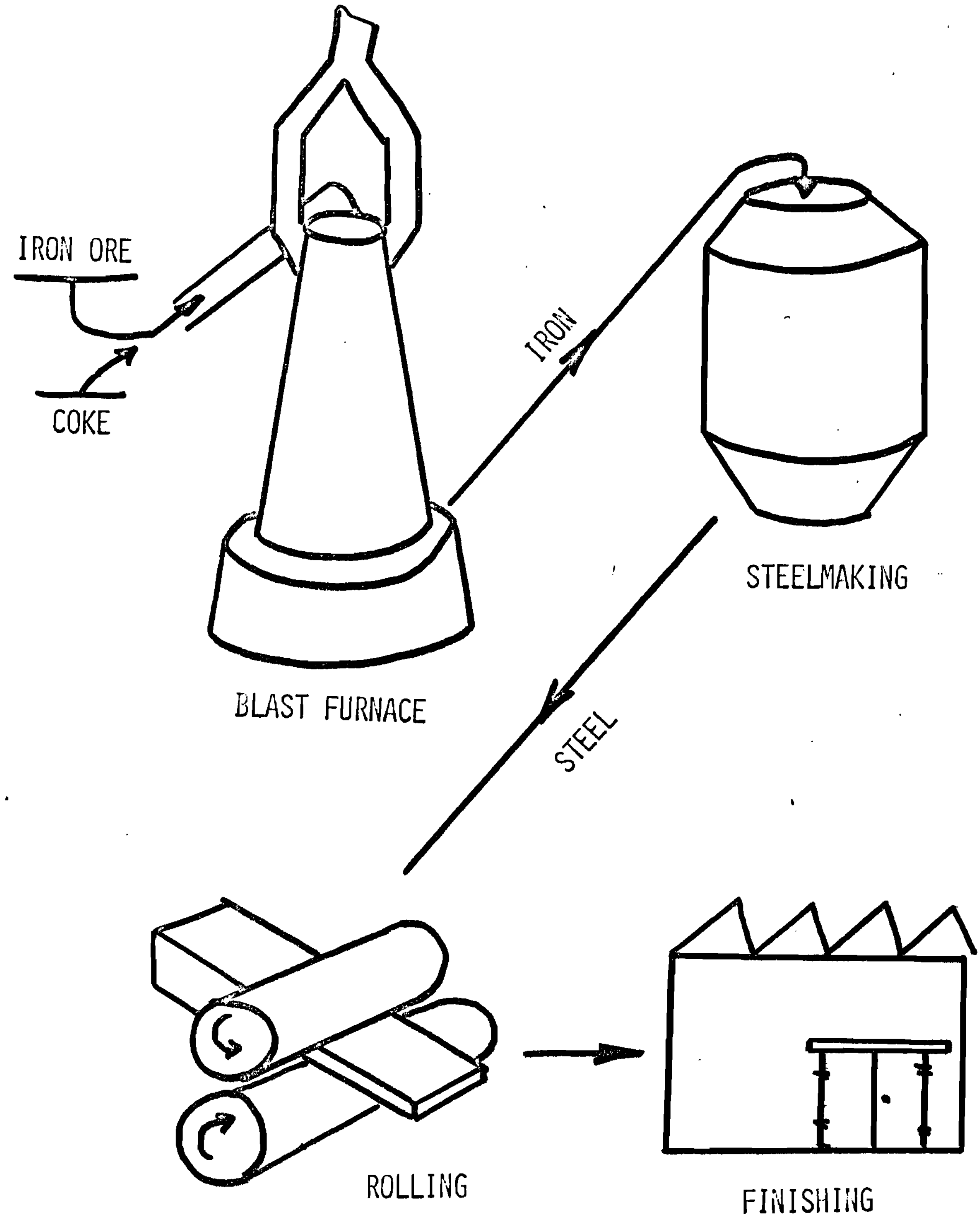

Fig. A.1 The fundamentals of Steelmaking

Since steel is required more frequently in strips, sheets and bars, the solid chunk of steel must be physically changed into longer, thinner forms. This cannot be achieved in a single operation and the first stages of reduction take place in a Rolling Mill. Basically, a rolling mill consists of two cylinders of steel called Rolls, with a gap between them which, rather like the old fashioned clothes mangle, can be set as required. The cylinders counter rotate and the steel, reheated to a red-hot state, is driven through the rotating rolls. Out from the other side the steel emerges a little thinner and, correspondingly, a little longer. This rolling process continues in many forms; some mills are said to be reversing mills because the steel is passed backwards and forwards between the rolls with a smaller gap at each pass. Other mills are set to reduce from one given thickness to another and the steel passes through only once, usually through a series of such mills.

Some later rolling stages involve the use of shaped rolls so that steel of different cross-sectional shapes can be produced, e.g. railway lines.

The remaining stage in this simplified description of making steel, is to cut the steel into the dimensions required by customers and to put the pieces through various Finishing processes. In general, these finishing processes either improve the quality, e.g. make sure railway lines are particularly straight, or apply some protective coating. The most usual coatings are tin and zinc, both of which prevent the steel form rusting, but plastic on top of the zinc is becoming increasingly popular since it can be coloured and textured and is pleasant to touch.

Steel products are further processed. For example, steel wire may be woven into cables, steel sheets may be formed into tubes and boilers, steel sections may be fabricated into bridges, etc..

A closer look will now be taken at some steel works processes and, in particular, some of the problems of planning and controlling a works will be mentioned.

The Blast Furnace

A blast furnace is physically a giant process which can be 75 metres (240 feet) in height (see Fig. A.2). It is basically a lined steel vessel which is charged from the top with coke, iron ore and limestone. Suitable proportions of these are taken by a "skip", or hopper, up the skip hoist and dropped in at the top.

The coke burns and provides both heat (up to about I.600°C) and is the source of carbon. Hot air is blown (or blasted) up through the bottom of the furnace to maintain a high temperature. The iron ore is, naturally, the source of iron while the limestone acts like a sort of scavanger, it soaks up and combines with unwanted impurities to form slag. Fortunately, slag is lighter than molten iron and so it floats on top.

Every 3 or 4 hours the furnace is tapped, that is to say the molten iron which has collected at the bottom is drawn off into a ladle or ladles for transportation to steelmaking. Iron continues to be tapped until the level of the floating slag is reached. At this point, the slag is drawn off separately and can be used, after processing, for road making or fertilizers.

Controlling a blast furnace is not an easy task especially since it must be fed with heterogeneous raw materials and the normal objective is to produce iron with constant characteristics.

Steelmaking

The most popular method of making steel today involves the use of an LD, or oxygen converter (see Fig. A.3). It is nothing

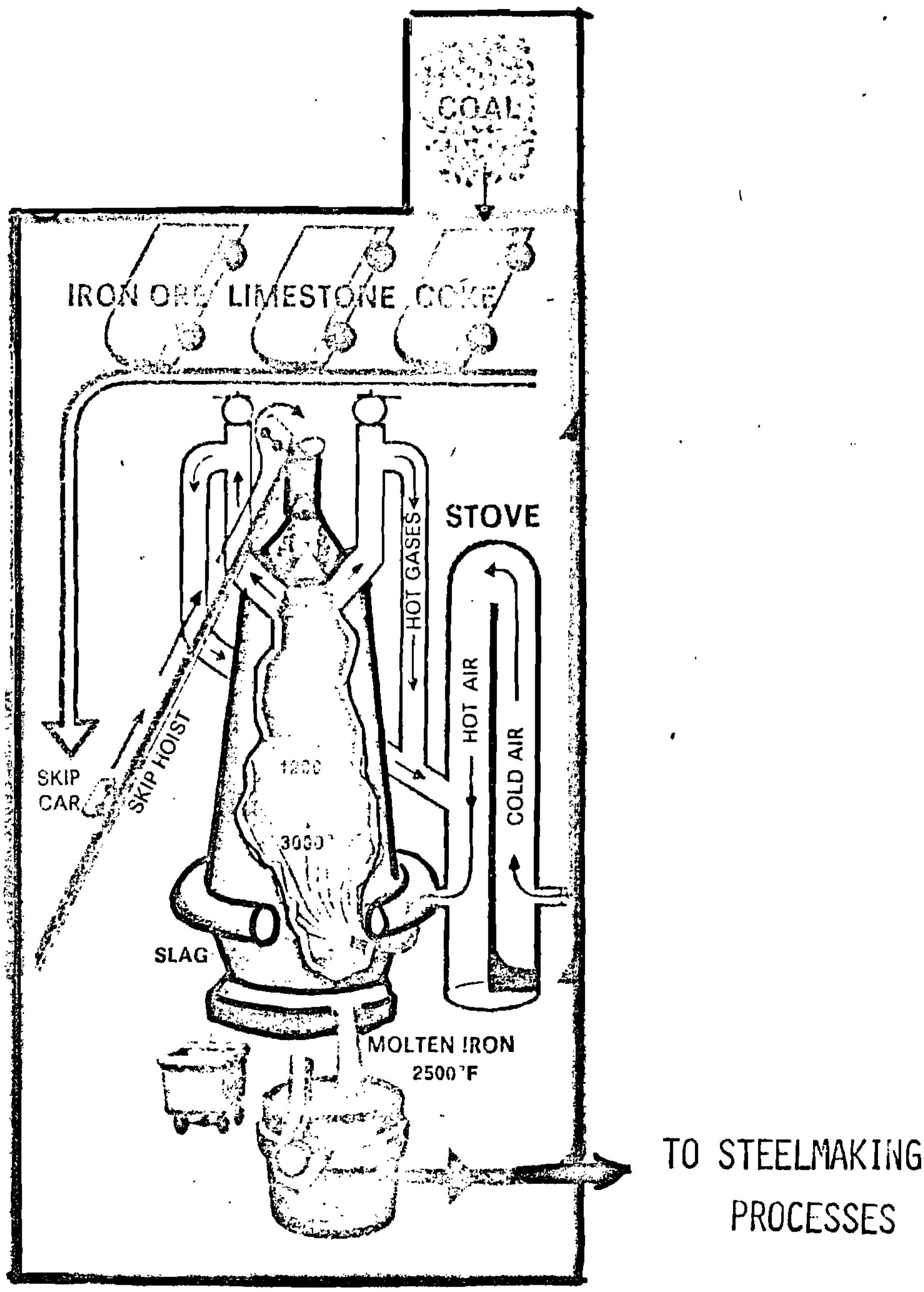

Fig. A.2 The Blast Furnace

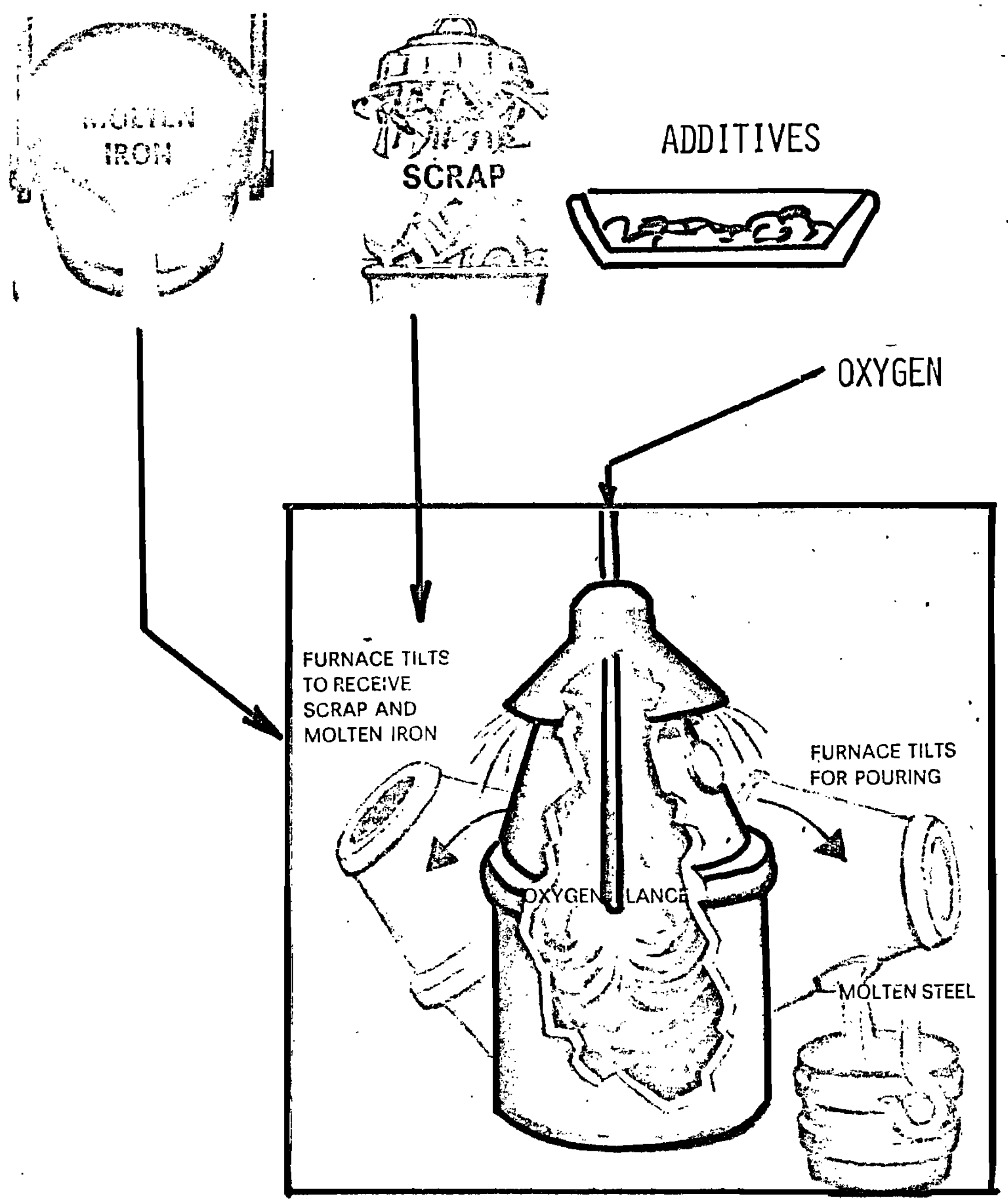

Fig. A.3 Basic Oxygen Furnace

more than a steel vessel, lined with refractory material, which can be tilted in a vertical plane.

Molten iron from the blast furnace is poured in and followed by steel scrap and other sources of particular elements called for in the final analysis. Limestone is again used as a scavanger just as in the blast furnace. A modern furnace will make some 200-300 tons of steel at a time and will take 40 minutes typically.

There is no external form of heating, rather oxygen is blown in through a lance in order to "encourage" the required (exothermic) reactions. Great turbulence can be experienced, the quantities of input materials and oxygen blown are carefully calculated, usually by computer, to arrive at the expected result.

Although more controllable than some predecessors, it remains a fact that not all attempts result in precisely the intended analysis. This causes problems of what to do with the mismade steel and how to speedily remake, or supply in some other way, the type of steel called for.

The other main problems are organizational, e.g. ensuring that all the materials arrive when needed and having suitable cranes available at the right time.

After the prescribed 40 minutes the steel is drawn off, or tapped, into a ladle which takes the steel to a teeming bay.

The other modern steel making process is the Electric Furnace (see Fig. A.4). The basic idea is still to produce steel of a specified analysis but the approach is quite different. No molten iron is used and so a works using the electric process does not need blast furnaces. Steel scrap is used as the main input material and it is melted by the heat caused when electrodes are lowered into the pile of metal.

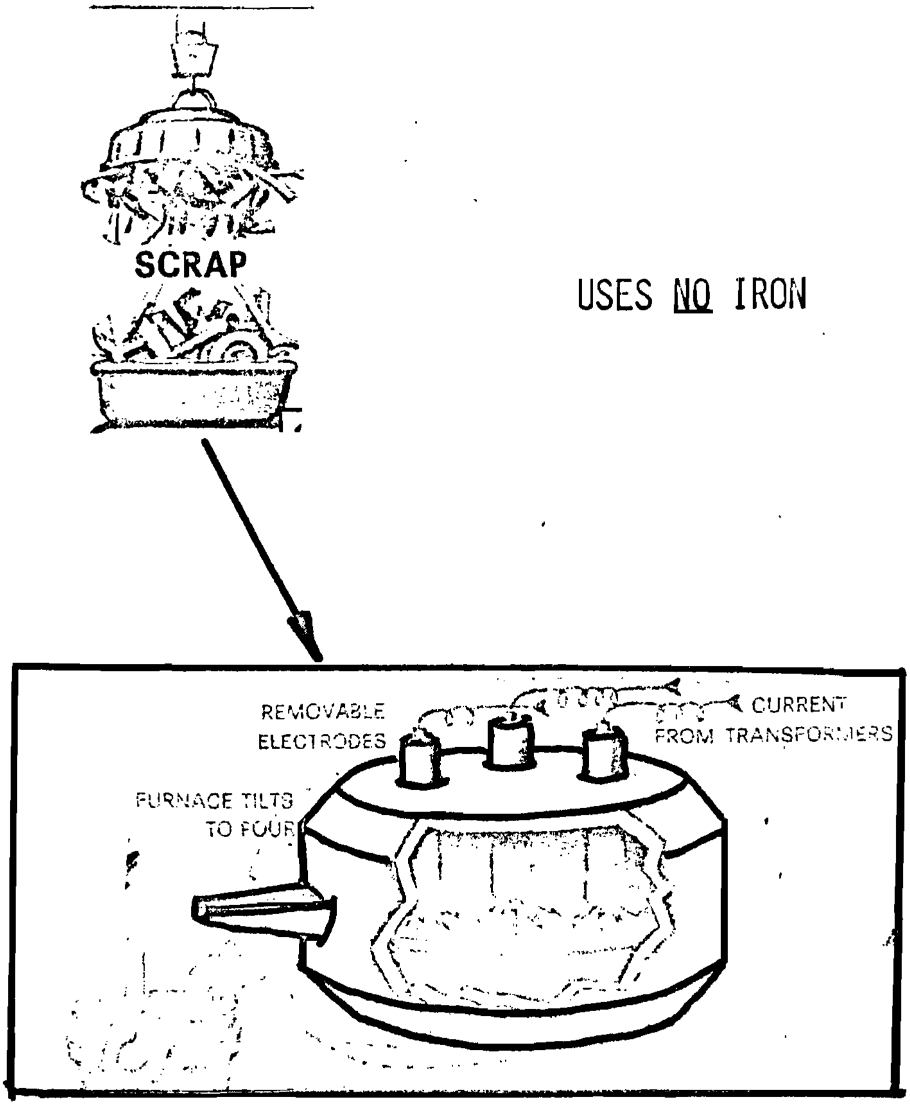

Fig. A.4 Electric Furnace

It is possible to take different quantities of steel scrap with known but arbitrary analysis and together with the addition of any missing elements, arrive at the required analysis by calculation. In practice, this works well and the electric furnace is used especially for critical steels such as alloys. If necessary, the molten steel can be sampled, rapidly analysed and the steel analysis adjusted by additions if it is found to be wanting.

Teeming, Stripping and Soaking

Whatever the steel making process, the result is molten steel hopefully of the required analysis. The next step is to mould the steel into an ingot (see Fig. A.5). Ingots come in a variety of shapes and sizes and the act of making the ingot provides yet another opportunity for affecting the final steel characteristics. This point tends to be technical and the curious should consult the references given.

A "simple" mould consists of a cast iron tube with a square or oblong internal cross section. The walls are thick (perhaps 20 cm) and the whole assembly sits on an equally thick base plate. The base plate itself sits on an ingot bogie and typically takes four moulds. A series of bogies makes up an ingot mould train.

Steel from a ladle is poured into each ingot mould and once the whole train of moulds has been filled, it is taken away to cool down. At this point it is worth noting that each ingot may weigh up to 50 to 60 tons and sometimes even heavier ingots are made.

As espected, an ingot cools on the outside first and so there comes a stage when, although possibly still liquid inside, the shell is solid enough that the ingot can be handled. The timing is a matter for care but the ingot train is next taken to a stripping bay. The moulds are designed with a slight

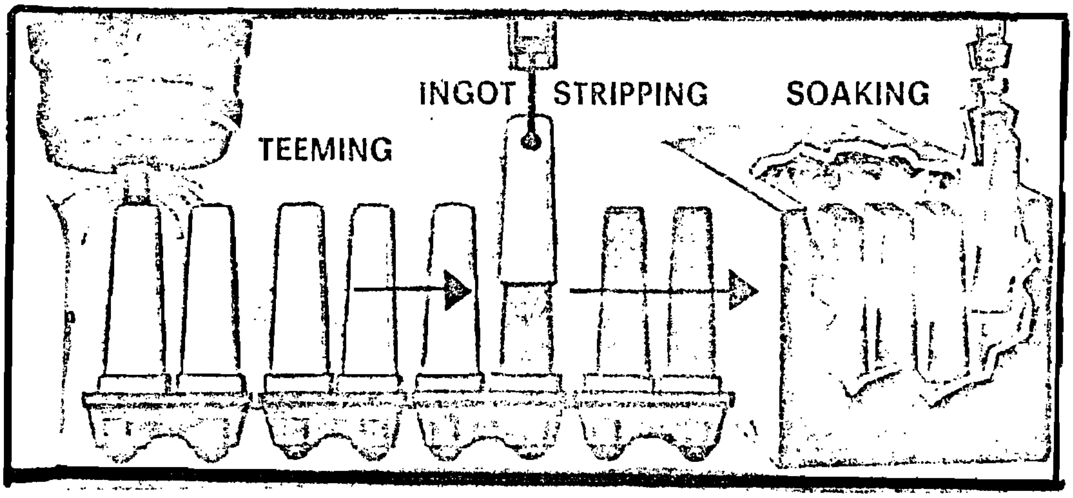

Fig. A.5 Teeming, Stripping and Soaking

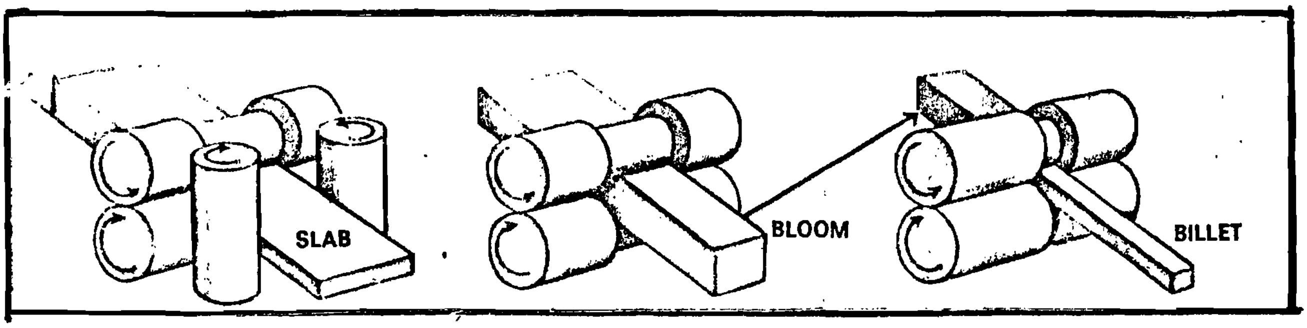

Fig. A.6 Rolling Mills

taper upwards and this allows the mould to be lifted of both the solid ingot and the base plate, an action known as stripping.

Stripped ingots will still have a nonuniform temperature profile and this precludes any physical deformation such as rolling since the results, even if not dangerous to the mill, would be unsatisfactory.

A type of furnace called a Soaking Pit becomes a home for ingots until the temperature profile evens out; the ingots are then available for rolling.

The problem associated with forming ingots and soaking them are mostly logistic. A fair amount of overhead crane activity is called for and the whole operation must match both steelmaking and rolling cycles and schedules.

Primary Rolling

Primary rolling is so called because it is the first stage of rolling inflicted on an ingot. A primary mill is almost invariably a reversing mill and a programme of reduction sequences during which the ingot moves backwards and forwards through the rolls, is calculated to reduce the ingot from its starting shape into another. Calculating an optimum pass sequence is complex and a computer is often used.

Already the final shape of a steel product has an influence and two main shapes are rolled out of an ingot, namely a slab and a bloom (see Fig. A.6). The slab is wide and relatively thin while the bloom is square in cross-section. The slab will go on to be further rolled into thin sheets or plates while the bloom will be used to produce sections (or railway lines for examples) and billets - much smaller than blooms but still a square cross-section.

Some primary rolling mills are capable of rolling either slabs or blooms, such are called Universal Mills. In works where such flexibility serves no purpose, a mill specially constructed to only roll slabs - a slabbing mill by name - or a blooming mill for blooms, will be used.

Since the further processing of slabs and blooms is different, they will be dealt with separately. Slabs go first onto a Hot Strip Mill or to a Plate Mill and blooms to a Billet or a Section Mill.

Hot Strip Mill

In most works, the slabs which are to be rolled on a hot strip mill spend some time in a slab stockyard after they leave the slabbing mill. This serves two purposes, namely it allows the slabs to be inspected for surface quality and repaired if necessary and it decouples the slabbing mill from the hot strip mill. This latter point is very important since the slab rolling sequence is rarely the same as the hot strip mill rolling sequence.

Being cold, each slab must be reheated in a furnace before it can be rolled on the hot strip mill. Such reheating takes place before most hot rolling processes.

A hot strip mill is one type of mill in which each pair of rolls is set to effect some specific reduction and the steel passes through once only (Fig. A.7). To roll a slab 20 mm thick into a strip of only 2 or 3 mm, the steel must pass through a series of such rolls and a modern hot strip mill may comprise up to 8 or IO stands. At each successive stand, the steel is further reduced and since the volume of steel remains constant, the more the steel is reduced, the farther it travels.

This presents a different control problem since the rolls of each stand must turn at a speed compatible with its neighbours

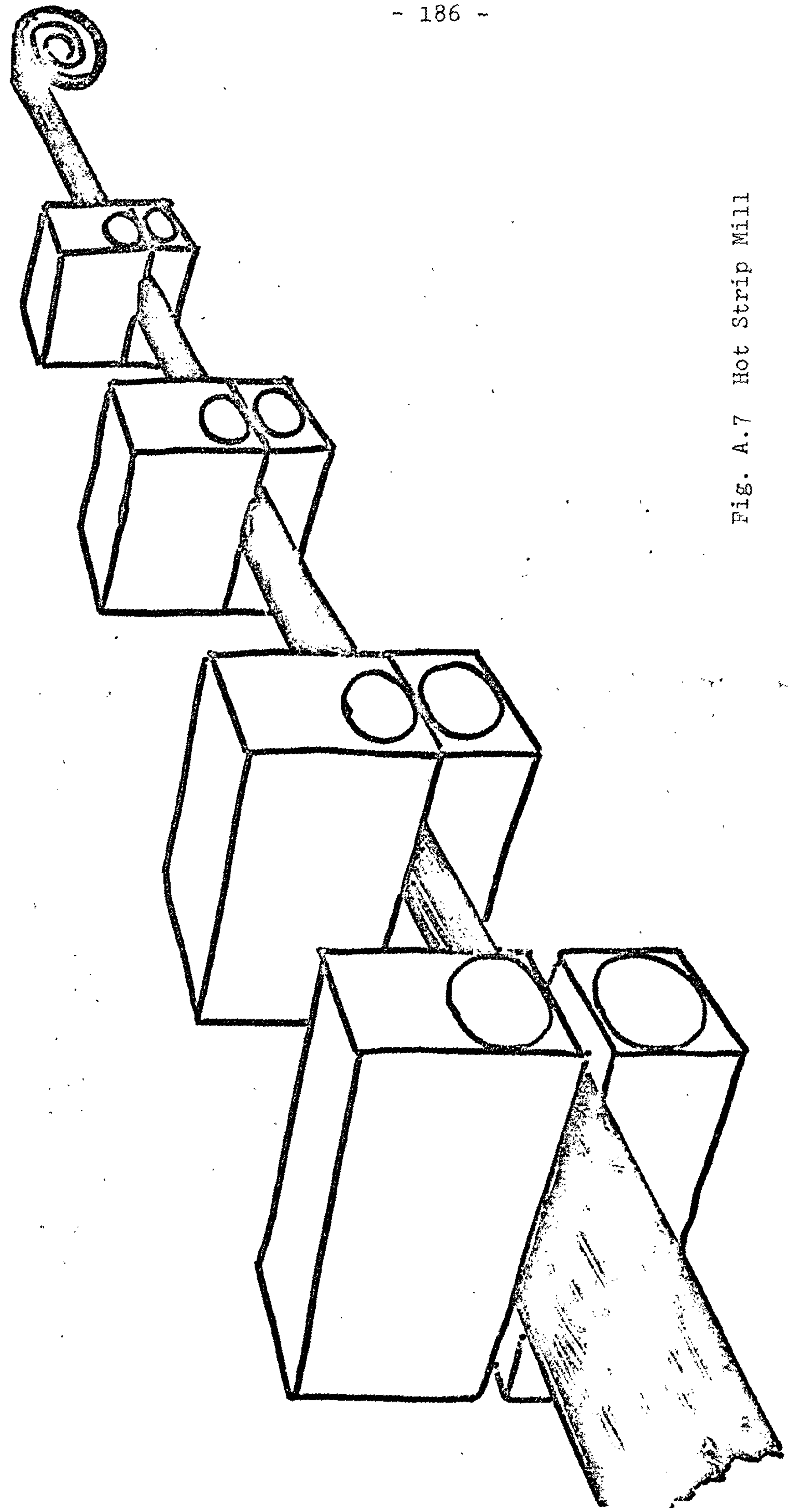

Fig. A.7 Hot Strip Mill

and at the same time ensure the correct thickness reduction takes place. Needless to say, this type of mill is normally computer controlled.

A thin strip of steel emerges from the final stand at high speed (50 k.p.h. for example); it is cooled by water sprays and coiled for ease of handling. The next process is the pickle line.

A description of a hot strip mill is not complete without mention of a hot strip mill rolling schedule. The rolls of a hot strip mill may be 2 or 3 meters wide and there is a natural maximum limit to the width that can be handled. Narrow strips can be rolled, but the portion of roll where the edge of a narrow strip runs is likely to become marked. If a wide strip is then rolled the markings can appear on the strip surface and a reject results. For this and other reasons, there are strict constraints on the feasible sequence of slabs through a hot strip mill. In general, the widest go first and the narrowest last, the rolls must then be changed for a fresh set.

Pickle Line

Coils rolled in a hot strip mill often exhibit scale and other surface imperfections. If the strip must go on to be rolled cold, for further slight reduction and for metallurgical reasons, it must first be cleaned.

The strip is passed through a pickle line which is basically an acid bath which cleans the surface by chemical action (Fig. A.8). Once through, strip is washed of any remaining traces of acid and is then recoiled.

Because of the difficulties of leading the front end of a coil through the acid bath, each coil is attached to the end of its predecessor and a continuous action is ensured.

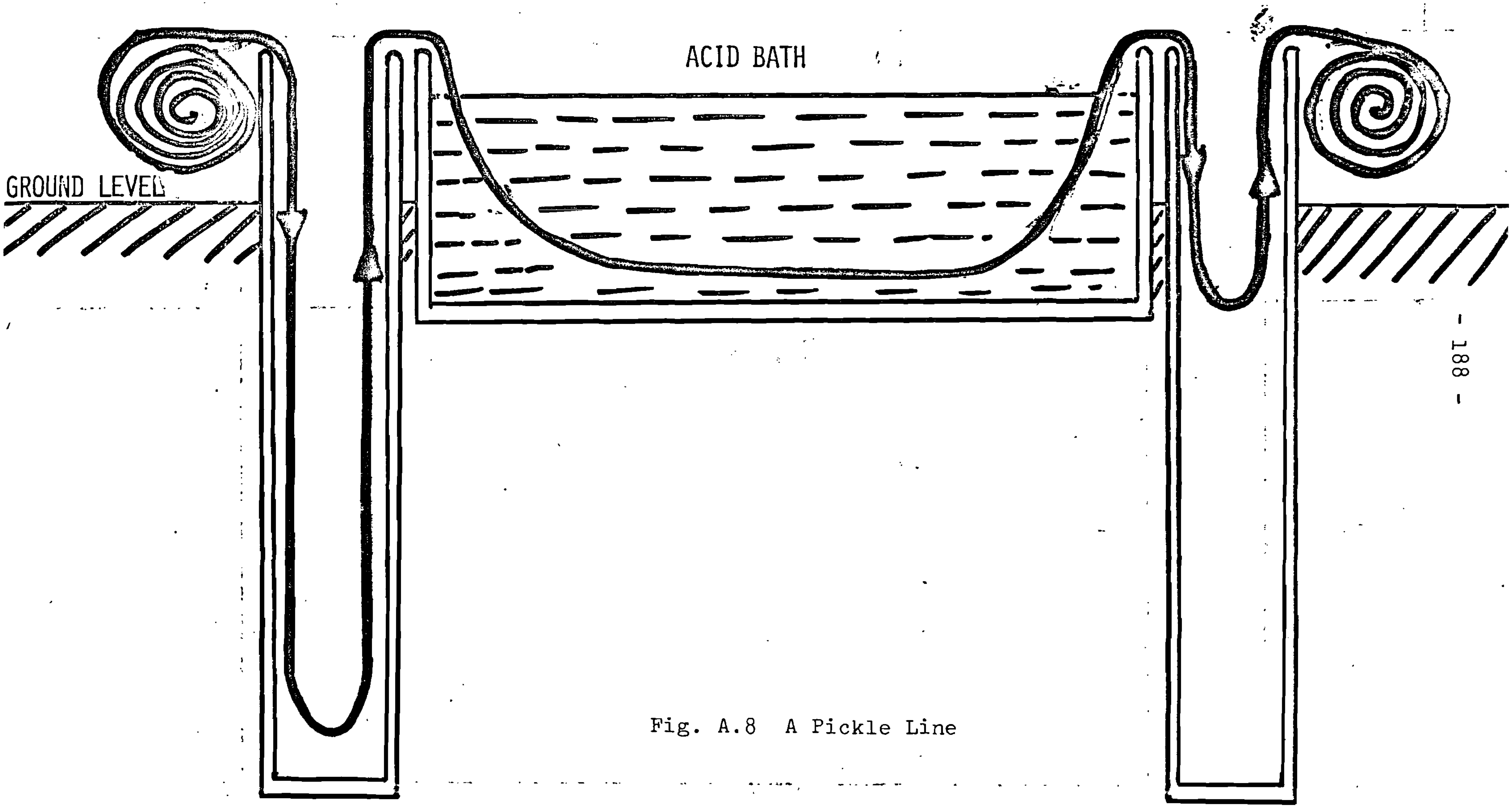

Fig. A.8 A Pickle Line

Cold Rolling Mill

A cold rolling mill works on a similar principle to the hot rolling mill but usually comprises only 4 or 5 stands. The degree of reduction is much less than for hot rolling and the emphasis is on surface quality.

The scheduling of a hot strip mill and a cold mill is complicated by the fact that, again, the preferred sequence for one is not the same as for the other. An intermediate stockyard for coils allows the sequence changes to be effected.

Strip Finishing

Following the cold strip mill, a series of possible processes can be utilized. They include annealing, both continuous and batch types, to relieve stresses caused by cold rolling, temper mills to harden the surface again, protective coating lines to apply zinc or tin and various painting, plastic coating lines, etc.

For dimensional changes, slitting lines turn a wide coil into 2 or more narrower ones, and cut up lines prepare sheets by cutting up the strip into lengths.

Plate Mill

While a hot strip mill can roll steel with a maximum final thickness of about I2 to I4 mm, anything over that amount will be called a plate. Typical dimensions are 2 or 3 meters by 5 to IO meters.

As mentioned earlier, slabs may also pass on to a plate mill for further rolling. A reheating stage is again needed and the plate mill, which is normally of the reversing type of mill, rolls the slab into a plate by successive passes. A plate is not as constrained by size sequences but otherwise shares all the problems common to the rolling process. It is becoming increasingly common to computer control such mills.

Billet Mill

One further use of blooms is the billet mill which may follow directly after the blooming mill without further heating or may be preceeded by a reheat furnace.

A typical billet mill is of the continuous variety - similar to the hot strip mill - and it comprises a series of mill stands each reducing the steel a little further. Since a billet has a square cross-section it must be reduced alternately across its vertical and horizontal sides. This is achieved by the mill stands themselves being alternately vertical and horizontal.

Due to the reduction, a billet would be several hundred meters long if it were not for the flying shear. This device is triggered to make a lightning cut through the emerging billet at intervals so that constant billet lengths are cut. The lengths are stacked side by side to cool in readiness for the next process or for despatch.

In a steel works billets may be further rolled into bars, small flats, wire, etc.

Section Mill

The other main outlet for blooms, again after reheating, is a section mill. A section is a class of steel shape normally used for construction purposes, pit props and railway lines. The shapes vary but "H's", "I's", "U's" and angles "L" are most common.

A section mill comprises a number of stands all with rolls which have been shaped so as to perform one stage in transforming a square bloom into the desired shape. A dozen or so stages are usual and each piece of steel is fed (quite often with manual guidance) through each aperture in turn.

Once rolled, a section is 200 to 300 feet in length and must be cut into the lengths ordered by customers. This is possible, while still red hot, by means of a circular saw.

Continuous Casting

From the molten state, steel passes through teeming, stripping, soaking and slabbing before the slab form is reached. A continuous casting machine (see Fig. A. 9) is a relatively recent innovation which allows slabs to be made directly from molten steel.

The heart of the process is a water cooled mould whose internal cross-section matches the required slab size and shape. Cooling is sufficiently rapid so that, although molten steel is poured into the top, the steel surface at least is solid by the time the continuous slab is pulled downwards by controlled rolls. The newly formed slab is further cooled by water sprays and then straightened by more rolls. A cutter shears off the required slab size which are then ready to go to a hot strip mill or plate mill.

A Complete Works

Figure A. 10 shows the flow chart for a steel works comprising all the processes mentioned in this appendix. However, two processes shown have not been referred to: one is the Coke Ovens and the other is the Sinter Plant.

Both prepare raw material for the blast furnace. Coke is needed for successful blast furnace operation and it is manufactured from coal. Some steel companies buy their coke but most make their own. A particularly hard variety of coke is called for and only certain types of coal are useable. Coke-making has useful by-products, gas being the most important as it can be used elsewhere for fueling furnaces or sold to the local authorities.

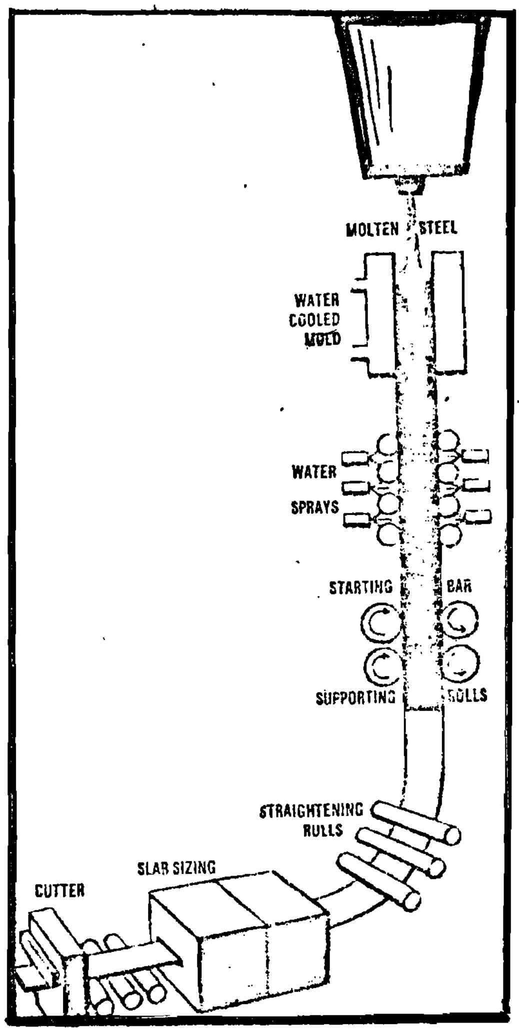

Fig. A.9 Continuous Casting

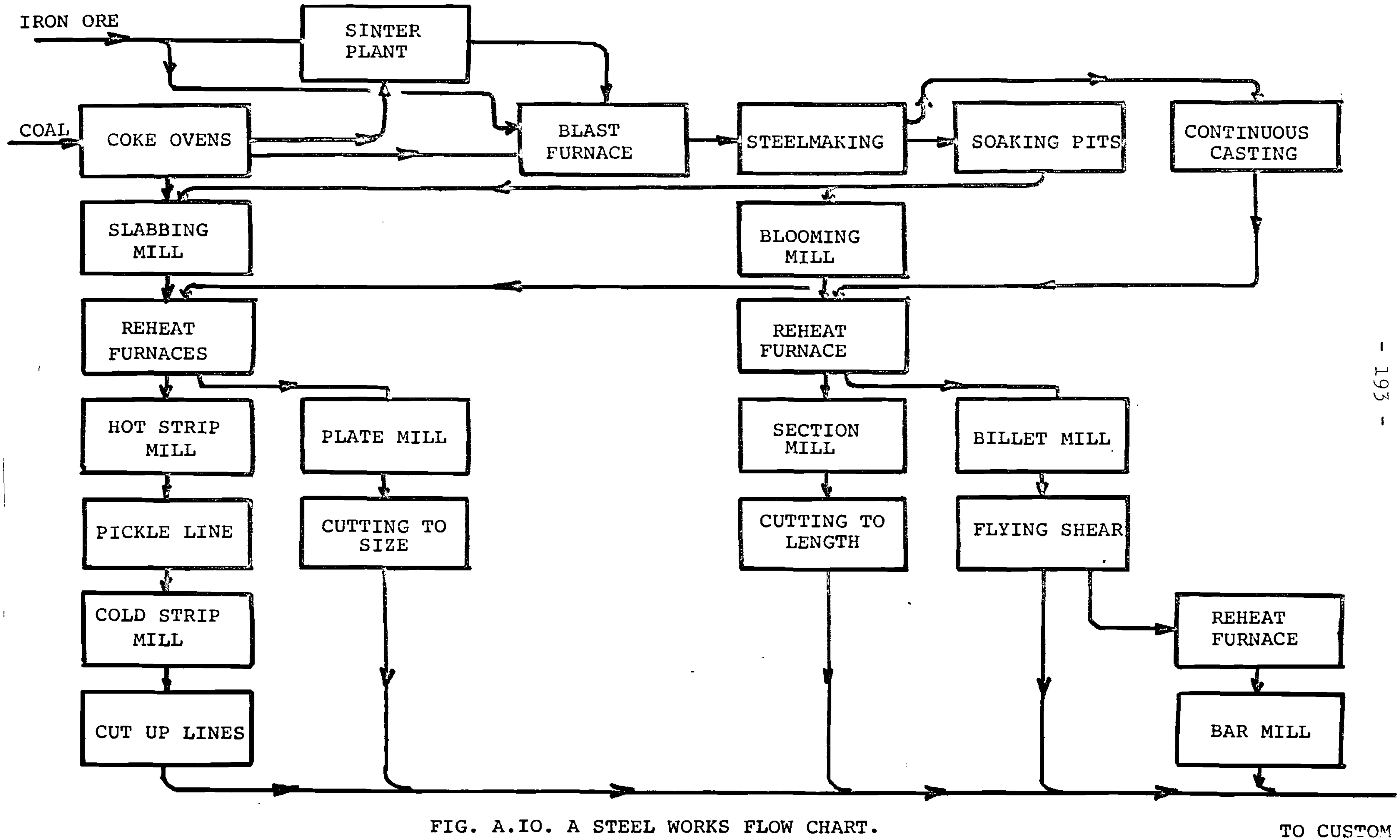

FIG. A.IO. A STEEL WORKS FLOW CHART.

Iron ore dust would block a blast furnace if included in the burden and thus restrict the flow of hot air. A sinter plant allows iron ore dust and small pieces to be amalgamated with coke to form a substance called sinter. This sinter is physically strong and porous and forms a useful component of a blast furnace burden.

Without meaning to deflate, this hypothetical steel works does not exist because, in practice, there are several more processes and the cross connections, multiple product flows, etc. are much more complicated than have been described here. However, most of the important features have been covered and it is hoped a reasonably accurate impression created.

Acknowledgements and Bibliography

Much of the content and the basis for many of the drawings have been taken from the United States Steel Corporation publication "The One-Leaf-Book Story of Steel". We are grateful for permission to use this material, which was willingly granted.

For further reading, the following is suggested:

"The Making, Shaping and Treating of Steel". United States Steel International Corporation.