Lecture Notes in Management and Industrial Engineering

Gideon Halevi

Industrial Management – Control and Profit

A Technical Approach

Springer

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Preface

The traditional approach to design of manufacturing systems is the hierarchical approach. The design is based on a top-down approach and strictly defines the system modules and their functionality.

Communication between modules is strictly defined as a one way and limited in such a way that modules are allowed to communicate only with their parent and child, were the parent sets constraints on the child, and the child set constraints on the following module parent.

For example: a process planner set the routing for each item. Production planning regards this routing as a constraint. It must plan capacity planning using this specific routing. In case of overload, or disruptions, it must search a solution with sophisticated theory of constraint mathematic algorithms. He is not allowed to search for technological solution, i.e. another routing.

Process planning was regarded as an art and not a science, therefore, the intentions, ideas and optimization used in formulating a routing are unknown, and it is a constraint.

Research developments proposed several computer aided process planning programs, were the user may generate a routing to his specifications and optimization without the support of a process planner. (The process planner task is redefined).

This option converted the process planning from art to science were routing should not anymore be a constraint, but a tool for user. For example, the production planning will solve scheduling problems by generating another routing.

Such option introduced flexibility to the manufacturing process. The stumbling block between manufacturing modules can be removed. The decisions made at each stage become observable, controversial and doubtful.

While restructuring the manufacturing process and preparing computer program, detailed specifications for any decision to be made had to be carefully analyzed and tested, and consult with the appropriate specialist(s) in the field. This stage conspicuous expose that there is a mix of experts interest in several manufacturing modules. Some decisions are engineering ones, but they affect economics interest, therefore they should be involving management decision or at least authorization.

This book intention is to enlighten engineering and management to where are the boundaries for making decision without the consent of management. Engineering must make operational decision but should be careful not to jeopardize company profitability. Such contravention areas are presented and discussed.

On the other hand management should consult with engineering concerning technological decisions.

The method of presentation is by dedication a chapter to each stage of the manufacturing process. The theme of the chapter is described. Assuming that the technological maters are handled satisfactory by the engineering professionals, therefore they are not referred in this book. However, the subjects which are calls for economic consideration, and therefore, management involvement is needed are marked as a section “Management control”. The reasons are detailed and explained.

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Part I Management Control Engineering

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Chapter 1
Introduction

Abstract The manufacturing process is a chain of activities aimed at meeting management objectives. These objectives are mainly carried out through the engineering profession.

Each stage in the engineering cycle has its own objectives and criteria of optimization according to its function. Not even a single stage considers management's primary criterion of optimization as its primary objective.

Most decisions are made by engineers who are not qualified to make economic decisions. Thus, there is vagueness as to who should make certain decisions, a situation with the potential to upset enterprise efficiency and profit. This chapter attempts to clarify the dilemma surrounding such decisions so as to improve efficiency.

1 Introduction

The main objectives of an industrial enterprise are:

- Implementation of the policy adapted by the owners or board of directors
- Optimum return on investment
- Efficient utilization of Man, Machine, and Money

In other words, industry must make profit.

To accomplish these objectives, the manager might implement the following stages:

- Planning
  Planning is deciding in advance what to do and how to do it. It is one of the most basic managerial functions. Planning bridges the gap from where we are to where we want to go. It makes it possible for things to occur which would not otherwise happen. This stage calls for a manager with vision, intuition, creativity, leadership, analysis, decision-making and economy, among other skills. Such skills in combination can often be regarded essentially as an "art", but they still may be enriched and improved through practice and experience.
- Staffing
  Staffing is the function by which managers build an organization through the recruitment, selection, and development of individuals as capable employees. This topic calls for an understanding of and the ability to evaluate human capability.

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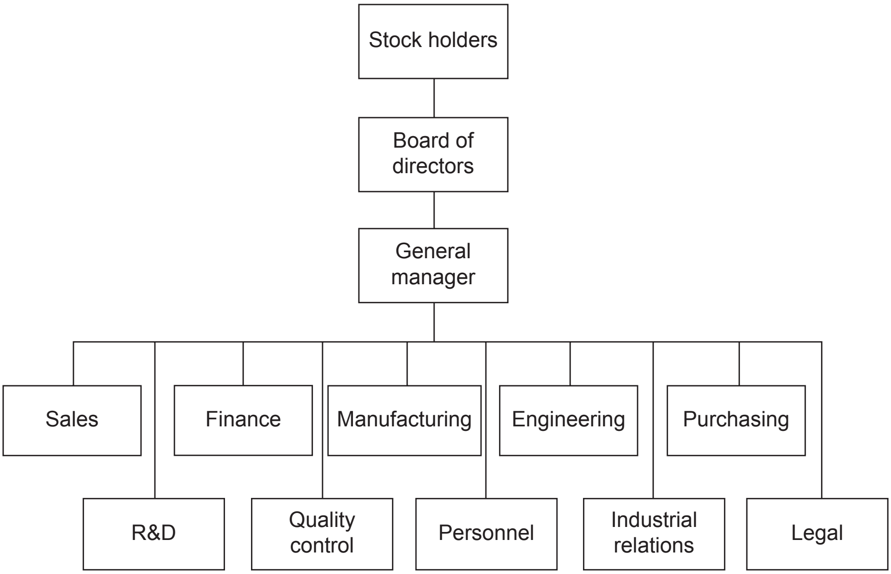

Fig. 1.1 Enterprise organizational chart

- Directing
  Directing means giving instructions, guiding, motivating and leading an organized staff in doing the work necessary to achieve the organizational goals. This stage calls for leadership, a trait that requires experience, natural charisma or, ideally, a combination of the two.
- Organizing
  Organization is the process of identifying and grouping the works to be performed, defining and delegating responsibility and authority, and establishing relationships that enable people to work most efficiently.
- A typical organizational chart of an industrial enterprise is presented in Fig. 1.1.

As can be seen in Fig. 1.1, an organization considers the point of view of many management disciplines such as:

- Marketing and sales
- Customer relations
- Economics
- Purchasing
- Cost and bookkeeping
- Storage, packing and shipping
- Inventory management and control
- Material handling
- Human resource planning

And manufacturing disciplines such as:

- Product definition and specifications
- Product design

- Process planning
- Production planning
- Scheduling, dispatching, etc.
- Shop floor control
- **Controlling** is a managerial function, like *planning, organizing, staffing* and *directing*. It is an important function because it helps to check errors and take corrective action so that deviation from standards is minimized and the stated goals of the organization are achieved in the desired manner. According to modern concepts, control is about foreseeing action, whereas earlier concepts were only implemented when errors were detected. Control in management means setting standards, measuring actual performance and taking corrective action. Thus, control comprises these three main activities.

To begin with, a set of objectives is defined by management. These objectives are mainly concerned with the production of tangible goods. A chain of activities, making up the manufacturing process, are then specified, as a rule, by engineers. Manufacturing and engineering are then further divided into stages according to the expertise required to perform each function of the manufacturing process. Such stages are shown in Fig. 1.2.

Scientific management calls for specialization in performing each task of the manufacturing process. No one can be an expert in all disciplines. Thus, a typical organization is based on a **hierarchical approach**, i.e., a top-down approach that strictly defines the system modules and their functionality. Module communication is allowed only between parent and child. In a hierarchical structure, modules cannot take initiative. The planning and execution regards previous decisions as unalterable, and, therefore, robs the production of flexibility and efficiency.

1.1 The Manufacturing Cycle

The manufacturing cycle is composed of the following disciplines:

Engineering Design The purpose of this stage is to transform management's objective into a detailed set of engineering ideas, concepts and specifications. Engineering design theories are employed, the objective is translated into engineering specifications, and the engineering task is defined. Thus, it is an innovation process. Many ideas and concepts will be formulated and analyzed, and the best conceptual solution will be determined. This conceptual solution will define the separate lower level engineering tasks (detail design) until the last detail of the design is decided upon.

The optimization criteria for the decisions made in this stage are, for the most part, engineering considerations: weight, size, stability, durability, ease of operation, ease of maintenance, noise level, cost, and so on. Some of the criteria conflict with each other, and thus, the decision will often be a compromise. However, the designer's primary criterion in making a decision is to meet the product objectives. This is the designer's most important responsibility, since errors in production are not as critical as errors in design. To be on the safe side, the designer will tend to incorporate as many safety factors as possible.

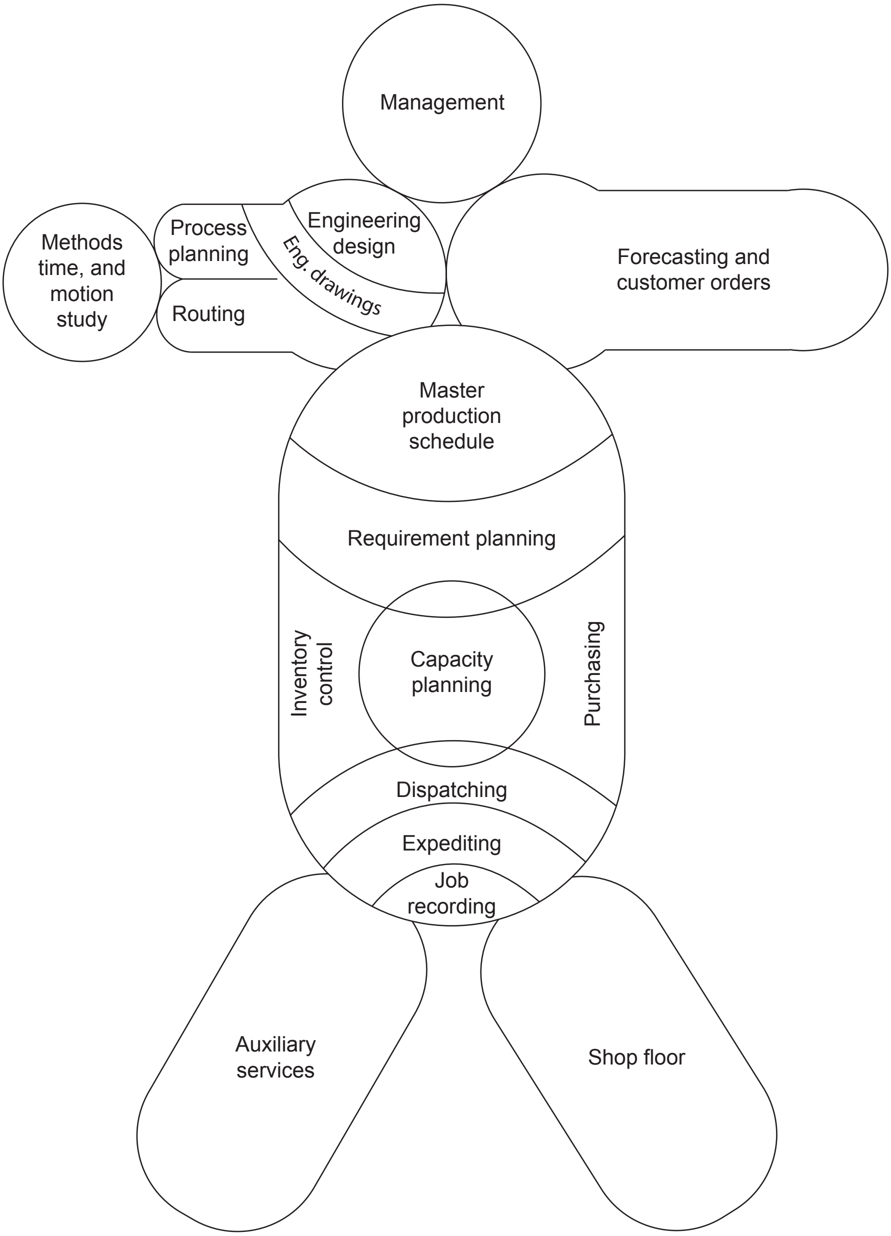

Fig. 1.2 The manufacturing cycle

Engineering Drawings In this stage, the design decisions reached in the engineering design stage are transformed into a set of detailed engineering drawings and part lists. It is an editing process, constrained by the explicit rules and grammar of engineering language, specifically drawings.

The decisions required in this stage are concerned with layout, the number of projections required, and, in some cases, the assignment of the non-critical dimensions. The optimization criteria for decisions made in this stage are clarity, readability, and flexibility.

Process Planning In this stage, the process that transforms raw material into the form specified by the engineering drawing is defined. This task should be carried out separately for each part, subassembly and assembly of the product. This stage is basically analogous to the engineering design stage, but here the nature of the objective is different.

Process planning is a decision-making task for which the prime optimization criterion is to meet the specifications given in the engineering drawings. The secondary criteria are cost and time with respect to the constraints set by company resources, tooling, know-how, quantity required, and machine load balancing. Some of these constraints are variable or semi-fixed; hence, the optimum solution obtained will be valid only with respect to those conditions considered at the time the decision was made.

Methods, Time and Motion Study The most economical way of performing the operations specified in the process planning stage and the time standards are established in this stage. It is a decision-making and computational process, and the optimization criteria are cost and time.

Routing The flow of work in the plant is prescribed in this stage. It is an editing process constrained by the data of the previous stages and taking into consideration plant layout, storage locations and the material handling system. The optimization criteria for decisions made in this stage are clarity, readability and inflexibility.

Forecasting and Customer Orders The purpose of this stage is to link sales and management strategy to manufacturing. It represents the driving force behind the manufacturing process that begins with orders and ends with deliveries. The specific type of industry and management policy adopted will determine the particular mode of operation, by confirmation of customer orders or by forecasting, or both.

Decisions made in this stage are mostly governed by economics and business factors not within the scope of the manufacturing functions. However, manufacturing provides much of the data required to arrive at optimum decisions. The manufacturing cycle regards this stage as an objective to be accomplished.

Master Production Schedule The master production schedule transforms the manufacturing objectives of quantity and delivery dates for the final product, assigned by the non-engineering functions of the organization, into an engineering production plan. The decisions in this stage depend either on the forecast or on confirmed orders, and the optimization criteria are meeting delivery dates, minimum level of work-in-process, and plant load balance. These criteria are subject to the constraint of plant capacity and to the constraints set in the routing stage.

The master production schedule is a long-range plan. Decisions concerning lot size make or buy, addition of resources, overtime work and shifts, and confirmation or alteration of promised delivery dates are made until the objectives can be met.

Material Requirement Planning (MRP, ERP, Etc.) The purpose of this stage is to plan the manufacturing and purchasing activities necessary in order to meet the targets set forth by the master production schedule. The number of production batches, their quantity and due date are set for each part of the final product. The decisions in this stage are confined to the demand of the master production schedule, and the optimization criteria are meeting due dates, minimum level of inventory and work-in-process, and department load balance. The parameters are on-hand inventory, in-process orders and on-order quantities.

Capacity Planning The goal here is to transform the manufacturing requirements, as set forth in the MRP stage, into a detailed machine loading plan for each machine or group of machines in the plant. It is a scheduling and sequencing task. The decisions in this stage are confined to the demands of the MRP stage, and the optimization criteria are capacity balance, meeting due dates, and the minimum level of work in process and manufacturing lead time. The parameters are available plant capacity, tooling, on-hand material and employees.

Dispatching, Order Release This stage serves as a link between production planning and execution. It initiates the productive activities by the issuance of orders to the shop floor according to the program formulated in the capacity planning stage. Although it is mainly an execution task, as a result of shop dynamics, immediate decisions concerning required changes may become necessary. The primary optimization criterion in this stage is to supply sufficient work to each station in the plant and department. The secondary criteria are meeting due dates, minimum level of work in process and inventory, and any parameter specified by the dispatching rules used in the particular plant.

Expediting (Follow-up, Plant Monitoring and Control) Expediting is used to ensure that the execution of jobs orders released to the shop floor by the dispatching stage will stick as closely as possible to the plan. Although it is mainly an execution task, unforeseen interruptions may occur even under good planning, and thus, decisions regarding the appropriate course of action would be required.

The primary optimization criteria are meeting production plans and scheduling, while the secondary criteria are coordination between production and supporting activities (such as inspection, material handling, maintenance, tool room, fixture design) and the amount of time operators spend waiting for work. In other words, the goal of optimization can be for the minimum manufacturing lead time and work in process.

Job Recording Job recording supplies data concerning work activity to the expediting stage and links manufacturing to cost, personnel, salary, incentive plans, and general management. It is not a decision-making task, but, rather, is clerical in nature, being based on company procedure.

Purchasing The purpose of this stage is to obtain the required quantity of supplies of the specified quality at the right time; it also serves as a link between the manufacturing data and management functions. Basically, the purchasing stage can be regarded as a manufacturing department where job orders are issued and items ordered are supplied. However, the decisions that procurement personnel have to make are of a different nature than those made by foremen in the shop. The decisions in purchasing concern selection of a supplier subject to the optimization criteria of quality, quantity, delivery date and cost. These optimization criteria may conflict with each other (e.g., cost versus quality or delivery date versus quantity), and procurement personnel must find the best compromise, taking into account the constraints of the requirement planning and master production scheduling stages, namely, quantity, quality and time.

Inventory Control The purpose of this stage is to keep track of the quantity of material and number of items that should be and/or are present in inventory at any given moment; it also supplies data required by the other stages of the manufacturing cycle and links manufacturing to cost, bookkeeping, and general management.

Inventory control is a clerical execution task based on company procedure. The decisions in this stage are usually confined to choosing the procedure to be applied in any given case.

Shop Floor The actual manufacturing takes place on the shop floor. In all previous stages, personnel dealt with documents, information, and paper. In this stage, workers deal with materials and produce products. The shop floor foremen are responsible for the quantity and quality of items produced and for keeping the workers busy. Their decisions will be based on these criteria.

Auxiliary Services We should not fail to mention the supporting functions that are essential to the manufacturing industry, namely, material handling, maintenance, tool room for preparing jigs and fixtures, set-up and programming of numerical machines, and quality control. Each of these functions has its own responsibility, and this responsibility serves as the primary criteria when decisions have to be made.

1.2 Basic Concepts and Objectives

Manufacturing consititutes only one discipline in the organizational chart of an industrial enterprise, albeit a dominant one, since it controls the daily activities of the other disciplines. However, it represents only one aspect of the activities of industrial management.

Management must consider all activities of the enterprise, and its main objective is to make profit. However, through the hierarchical approach, not even a single stage of the manufacturing process considers finance, economics and cost as their primary objective. Each stage optimizes its task to the best of its ability. Each stage in the manufacturing cycle has its own objectives and criteria of optimization according to its function. Even if each stage functions optimally, this does not necessarily guarantee overall optimum success with respect to management's prime objectives.

The hierarchical approach to manufacturing is a one-way chain of activities, where each link has a specific task to perform and the previous link is regarded as a constraint. Thus, for example, master production schedules accept the routing and bill of material as fixed data (as well as quantities and delivery dates); it does not question these data and its planning must comply with them. Process planners accept the product design and its bill of materials without question; in fact, they do not even consider the product as a whole, but, rather, regard the production of each part as a specific task. Only if problems are encountered in defining the process for a particular part do they turn to the product designer and suggest or ask for a change in design. The capacity planner accepts the routing as fixed data, and employs sophisticated algorithms to arrive at an optimum capacity plan.

Therefore, the chain of activities that comprises the manufacturing cycle is considered to be a series of independent elements having individual probabilities of achieving a criterion. The probability of success for any link is independent of every other link with which it is functionality associated. Thus, the overall probability of the chain optimally achieving a particular criterion is:

$$\mathrm{Pj} = \mathrm{Pj1} \times \mathrm{Pj2} \times \mathrm{Pj3} \times \ldots\ldots \times \mathrm{Pjn} = \prod_{i=1}^{i=n} Pj,i \tag{1.1}$$

where

Pj = the overall probability of the chain achieving criterion j,
Pji = the probability of achieving criterion j in link i.

The six stages of the manufacturing cycle subject to financial criterion are shown in Table 1.1.

As can be seen, the financial criterion appears in all stages as the third criterion, not as the primary. If we assume an 80 % probability of achieving the financial criterion in each of these six stages, then the overall probability of the financial criterion being optimally achieved in the manufacturing cycle will be (by using Eq. (1.1)) $0.8^6 \times 100\,\% = 0.26\,\%$. It should be noted that the ability to predict each probable Pj,i is difficult at best; therefore, the discussion is only qualitative.

The budget is a document that forecasts the financial results and financial position of a company for one or more future periods. A primary use of the budget is as a performance baseline for the measurement of actual results. This can be misleading, since budgets typically become increasingly inaccurate over time, resulting in large variances that have no basis in actual results. To reduce this problem, some companies periodically revise their budgets to keep them closer to reality, or only budget for a few periods into the future, which gives the same result.

Another option that sidesteps budgeting problems is operating without a budget. Doing so requires an ongoing short-term forecast from which business decisions can be made, as well as performance measurements based on what a peer group is achieving. Though operating without a budget can at first appear to be too slipshod to be effective, the systems that replace a budget can be remarkably effective.

A more complex budget contains a sales forecast, the cost of goods sold and expenditures needed to support the projected sales, estimates of working capital requirements, fixed asset purchases, a cash flow forecast, and an estimate of financing needs. This should be constructed in a top-down format, so a master budget will contain a summary of the entire budget document, while separate documents containing supporting budgets roll up into the master budget, and provide additional detail to users.

Table 1.1 The manufacturing stages (links) and their criterion

Link i =	Stage	Criterion j
1	Engineering design	$P_{1,1}$ = Performance $P_{2,1}$ = DFM, DFA $P_{3,1}$ = Finance …. $P_{n,1}$
2	Process planning	$P_{1,2}$ = Performance $P_{2,2}$ = Time $P_{3,2}$ = Finance …. $P_{n,2}$
3	Methods, time and motion study	$P_{1,3}$ = Time $P_{2,3}$ = Ease of $P_{3,3}$ = Finance …. $P_{n,3}$
4	Master production schedule	$P_{1,4}$ = Load profile $P_{2,4}$ = Delivery dates $P_{3,4}$ = Finance …. $P_{n,4}$
5	MRP (Material requirement - resource planning)	$P_{1,5}$ = Delivery dates $P_{2,5}$ = Load profile $P_{3,5}$ = Finance …. $P_{n,5}$
6	Capacity planning	$P_{1,6}$ = Due dates $P_{2,6}$ = WIP (Work in Process) $P_{3,6}$ = Finance …. $P_{n,6}$

The budget might be a good tool for planning the future of the company and measuring its long range efficiency. But it ***cannot serve*** as an on-line management control of the daily activities of the company and ensure that the individual discipline of the manufacturing cycle will consider profit as one of its responsibilities.

Another tool is the operation of the company. A company is organized with respect to key functions, each function being concerned with a different aspect of the operation and stolidly representing its point of view. For example, sales would want to be able to promise early delivery and competitive prices, and thus, would favor a high level of inventory and low-cost production; finance would prefer a minimum amount of capita tied down in production, and thus, would favor a low level of inventory and short lead time production; finally, the production manager would emphasize that all work stations have jobs, and thus, would favor a high level of in-process inventory and long lead times. Only if each of the functions stands up for its own interests will a good balance in the overall operation of the plant is reached.

Value engineering is another tool that management can use to examine and improve the various manufacturing activities. It will usually be used when providing support to a particular product in response to market demands. Although value engineering is an important tool, it is seldom employed as a part of the normal manufacturing cycle; if it were to become a standard part of the manufacturing cycle, it would be part of the "Establishment" and probably cease to serve its original purpose.

Standardization and simplification are additional tools that can be used to improve the financial aspects of manufacturing. However, they are administrative measures without real control.

Another approach that management may take is to focus on profit opportunities rather than on efficiency.

1.2.1 Management Control

Management must have tools (controls) in order to achieve its own objectives and exercise control over operations. One of these tools is the budget.

Manual tools can be inefficient, and, consequently, the use of the computer can assist management in performing its task in an approved manner.

1.3 Reviewing and Evaluating: The Traditional Approach

The traditional approach for manufacturing systems is hierarchical, as previously described.

The basic notions behind the hierarchical approach are:

- Use the "best" routine for the job
- The "best" routine, optimized for maximum production, will result in the shortest throughput
- The larger the quantity, the better the productivity.
- Therefore, MRP (Material Requirement Planning) considers all orders, explodes the orders into its product tree, and combines the quantity of individual items, when possible.

But these basic notions have been evaluated and proven to be inherently flawed. Recent research in the field of process planning has strongly indicated that ***routing is an obscure term***. There is no such attribute as the "best" process. For each item, there may be many different methods of routing, which differ from one other in processing time and processing cost. Usually, the shorter the processing time, the higher the processing cost.

For example, twenty two alternative routings for the item "CROSS" were generated by the CAPP system, the results of which are shown in Table 1.2.

Which one of the routings should be used for production and management planning?

Which one of the routings should be used for resource planning?

Who should make such a decision, management or the engineers?

The notion that the "best" routine for "maximum production" will result in the shortest throughput proved wrong. Simulating the processing of products with 2 orders, 12 items, 35 operations and 15 resources with several scheduling strategies for the maximum production strategy resulted in the longest throughput. Checking this

Table 1.2 Alternate processes by using different machine combinations

No.	Total cost	Total time	Max. time	Resource costs $	Best routing selection for
1	23.76	5.9	5.94	400,000	Max. production
2	19.02	6.34	6.34	300.000	
3	15.54	11.10	11.10	70,000	Min. investment
4	24.98	12.49	12.49	100,000	
5	19.80	5.84	4.48	500,000	***
6	17.70	8.94	5.72	420,000	
7	22.80	7.10	5.00	405,000	
8	19.57	6.59	5.89	700,000	For ROI
9	16.97	6.22	4.83	400,000	Max. profit
10	15.53	9.19	5.72	320,000	
11	18.15	7.45	5.35	305,000	
12	15.18	9.99	7.73	370,000	
13	14.98	12.42	6.40	90,000	Years for ROI
14	15.19	10.47	9.08	170,000	
15	24.90	13.50	11.40	105,000	
16	16.09	13.3	9.99	120,000	
17	14.94	12.98	6.40	95,000	
18	17.66	8.90	3.88	425,000	
19	14.90	10.09	6.23	375,000	
20	14.34	10.81	5.72	390,000	***
21	14.83	9.36	6.85	470,000	
22	14.30	10.77	3.88	395,000	Min. cost

The noted minimum and maximum alternatives are mathematically optimal but not practical as designed by *** (some other alternatives have negligible differences)

astonishing result, it was found that using the "best" routine creates a long queue. A long queue results in an increase of work in process (WIP) inventory.

Who should make such a decision, management or the engineers?

The notion that "the larger the quantity, the better the productivity" sounds logical and reasonable. The larger the batch sizes, the lower the set-up cost and time consumed per single item.

Research in the dispatching rules field states that "Mean lateness is minimized by SPT (Shortest Processing Time) sequencing". SPT is affected by order quantity and routine. Increasing the quantity increases the processing time, and thus, affects the throughput. The conclusion might be to recommend not increasing the quantity by combining items from different orders.

Table 1.3 shows simulated results of the effect batch size and routing. The numbers in the body of the table are the number of periods it took to process the orders.

There are two routings, one for maximum production and one for minimum cost. One case is marked as *Cost/Production*, which means: begin scheduling with minimum cost routing, but if an operation has to wait for a resource for a limited number of periods, switch to an operation of maximum production routing.

The second case is marked as *Production/Cost*, meaning to begin scheduling with maximum production routing, and if an operation has to wait for a resource, then switch to an operation of minimum cost routing.

Table 1.3 Simulation results of batch size and routing effect

Batch quantity	Criteria of optimization			
	Max. prod.	Min. cost	Cost/Prod.	Prod./Cost
120	49	53	55	59
60+60	46	42	36	40
80+40	44	46	35	46
40+80	46	45	41	44
40+40+40	45	37	29	36

It shows that the best results were achieved by using the *smallest batch size* when starting with minimum cost routing.

The points raised the question as to which routing and batch size to use.

Who should make such a decision, management or the engineers?

The above results are very conclusive; however, they do not qualify by standards of scientific research. They may only be representative of a special case and not universal results. They may merely indicate a trend of increasing production productivity as the flexibility increases.

In addition, this demonstrates that there are actually many methods for producing an item. Traditionally, one of the many possible routings is selected and used (for production planning) for as long as the design of a given item is not modified. The consequences of making this selection are unknown at the time this decision is made.

1.3.1 Management Controls

The conclusions of this exercise are:

1. Treat each order, with its product structure, individually. Do not attempt to increase quantity by combining similar items into one processing batch. In one case, processing time increased by 43 % when items were combined (from 37 to 53 periods)
2. Selecting a routine based on maximum production criteria of optimization does not assure reduction of product mix processing time.
3. Limited flexibility reduces the processing time from 53 to 22 periods
4. Total flexibility reduces the processing time further to 16–18 periods

1.4 Introduction to the Management Control System

The management function is aimed at achieving defined goals within an established timetable, and usually understood to have the following components and the following management control steps:

- Setting performance standards.
- Measurement of actual performance.

- Comparing actual performance with the standards. The deviations between these two are measured.
- Analyzing deviations, and identifying the causes contributing to the differences.
- Determining corrective action to be taken to eliminate or minimize the deviations.

What is control?

- Control is a management process
- Control is a tool for achieving organizational activities
- Control is embedded in each level of the organizational hierarchy
- Control is a continuous process
- Control is closely linked with planning

Section 1.2 showed that the ***efficiency of the enterprise*** is subject to limitation due to the organizational approach and the conflict of objectives between the engineering disciplines and management objectives. Special diagnostic techniques may be required to isolate the trouble areas and identify the causes of the difficulty.

Management of an enterprise is a decision-making process. The technical data for decision-making is generated and supplied by engineers. However, an engineer's criteria of optimization in making decisions are not usually the same as those of management. The most common criterion of engineering optimization is either minimum cost or maximum production. Engineering decisions, i.e., design and process planning, vary according to the criterion employed. Engineers are generally not economists or production management experts. They are experts in product design and process planning. However, they are required to make decisions on topics that are outside their expertise, and those decisions are transferred to management who, based on that data, implement sophisticated mathematical management decision models. Therefore, ***management decisions are restricted*** by their dependence on engineering data.

Management must have tools to control enterprise efficiency and profitability.

The evidence shows that the economic benefits to be gained from organizational integration far exceed those benefits directly attributable to individual development efforts. This is particularly true in industries that manufacture discrete part-batches because of such factors as the need to maintain both a flexible fabrication base and highly efficient controlled operations. Such companies comprise a high percentage of U. S. industry, but their individual outputs are relatively small. Planned integration of systems would result in the evolution of programs that consider not only advances in individual areas of manufacturing, but also the potential relationships between these areas. A flexible system would appear to be superior to an integrated system, since it does not contemplate the relationships between individual areas and activities, but rather dissolves them into one single system.

A flexible roadmap provides the means for generating routing in less than a second of elapsed time; therefore, it can introduce new degrees of freedom and can treat the whole manufacturing process as one all-embracing dynamic system. Thus, each link is no longer constrained by the previous link, and the overall efficiency of the enterprise may be increased.

Op.	TP time	Priority	Mac. #1	Mac. #2	Mac. #3	PP time
010	2.0	0	3.3	2.8*	4.3	2.8
020	0.9	010	1.5*	2.4	2.1	1.5
030	2.2	010	2.6	2.2*	3.6	2.2
040	1.8	020	2.9	4.0	2.3*	2.3 ↓
050	1.2	040	1.6	1.8	1.2*	1.2 ↓
60	0.7	050	1.4	1.5	0.9*	0.9
070	0.6	020	0.6*	0.8	1.1	0.6
080	1.4	060	2.1	2.0	1.7*	1.7
Total	10.8		16.0	17.5	17.2	13.2

Table 1.4 Roadmap for item routing optimization

In manufacturing, there are several levels of optimization:

- Optimization of a single operation
- Optimization of an individual item
- Optimization of producing a product (several items)
- Optimization of producing a product mix
- Optimization of factory business.

The task of management is to achieve optimization of factory business; therefore, management must control each economic decision made by the individual disciplines. Optimization of a single operation does not assure optimization of an individual item.

Table 1.4 demonstrates a roadmap for an item requiring eight operations and three resources.

The optimization of each single operation is marked. What will be the optimization of the item? It surely depends on the batch quantity. Moving operations from one machine to another adds transfer time/cost, and thus, is referred to as a penalty. The amount of the penalty is equal to the transfer quantity divided by the batch size. For a high batch size, the penalty is negligent; therefore, the routing will use the best operation and the routing time will be 13.2. However, for a low batch size, the penalty might be larger than the difference in operation time, and so the routing will select to process the item on the one machine with the minimum total time, i.e., 16.0. The medium batch size must be somewhere between 13.2 and 16.0 and the optimum must be computed.

Such a search for the optimum occurs in all stages of the manufacturing cycle.

1.5 Notions for an Industrial Organizational System

The proposed manufacturing strategy approach makes use of the following notions:

- There are infinite ways of meeting design objectives.
- In any design, about 75 % of the dimensions (geometric shape) are nonfunctional (fillers). These dimensions can vary considerably without affecting the design performance
- There are infinite ways of producing a product
- The cost and lead time required to produce a component are functions of the process used
- Transfer of knowledge between disciplines working to produce a product should not include transferring decisions, but rather transferring alternatives, ideas, options considered, reasoning, etc.
- The company database should be "open" and available to all disciplines
- Engineering stages are incorporated into the production and management stages
- All stages of the manufacturing process should work toward a single objective. Each stage should consider the problems and difficulties of the other stages
- The objective is to increase productivity, decrease lead times, and decrease the manufacturing cost of the product mix in any given period, rather than to optimize any single product, component, or operation
- No artificial constraints should be created or considered
- The manufacturing process should be kept dynamic and flexible
- Each technical decision is made by computer algorithm
- Each decision is based on real facts and not on assumptions
- Each decision is made at the time of execution, independent of previous decisions
- Each decision may be changed when circumstances change
- Keep the system simple

The proposed organizational system is based on the roadmap technique and imitation of human behavior. The basic philosophy is that all parameters in the manufacturing process are flexible, that is, any of them is subject to change if such change contributes to increased productivity in manufacturing the product mix required for the immediate period. The parameters, including the process plan and product design, become fixed and frozen only at the last minute before starting the actual processing. In such a flexible and dynamic environment, the only constant parameters are the products to be manufactured and the facilities available at the shop.

The manufacturing cycle is divided into three main modules, as shown in Fig. 1.3.

The theoretical optimum design and planning module includes product design, process planning, and methods, time and motion study. It is called theoretical because it optimizes each item separately and is subject to change, yielding higher-level optimization (i.e., that of a product mix required in any time period).

The master production planning module is a coordinating function between manufacturing, marketing, finance, and management. Its main objective is a realistic production program to be released to the shop floor for production.

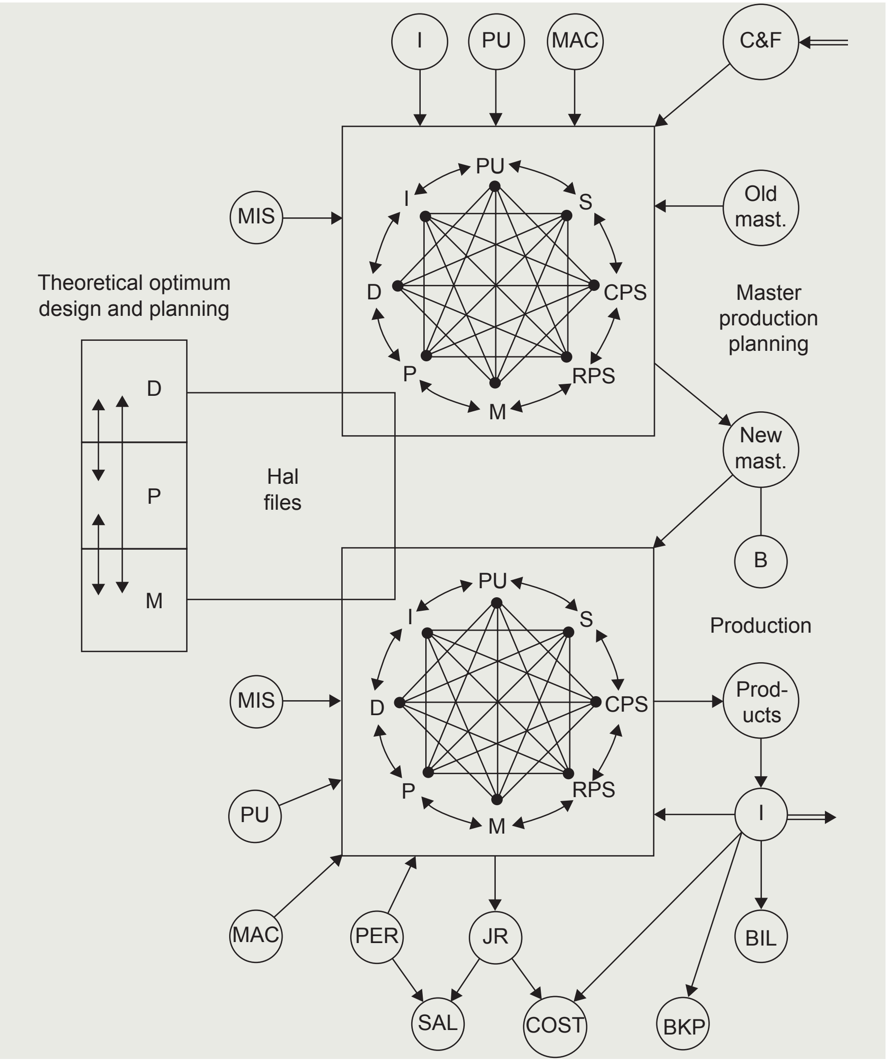

Fig. 1.3 Manufacturing cycle. (Notation: *D* product design, *P* process planning, *M* methods, time, and motion study, *RPS* requirement planning, *CPS* capacity planning, *S* shop, *I* inventory, *PU* purchasing, *MAC* machine file, *C&F* customer orders and forecasting, *MIS* miscellaneous, *B* budget, *PER* personnel, *JR* job recording, *SAL* salaries, *COST* costing, *BKP* bookkeeping, *BIL* billing)

By its flexibility, it can overcome most problems caused by shop dynamics. This module combines traditional master production scheduling, requirement planning, and capacity planning into one phase.

The output of this stage is a list of products and quantities that must be manufactured in a given time period in each department and work center. This list must be practical. The methods employed and deviations from the optimum made in order to balance the load (i.e., to guarantee the possibility of producing the items on the list) must not be considered fixed. The next phase will do the actual loading and will optimize the product mix on the list by starting with the optimum data.

The production module covers the actual manufacturing. The input is the product mix that must be produced in the given period. The output is the items. The purpose of this module is to make sure that all of the items planned for the period will actually be produced and in the most economical way possible. To achieve this, total flexibility concerning process plans, product design, inventory items, and so on, is assumed, that is, deviation from the theoretical optimum input data is allowed. In this module, capacity planning is done simultaneous to the actual manufacturing. The facilities are fixed and all must be loaded. The list of products and items to be manufactured within the given period is fixed and assumed to be practical.

The flexibility lies in the sequence and method of production and in the allocation of available material or semi-finished items. The first scheduling attempt is set according to the theoretical optimum data and using the dispatching rule SIMSET (similar set up). If this fails to produce satisfactory results, the following measures are taken: alter the process, contrive the process to suit an existing set-up of an unloaded machine, use and modify the in-process item, change filler dimensions in item design, and so on. The limiting factor in the use of the above measures is an economic consideration: The increase of the product mix cost due to deviation from the theoretical optimum must remain below the expenses resulting from not meeting due dates, idle machines, etc. The output of this module is finished items and the administrative documents required. Billing, costing, salaries, and so on, remain.

1.5.1 Management Organization Control

The main advantage of the proposed organizational system is that the various manufacturing activities are independent of one another, and therefore, the overall efficiency of the enterprise will be that of the lower efficient link, the previous example of which estimated link efficiency at 80 % and, therefore, the overall efficiency at 26 %.

The proposed organizational system considers a series of independent elements as having individual probabilities of achieving a criterion. The probability of success for any given link is independent of that of every other link with which it is functionally associated.

Thus, the overall probability of the chain achieving a **particular criterion is at least 80 %**. Due to system flexibility, it expected to be even higher.

1.5.2 Introduce Simplicity

A common shared excuse for regarding production planning as a complex task is that the production environment is a dynamic one: power failures occur, as do mismatches between load and available capacity, unrealistic promises as to delivery dates, etc.

The manufacturing control system makes clear that this complexity is a result of the attempt to find solutions and is not an inevitable occurrence. Most disruptions are a result of the stiffness of a system where decisions are being made too early in the manufacturing process. Through a different approach, one that will introduce flexibility to the manufacturing process, most of the disruptions can be solved by elimination.

The traditional approach to the design of manufacturing systems is the aforementioned hierarchical approach that leaves the system sensitive to perturbations, and its autonomy and reactivity to disturbances weak.

The objective of each stage is clearly defined and optimized by the system. However, the criteria of optimization are not always synchronized with the total objective. Local optimization of a single operation does not necessarily lead to optimization of the item. Item optimization does not necessary lead to optimization of the product. Product optimization does not necessarily lead to optimization of the product mix. And product mix does not necessarily lead to optimization of the business.

Moreover, the planning and execution regards the routing as static and unalterable, thereby robbing the shop of productive flexibility and efficiency as it optimizes with a non-optimized routing. The basic notions of the hierarchical approach are questionable, and thus, contribute to system complexity.

A manufacturing control system is a system that aims to dissolve the complexity of the manufacturing process and restore the inherent simplicity. It claims that ***production is very simple*** and flexible by nature. However, the complexity is a result of a traditional production system approach that makes it rigid and, therefore, complex.

A manufacturing control system introduces flexibility to production planning, and eliminates constraints, bottlenecks, and disruptions automatically while restoring the simplicity. No decision is made ahead of time, but only at the time of execution. Therefore, it considers the present state of a company's orders and shop floor. It introduces technology as a dominant part of manufacturing. It is a computer-oriented system, but it **imitates human behavior**, i.e., behaving practically, as any of us might behave in our daily personal lives.

The objectives of manufacturing control system technology are to increase productivity and reduce manufacturing costs. It treats the manufacturing process as a single entity, beginning from engineering design to product shipment. It considers the manufacturing process as a nucleus and its satellites, rather than a chain of activities. The engineering activities are the nucleus and the other activities are the satellites.

1.5.3 The Roadmap Tool

A roadmap is the tool that introduces flexibility to the manufacturing system. A roadmap postpones the decision of selection of a routing to the time it is considered necessary. Such necessities may be at any stage of manufacturing and of management control. A roadmap is a set of alternative routings. As with a GPS system, one states the present location and the destination, and the GPS informs you of the best route to follow in order to get there. Moreover, if it foresees disruptions of any kind, it automatically generates a new route and gives new instructions to the user.

In manufacturing, the task of the roadmap is exactly the same. The roadmap is a list of all available processes for each item, as shown in Table 1.4. For each operation, the roadmap simulation is a row in the table, while, for the item itself, it is the entire table. According to the application, the data may be processing time or processing cost. The transformation from one to another is done automatically. Routing is generated by an algorithm in a split of a second. The algorithm parameters are one of the controls of management. (No need for process planner interference.)

Applying the roadmap approach, one must regard routing as a variable; it, therefore, meets the criterion, as described above, for a manufacturing control system: decisions are left to time of execution and consider the present state of the company's orders and shop floor. Disruptions and bottlenecks are dissolved whenever encountered (confronted) by roadmap tools.

1.5.4 Management Controls

Manufacturing is a decision-making process, with several decisions being made in the planning stages, and others required along the way to overcome problems that arise. Many decisions arise that necessarily must be made by those unqualified to make such decisions. For example: a scheduler who encounters a bottleneck problem, and thus, must decide which job to prioritize. Or the designer who has to choose a design that will be easy to process. All such decision points are candidates for management interference points.

The proposed enterprise organizational system makes the interference control points straightforward. Control policies are applied at each decision point: technological, operational, planning, and performance ratings of all manufacturing disciplines. Furthermore, ***the proposed organizational system enables management to make their decisions based on up-to-date, unbiased data***.

Part I
Management Control Engineering

Chapter 2
Product Design

Abstract Product specification is a task in which most management disciplines, as well as engineering, take part. It is an innovative task and depends on the creativity of both management and the product designer.

The product designer's task is to develop a design to meet product specifications. It is up to engineering alone to make design decisions. However, during the design process, several decisions will arise that will affect the cost of the product. Such decisions should be made with the approval of management.

Several such decisions are presented in this chapter.

1 Introduction

Product specification, as well as product design, are innovative tasks and require creativity on the part of both management and the product designer. Several product specification methods are used by management for new products or improving the design of existing products.

A product has to seduce the customer with its options, appearance and cost. To arrive at such product specifications, almost all management disciplines, including manufacturing, should be involved.

There are several methods to assist management in coming up with ideas. These include:

- Conceiving ideas that would help make our everyday lives easier by fulfilling the needs of a specific task; this can lead to a new product or the improvement of an existing one
- Imaginative thinking; brainstorming
- Research and observation of the world and everyday life to inspire ideas about unfulfilled needs and to come up with product design ideas to fill those needs
- Basic research on market and consumer trends
- Observation of competitors; use of corporate spies, trade shows, and other methods may also be used to get an insight into new product lines or product features
- Creation of focus groups, employees, salespeople

Numerous ideas can be generated, and management has to evaluate and decide which ones deserve development, eliminating unsound concepts prior to devoting resources to them. To arrive at a sound decision, the following questions need to be asked:

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- Will a customer benefit from the product?
- What is the size and growth forecasts of the market?
- What price range is anticipated?
- What is the current or expected competitive pressure for the product idea?
- What industry sales and market trends is the product idea based on?
- Is it technically feasible to manufacture the product?
- Will the product be profitable when manufactured and delivered to the customer?
- What features must be incorporated into the final product?

The remaining ideas are further analyzed for their potential business value. Management, i. e., marketing, sales, finance, etc., with the counseling and including the manufacturing, decides on the one product to develop and prepares product specifications of the main and secondary objectives and its features. Examples of the latter (values and priorities) may be specifically defined as follows:

- Ease of operation
- Durability (product lifetime)
- Reliability (low maintenance)
- Efficiency (low operating cost)
- Safety
- Ease of maintenance
- Noise level
- Weight
- Floor space occupied
- Aesthetics
- Cost
- Ease of installation
- Ease of storage

Etc.

The features as defined are a compromise of the conflicting interests of the various disciplines, and the definitions are of a business nature and not of engineering. Management will instruct manufacturing to produce the product as specified.

1.1 Manufacturing—Product Specifications

The designer's work must always be directed toward a goal. This goal is usually stated in general non-engineering terms without any implication as to the means to be adopted to achieve it.

Product design specification is a statement of what a product is intended to do. Its aim is to ensure that the subsequent design and development of a product meets the needs of the user. Product design specification acts as an initial boundary in the development of a product. The product specifications that instruct manufacturing are of two natures: qualitative and quantitative. The distinction can be seen as the difference between "What does the product do?" and "How will the product do it?"

Product specification indicates what is required but not specification of the product itself. Describing the actual product is done through the technical specifications once the product has been designed. The difference is important, since describing the product itself at the stage of creating a product design specification would effectively constrain the range of alternatives considered during the design process.

It is important that the designer does not rush into solving the problem as stated in the goal. The purpose of the task must first be understood, and then must be converted into a set of quantitative engineering specifications. For example, if the goal is to design a conveyor belt, it should be realized that the purpose of the endeavor is to move items from one place to another. The conveyor belt is only one possible solution. Another possibility to be considered is rearrangement of the shop-floor layout in order to eliminate the need to move items. The goal in designing an air-conditioning unit is to create comfortable conditions of temperature and humidity. If the problem is initially stated in broad, general terms, more possible solutions will be considered, thus enabling better solutions to be found.

The second stage is to transform the general terms used in the task specifications into values. This will be done by collecting information and by computations. The term "comfortable conditions" used in the air conditioning example must be converted into a statement of the form "room temperature of 22 °C and relative humidity of 50 %." Such factors as room size, the normal temperature in the area, time required to reach the desired conditions, the wall sizes and locations, and the number of people in the room must be specified. In addition, the amount of heat transfer and the air flow must be computed in order to reach the proper engineering task specification. The engineering task specification does not worry about air-conditioning; it concerns itself with specified values.

The secondary objectives of design include many requirements, several of which are contraindicative to one another. ***Management and design*** should discuss this problem with one another in order to come up with an agreeable and efficient compromise. Some of these requirements are:

Ease of operation:

- Durability—product lifetime
- Reliability—low maintenance
- Efficiency—low operating cost
- Safety
- Ease of maintenance
- Noise level
- Cost
- Aesthetics
- Ease of installation
- Ease of storage
- Ease of transportation
- Compatibility with its environment

Ease of production:

- Size
- Weight
- Volume
- Mechanical strength
- Ease of assembly
- Product design specification
- Floor space
- Recycling
- Ease of maintenance, etc.
- Ease of operation
- Durability, long service life
- Reliability, low maintenance cost and short down time
- Efficiency, low operation cost
- Volume, plan area, front area
- Use of available resources
- Use of standard parts and methods
- Reduction of rejects, scrap parts and material
- Design for distribution

1.1.1 Management Control

Design should utilize the two groups of ease of operation and ease of production as check lists so that management can be certain all points have been covered.

1.2 Manufacturing—Product Design

Product design's primary function is to conceive a product that meets management's product specifications. Management specifications are set through discussion groups involving all management disciplines, including manufacturing. There exists the possibility of bias due to the power of a specific management group's interest or through the persuasive powers of a specific member. Regardless, management has the final decision as to what the product should be and what it should look like.

Engineering's task is to prepare drawings for product assembly, product structure, subassemblies and items, and, finally, process planning. The drawings are the obligatory document for driving the phases of production. Some control must be exercised over these stages. The process planner is bound by the defined drawing and, therefore, should work with engineering in an *interactive manner*.

The designer is a problem solver who, given a problem (in this case, a need), applies such fields as physics, mathematics, hydraulics, pneumatics, electronics, metallurgy, strength of materials, dynamics, magnetism and acoustics in order to find a solution, namely, the new product. His/her main responsibility is to design a product that meets the customer specifications. A parallel target is to design a high quality, low cost product.

There is no single solution to a design problem, but rather a variety of possible solutions surrounding a broad optimum. The solution can come from different fields of engineering and apply different concepts. The designer is bound by constraints that arise from physical laws, the limits of available resources, the time factor, company procedures, and government regulations. Among all these possible solutions, the designer, in consultation with the process planner, selects the one that seems most suitable.

Product designers are not process planners. However, whatever ideas they develop during the design stage will significantly affect the manufacturing process and the process planning. They do not go into the details of the manufacturing process, but usually work by intuition. However, parts that were designed with a specific manufacturing process in mind might turn out to be very difficult to manufacture if the process has to be changed. In such cases, it should be remembered that parts are designed subject to functional, strength or manufacturing constraints. The drawing of a part should always be seen as a constraint by the process planner; it might be an ***artificial constraint*** if the manufacturing process is the controlling factor in part design.

Studies have indicated that the incurred cost of the engineering stages, i. e., product design, detail design, testing and process planning, is about 15 % of the product cost, while the production stage accounts for 85 %. However, since the committed cost of the product is about 90 % established in the engineering stages, it is worthwhile not to rush but rather to extend the thinking time in design before making decisions.

The product designer should bear in mind the manufacturing process that will produce the designed part. Each manufacturing process has its advantages, capabilities and limitations. The cost of a part can be kept to a minimum if its features, dimensions and tolerances match the capabilities of one of the available processes. Otherwise, the cost might be excessively high or the production might even be impossible. Designers do not define the process plan, but rather steer toward utilization of existing processes, preferably to one available in their own plant.

The quality and reliability of the designed product are determined and controlled by the designer.

Quality is a measure of how closely the product conforms to the secondary objectives set by management and the compromise made among these conflicting objectives.

Reliability is defined as the probability that the product will perform a required function under given environmental conditions for a specific period of time. Reliability is measured mainly in terms of failure rate.

Management should make sure that the designer has considered at least three possible design solutions, and that they were discussed with the process planner before establishing the final design.

1.2.1 Product Material Selection

Choosing the right material for a product can be critical to the success of that product. In some cases, the decision as to what material to use is obvious, but in others it may need some creative thinking and computation.

Material selection is part of the process of product design. The main objective of material selection is to minimize cost while meeting product performance objectives.

Materials are an important concern for any manufactured product. Choosing the right material for the right product is as important as any of the main criteria that would normally be involved in bringing a product to market. The selection can influence design on many levels. Perhaps the most obvious considerations are manufacturing costs and performance of the end product. A balance needs to be sought between costs, manufacturing feasibility and finding the right material for the job.

Clearly, different materials have different properties:

- Metals are easy to form, from liquid, by solid deformation, or by metal removal
- Ceramics are particularly heat resistant and hard
- Plastics can be easily formed into an infinite range of shapes and colors
- Glass is hard and has some outstanding optical qualities
- Wood is easy to work without necessarily using expensive machinery and is also naturally highly decorative

It is easy to consider materials purely from the perspective of their obvious functional attributes—for example, the hardness of ceramics versus metals or the formability of plastics over wood—but the emotional and visual qualities of materials help define the product as much as the form and function. The surface texture, the translucency, the sponginess or hardness, all have an effect on the way a product is perceived and used. A specific quality may well be the starting point for an idea: 'We need a packaging that has a seductive quality', or 'We need something aggressively modern'.

Evaluating the requirements for the final product should help in deciding the right material. Mobile phones, for example, need to be produced in high volume, they need to be made from a fairly rigid but resilient material, and they need to be formed into a variety of complex, sometimes highly detailed shapes.

1.2.2 Management Control

Of course, cost per kg is not the only important factor in material selection. An important concept is 'cost per unit of function'. For example, if the key design objective was the stiffness of a plate of the material, then the designer would need a material with the optimal combination of density, Young's modulus and price. Optimizing complex combinations of technical and price properties is a difficult process to achieve. Adding to the complexity is the fact that the designer has the option of arriving at the same product stiffness and strength with several materials through different configurations of the part. The strength is a function of the part's cross-section. One may select a material of extra strength and cost by reducing the weight of the part (cross-section), or by increasing the part's cross-section and weight.

Management should follow the designer's material selection carefully and critically.

1.2.3 Standard and Purchase Items

The product designer is responsible for meeting management's product specifications. They use their expertise and creativity and no one should interfere in their engineering decisions, unless those decisions are managerial or economic in nature.

In design, there are decisions that are mandatory for meeting the product specifications and there are fillers. For example: assume a need for a shaft with bearings at the two ends. The length of the shaft and the bearing type are mandatory to the product. But a bearing needs housing, and housing needs something to support it. These are essential to the design but are also ***"fillers"***, meaning they are not essential to the product's performance. No designer would even think of designing a ball bearing, because it is a ***standard item***, produced by a specific factory whose business is bearings. It should be bought. The housing support is "filler" in the sense that its design usually does not contribute to the product's performance. It is also possible that there are some standard items that might do the job at a lower cost, or that they could just set a simple plate to hold the bearing.

1.2.4 Management Control

Management should oversee the design from an economic perspective and encourage the designer to check the benefits of using standard items and simple "filler" designs as much as possible.

1.2.5 Safety Factor

To avoid failure, the designer must apply mathematical procedures. A good designer will distinguish between the mode of failure and the failure mechanism. To do so, the following procedure will most likely be applied:

- Determine the mode of failure
- Define the failure mechanism
- Select a theory of the failure
- Setup a mathematical model to determine the relationship between the variables
- Solve the mathematical expression and assign dimensions

Simple assumptions, for example, that the materials are homogeneous and ductile, must be made in order to construct the mathematical model describing the physical situation and predicting the behavior of the element being designed. The designer must be aware of these assumptions and decide if they are applicable in the particular case.

Potential errors in design can result from the following scenarios:

- The designer fails to foresee all possible modes of failure
- The designer foresees the mode of failure, but is unable to select and set up a mathematical model

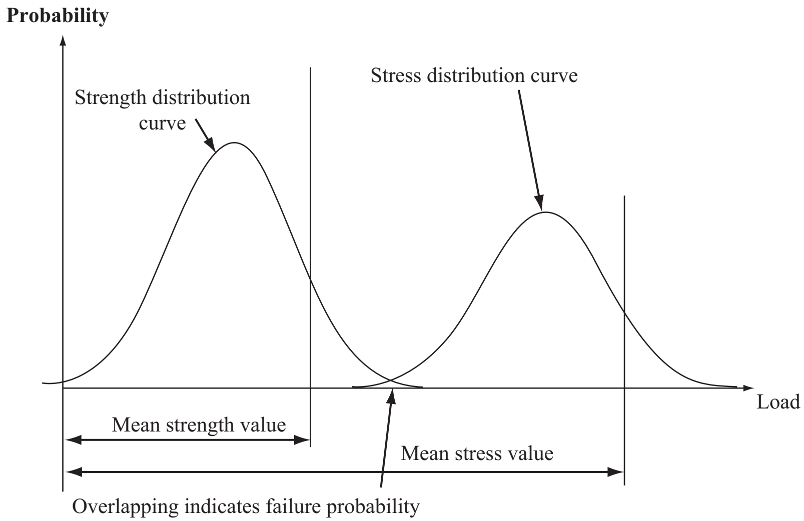

Fig. 2.1 The relationship between the distribution of strength and stress

- The designer is successful in the above steps, but has made a mistake in the calculations or in the manipulation of the model
- The designer is willing to accept a small risk

To ensure against failure, the designer must provide a margin of safety - the ***"safety factor"***. The safety factor is determined as a ratio of the design strength to the applied load and is always greater than 1. Tables for factors of safety are given in all engineering handbooks. For mechanical items, it is customary to use a factor from 4 to 40. In this method, the designer assesses the global situation and decides on the magnitude accordingly. Another approach to the selection of the safety factor is illustrated in Fig. 2.1.

Both the load capacity (strength) and the actual load (stress) are not fixed values, but, due to the nature of the design, have a certain distribution around a mean value. The specific shape of the distribution curve depends on the particular problem. The safety factor is defined as the ratio of the mean load capacity to the actual load. The overlapping area of the distribution curves indicates the probability of failure. The designer *can choose any desired reliability value* by using statistical theory to compute the corresponding safety factor.

The master product design method exists so that the designer can check and be reminded that the reliability of the product is a design parameter, and to assure that the designed probability of failure is a conscious decision and not the product of negligence.

1.2.6 Management Control

The decision as to the value of the reliability factor cannot be made by the designer alone, and must be communicated to and approved by management. This decision affects the cost, weight, and processing time of the product, as well as the product's performance. Above all, it minimizes the possibility of failure and breakdown of the product.

In case of failure, it may be automatically determined if the failure could have been predicted by the designer. If not, re-evaluation of any of the following may indicate where the error lies: mode of failure; the failure mechanism; the theory of failure; the mathematical model; the solution of the mathematical expression and assigned dimensions; the data used for the dispersion of the load, the actual load, and the method used for the applied load (Fig. 2.1). A software algorithm will be initiated and a recommendation for action can be reached automatically.

1.2.7 Tolerances

Potential errors in manufacturing can either affect production performance, product life, and product assembly or have no significant effect on the product at all. In manufacturing, it is impossible to make each dimension and characteristic agree exactly with one specific value. Every element will deviate from the theoretical value. In many cases, even a gross deviation from the component geometry and characteristic can exist with no significant effect on product performance. On the other hand, in some cases, a microscopic deviation can have a catastrophic effect.

To ensure against failure, the designer specifies the permissible deviations, that is, the acceptable range of values. In other words, the designer specifies a tolerance.

In mechanical parts, there are three types of dimensional characteristics which need to be controlled by tolerances: Size, Shape and Location. There are three classes of fit between mating parts, e.g., shaft and holes:

1. Loose fit. Used for dynamic fit.
2. Neutral fit. Used for static fit with no load.
3. Tight fit. Used for static-fit loaded parts.

There are two methods of applying the tolerance:

1. Basic hole system.
2. Basic shaft system.

Which system is adapted depends on the method of processing and the state of the raw materials prior to processing. In making a tolerance choice, the designer will usually refer to standard systems of tolerance and charts that are well represented in the literature.

Tolerances are applied not only to diametric dimensions, but also to longitudinal dimensions and assemblies. The calculation of tolerances is always based on "allowances", that is, the allowed difference in dimensions between the mating items.

The designer may specify and divide this allowance in any way he/she chooses, as long as the total allowance is secured.

The following example demonstrates the "risk" that the designer is willing to take in assigning tolerances. For example, the assembly of five items in a row may have an allowance of 0.25 mm. In order to assign a tolerance to each component, an even *arithmetic distribution* can be used and each component assigned a tolerance of

$$T = 0.25 / 5 = \mathbf{0.05mm}.$$

If the items are processed individually, and each one deviates along the full range of the tolerance, ***statistically*** controlled conditions prevail. In such cases, statistical tolerance can be used. The principle involved is that statistical deviation of an assembly is equal to the square root of the sum of the squares of the standard deviations of the dimensional involved. In the tolerance field, this principle is expressed as follows: *The assembly tolerance is equal to the square root of the sum of the squares of the item tolerances*. Thus, in the example considered above, the assembly tolerance, which consists of five items with allowance of 0.25 mm in even distribution in each item of tolerance (T), will be as follows:

$$0.25 = (5 * T^2)^{1/2} \quad T = .25 / 5^{1/2} \quad T = \mathbf{0.11mm.}$$

This is a considerable difference from the item tolerance of 0.05 mm obtained with arithmetic distribution.

1.2.8 Management Control

The personality of the product planner should be one of skill, intuition, imagination and creativity. This position is usually held by an experienced engineer. After forming the concept and main subassemblies and items for functionality and strength of the product, the product designer's next task is to transfer these ideas, i. e., to prepare assembly and detail drawings. This task is an editing process, constrained by the explicit rules and grammar of engineering language, namely, drawings. The decisions required at this stage are concerned with layout, and the noncritical dimensions. The personnel for this stage are young engineers or draftsmen. They also usually prescribe the tolerances. They may not always know the designer's intentions, but they control the tolerances and the dimensioning method.

Tight tolerances afford the designer peace of mind and security; however, they also raise the cost of processing, the processing time, and the utilization of resources. This often becomes an area of internal conflict between manufacturing themselves, i. e., between the designer and process planner, as well as external conflict with the shop floor.

In the metal cutting process, there is a direct relationship between tolerance and maximum depth of cut. A low tolerance calls for a small depth of cut for the final cut and a low feed rate, which increase the processing time. Furthermore, a low

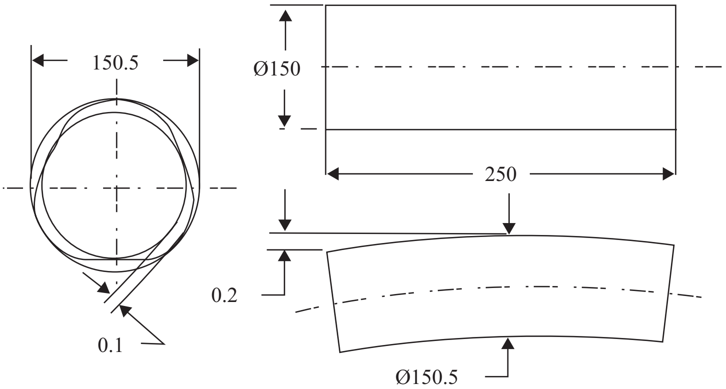

Fig. 2.2 Possible good part that meets diameter tolerance

depth of cut calls for added cutting passes, which further increase processing time of the item.

In many cases, the processing time for the required tolerance and the specified tolerance might be increased by ten times.

Therefore, management should be involved in order to make sure that reasonable tolerances are specified. The product planner should, thus, be kind enough to check the drawings carefully before approving them.

1.2.9 Geometric Tolerances and Surface Roughness (Integrity)

All bodies are three dimensional, and, in an engineering drawing, a body is assumed to be placed in a system of three perfect smooth planes oriented exactly 90° to each other. However, perfect planes cannot be produced. The shape tolerances cannot guarantee that the part produced will meet the designer's intentions.

For example: At the top of Fig. 2.2, a drawing of a straight shaft diameter of Ø150 ± 0.5 is shown. At the bottom of the figure, the produced part is shown. The produced part meets the specified tolerance. At any cross section of the part along its length, the diameter will be Ø150 ± 0.5; however, the center line is not a straight line but a curve. No indication on the drawing prevents such a curve. Furthermore, the shape must not be a perfect circle, as can be seen in Fig. 2.2. The circularity of the part must be within two circles, one of Ø150 and the other Ø150.5.

Another example is shown in Fig. 2.3. The drawing on the left shows the designer's intentions, and on the right the produced part that meets the drawing specifications. The drawing does not specify that the two cylinders must be concentric.

Geometric tolerances come to enable the designer to specify their intentions more precisely. There are several geometrical tolerances specifying form and positions,

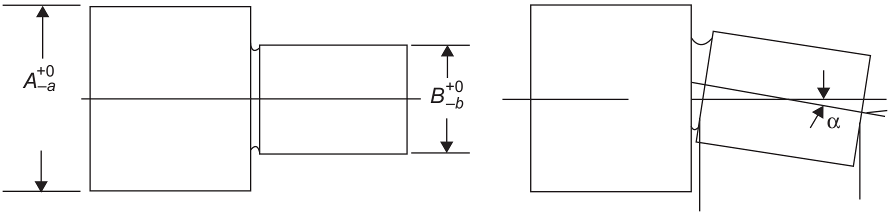

Fig. 2.3 Part that meets drawing specifications

such as: flatness, straightness, perpendicularity, concentricity, etc. These are defined in the *ISO Standard for Tolerances of Form and Positions*.

Surface roughness (integrity) While the preceding standards are related to macro-geometric properties, it is also important to define the micro-geometric characteristics of mechanical surfaces, which can have a functional significance as important as that of macro-geometric tolerances. The *ISO Standard Surface Roughness* gives basic definitions of roughness criteria and definition of surfaces of reference, as well as the symbols to be used in drawings, e.g., 3.2 µm R_a to characterize the arithmetic mean roughness taken relative to the center line reference. There are more than 50 different parameters available that describe surface conditions. Actually, most manufacturers use combinations of no more than two to four parameters for accurate surface-finish measurement. Listed here are some of the surface-finish parameters used in the industry today.

R_a Arithmetic averages roughness

Roughness averages are the most commonly used parameters because they provide a simple value for accepting/rejecting decisions. Arithmetic average roughness, R_a (also designated AA or CLA), is the arithmetic average height of roughness-component irregularities from the mean line, measured within the sampling length, L.

R_q—RMS—Geometric averages roughness

Geometric averages roughness R_q, or root mean square (RMS) is more sensitive to occasional highs and lows, making it a valuable complement to R_a. R_q is the geometric average height of roughness-component irregularities from the mean line measurement within the sampling length.

1.2.10 Management Control

Geometric tolerances and surface roughness (integrity) might be required for aesthetic purposes but usually increase processing time and limits, and constrain both resource utilization and jigs and fixtures required.

Management should be active in making a decision as to which definition standard to use, and to make sure that the tolerance values will not be overstated. Many designers put aesthetics over cost, and they must be controlled.

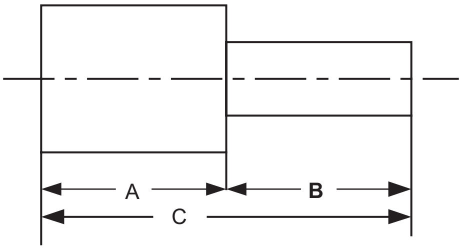

Fig. 2.4 A redundant dimension can be the cause of out-of-tolerance parts

1.2.11 Dimensioning and Datum

The design decisions reached in the engineering design stage are transferred to the process planning stage and other manufacturing stages in the form of technical drawings. The technical drawings act as the input to process planning. They include complete information on the geometry and associated data, such as: geometric shape of the parts, dimensions, tolerances, geometric tolerances, surface finish, and the raw material. Each one of these data affects the process planning decisions.

An item should be defined in such a way that, when assembled with the whole mechanism, it will fulfil its technical functions and be of a dimension and tolerance so that it can be mounted in a subset of parts in a completely interchangeable manner. To dimension the items, which would be assembled with each other, the dimensioning should originate at a ***datum***. Datum is usually marked with a letter of the alphabet and placed in a box attached to the edge view of the surface. The drawing may, of course, contain any unimportant details which have nothing to do with functioning and assembly. The dimensions for these need not originate at a datum.

An example of *correct and incorrect dimensioning* is shown in Fig. 2.4. Considering the horizontal dimension of an item, it includes three dimensions: A, B, and C. A redundant occurs when all three dimensions are given as:

$$A = 50;\ B = 30;\ C = 80.$$

The arithmetic is correct, but, due to variations in processing (tolerances), the part cannot meet the defined tolerances, which might be, for example:

$$A = 50 \pm 0.1\,; B = 30 \pm 0.1\,; C = 80 \pm 0.1.$$

The difficulty can be corrected by omitting one of the dimensions. The two dimensions that should be retained depend on manufacturing convenience or the functional requirements of the part. From the discussion above, it is obvious that only sufficient dimensions should be placed on a drawing. Any additional dimensions will nearly always result in items that meet the drawing but outside of the specified tolerances.

To meet the functions of an item, and due to machine inaccuracies, any dimension on a drawing must be accompanied by tolerances. The stack-up tolerances are a function of the dimensioning method assigned by the designer.

The basics of tolerance arithmetic are explained in the following examples:

Figure 2.5a shows a chain of four dimensions with their tolerances. One task is to define the length of the part overall. The nominal length will obviously be:

$$L = A + B + C + D.$$

The maximum length will be:

$$A + a + B + b + C + c + D + d = A + B + C + D + (a + b + c + d).$$

The minimum length will be:

$$A - a + B - b + C - c + D - d = A + B + C + D - (a + b + c + d).$$

And the tolerance will be:

$$l = a + b + c + d.$$

Figure 2.5b shows the total length with its tolerance (L±l), as well as the tolerance of dimensions A, B, D. The problem is to define the tolerance of C.

The nominal dimension of C is:

$$C = L - (A + B + D).$$

The maximum length will be:

$$C = L - (A + B + D) + (l + a + b + d).$$

The minimum length will be:

$$C = L - (A + B + D) - (l + a + b + d).$$

And the tolerance will be:

$$c = l + a + b + d.$$

The resultant dimension is, therefore:

$$C \pm c(l + a + b + d).$$

These results show that, whether the dimensions are added or subtracted, the resultant law of tolerance is as follows:

The interval tolerance of the result is equal to the sum of the tolerance of the components.

Figure 2.5c shows an example with the same four dimensions, except that A and E are not dimensioned individually, but their sum is B. If B is the tolerance as before, the tolerances of A and E have to be reduced (dimension A or E should be omitted). On the other hand, the tolerance of C will be reduced to $c = l + b + d$, assuming, of course, that the different tolerances are of the same magnitude as in the cases of 2.5a and b.

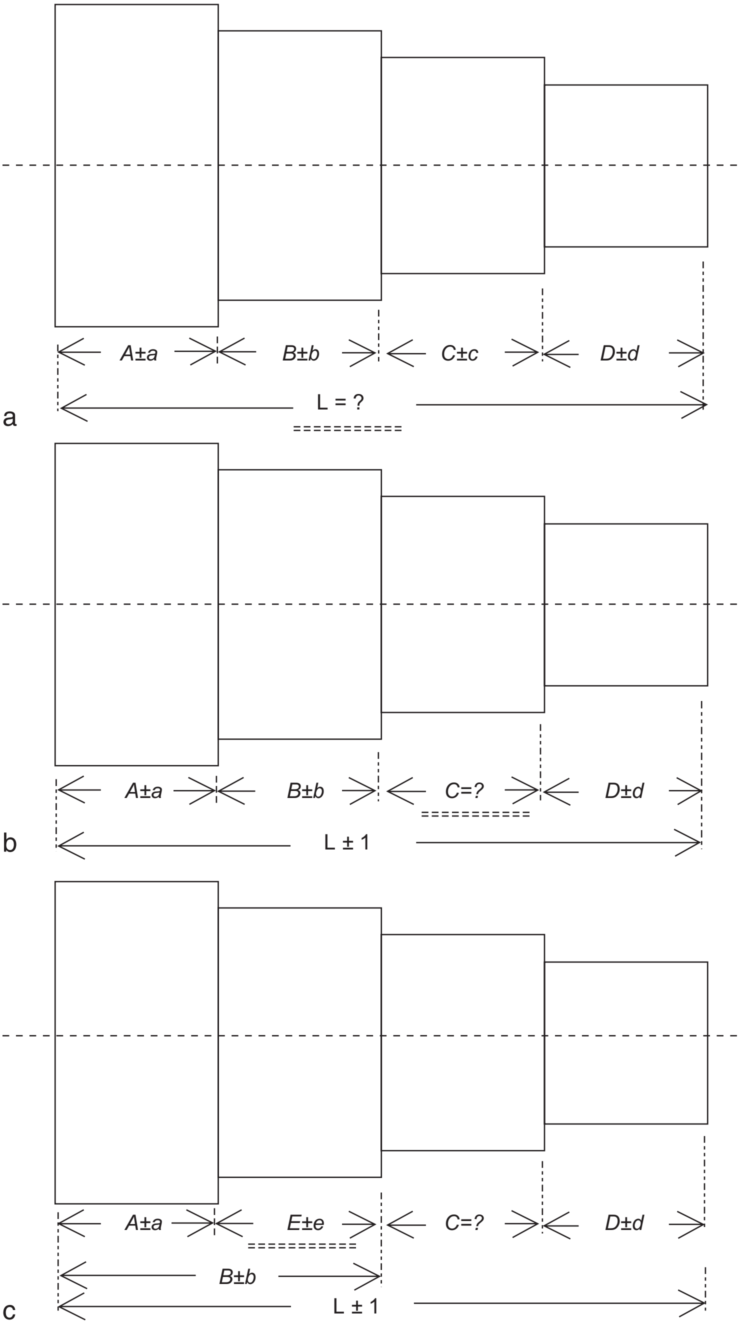

Fig. 2.5 Dimensioning method effect on tolerance stack-up

1.2.12 Management Control

The importance of correctly determining tolerance and setting in production cannot be over-emphasized. A process plan which cannot guarantee the manufacturing dimensions required by the design department would be meaningless for a manufacturing industry.

The use of correct methods of diminution in determining tolerance should be a great help to process planners. Management should enforce the interaction between the product designer and process planner.

1.3 Production Design and Process Planning

1.3.1 Accuracy Problem in Manufacturing

A detailed and comprehensive examination of an item drawing is not only a condition to producing the item so that it is functionally correct, but is also the best approach for finding a suitable process for manufacture and inspection of the desired item.

However, it is also important to emphasize that the technical drawing does not limit the freedom of the process planner when designing a suitable process plan. In fact, it is possible that, in certain circumstances, the process planner will suggest changes in the design, for example, a better tolerance method because of constraints in production. The process planner has plenty of freedom in designing the process plan, after first fulfilling all of the functional conditions defined by the product design.

The process planner's task is to translate the requirements expressed by the rich and powerful language (the drawing) into a machinery language (the machine, the fixture, the tool) with a much more limited vocabulary than the drawing. However, for various reasons related to the selected process plan, such as the mode of clamping the item onto its fixture and economic considerations, it very often happens that the functional dimensions are not executed directly in manufacturing. In this case, the functional dimensions are obtained as indirect dimensions, rather than direct dimensions, or, in other words, as resultant dimensions of a chain of direct dimensions. The tolerance of a resultant dimension is then the sum of the tolerances of the component dimensions which are given by the process used in manufacturing.

Obviously, the result of this is that the tolerance of the component dimensions has to be small enough for their sum to comply with the tolerance of the resultant dimension given on the drawing. This can raise problems of tolerance in production when production equipment is not able to produce items at the small tolerances required. In this case, the only solution is to increase the tolerance of the resultant dimension, which can contradict design requirements, or to change the process plan and to use more precise equipment, which means *increasing the cost of manufacturing*. This situation can be considered to be the fundamental accuracy problem in manufacturing.

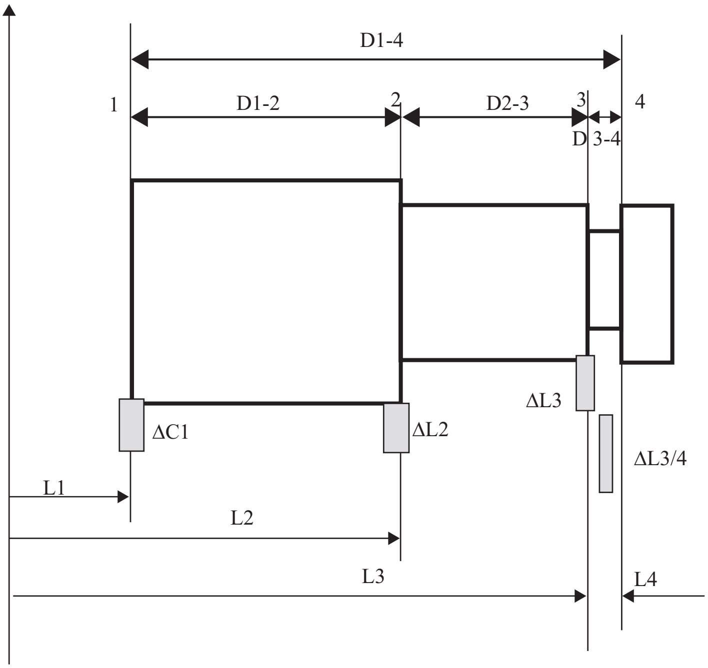

Fig. 2.6 Possible errors in meeting the longitudinal dimension

Before going into details of determining tolerance, it is useful to define the different types of dimensioning encountered in manufacturing:

- *Work piece drawing* – defined by the designer to assure correct functioning of the work piece
- *Machined or manufacturing drawing*—specified by the process planner to instruct the machine operator or NC programmer so as to assure that the work piece will conform to the drawing
- *Setting drawing*—defined by the process planner, defining the tools and fixture positioning in the machine system of reference

In part-drawing, there is a reference point to each dimension. However, in machining, a *different reference point* is used, that of the machine and the fixture reference point.

The process of transferring dimensions from the work piece drawing to the machining and setting drawing may result in stack-up tolerances and might create errors.

An example of determining the tolerance of an item is given in Fig. 2.6.

The D dimensions are the drawing dimensions, the L dimensions are the dimensions from the machine datum lines. The resultant dimensions are computed dimensions. The possible errors and deviation from the nominal are shown by shaded areas. For example, the ΔC1 error is due to an inaccuracy in placing the part on the machine depending on the type of positioning, by a plane contact or by punctual contact. ΔL errors are due to machine accuracy and repeatability. A ΔL3/4 error is due to tool dimension.

The possible accumulation of errors is taken into consideration in computing the chucking location and type, and in selection of a proper machine for the job. If a problem arises, re-evaluation of the parameters will be made and a permanent correction (learning feature for specific machine capability or system) or a temporary correction for a specific fixture will be made. The process will then be re-computed.

The importance of correctly determining tolerance and setting in production cannot be over-emphasized. A process plan which cannot guarantee the manufacturing dimensions required by the design department would be meaningless for a manufacturing industry.

The use of correct methods of diminution determination of tolerance should be a great help to process planners. Management should enforce the interaction between the product designer and process planner.

1.3.2 Management Control

From the previous derivations, we reach the following conclusions

- The machine accuracy is not established by the smallest item tolerance.
- The actual tolerance is not according to the designer's (drawing) tolerance but according to the machine and fixture accuracy and the sequence of operations.
- If no machine of the required accuracy is available, then management should interfere and call the product designer and the process planner to propose solutions. The manager will then select the best solution.

1.3.3 Production Variation and Failure Due to Processing

Failure of products due to processing may occur in the case of errors in defining the process plan or due to improper dimensioning of the design.

The quantities in manufacturing are of a stochastic nature because many errors/factors influence their values. The distribution of these values can be described by statistical laws such as normal law, which is applicable to many random distributions in manufacturing. The normal law can be represented by the curve shown in Fig. 2.7.

Figure 2.7 shows that 68 % of the values are in the range of ± σ and that 99.75 % are in the range of $\pm 3\sigma$ which is taken as the ***tolerance interval*** because it rejects only a percentage of 0.25 % of the parts when production is well-centered in the tolerance interval.

Statistically, dimensions are based and logically built around the phenomenon that variation in a product is ever-present. There is a natural variation inherent in any process due to wear of tools, material hardness, spindle clearance, jigs and

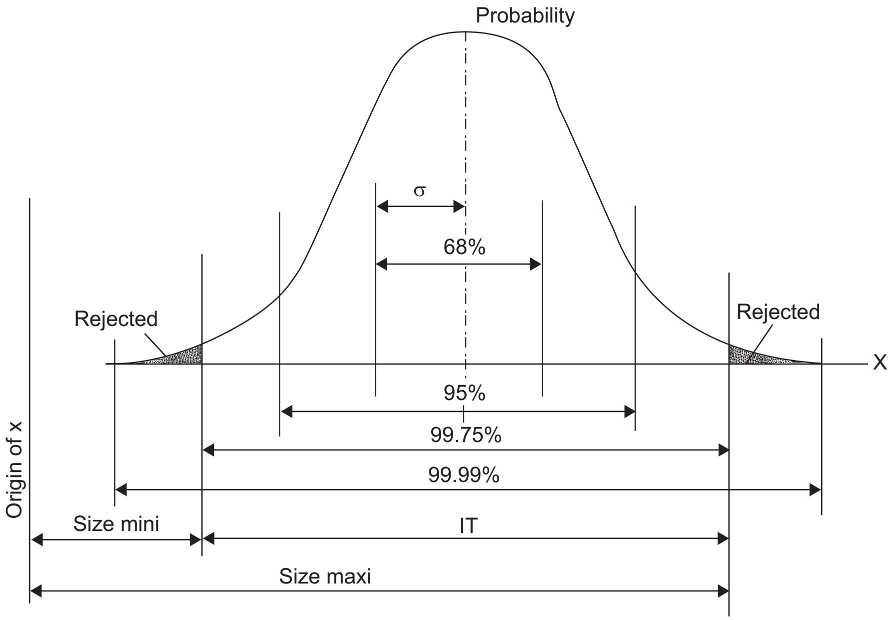

Fig. 2.7 Normal law and interval of tolerance IT

fixtures, clamping, machine resolution, repeatability, machine accuracy, tool holder accuracy, accumulation of tolerances, operator skill, etc.

Variation will exist within the processes. Parts that conform to specifications are acceptable; parts that do not conform are not acceptable. However, to control the process, reduce variation and ensure that the output continues to meet the expressed requirements, the cause of variation must be identified in the data or in the dispersion of the data. Collections of these data are characterized as mathematical models called “Distributions” that are used to predict overall performance. Certain factors may cause variation that cannot be adequately explained by the process distribution. Unless these factors, also called “assignable causes”, are identified and removed, they will continue to affect the process in an unpredictable manner.

A process is said to be in statistical control when the only source variation is the natural process variation, and “assignable causes” have been removed. A control identifies changes between items being produced over a given period, and distinguishes between variations due to natural causes and assignable causes. Corrective action may, therefore, be applied before defective products are produced. Parts will be of the required quality because it is manufactured properly, not because it is inspected. In most cases, quality should not be left to chance. Sorting conforming parts from nonconforming ones to produce a yield is not usually the most cost effective method.

Variations that are outside of the desired process distribution can usually be corrected by someone directly connected with the process. For example, a machine set

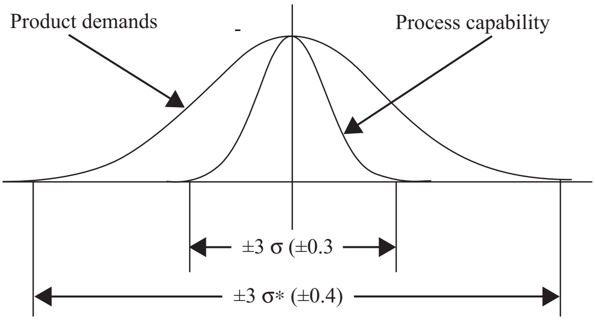

Fig. 2.8 Product demands and process capabilities

improperly may produce defective parts. The responsibility for corrective or preventive action in this case will belong to the operator, who can adjust the machine to prevent recurring defects.

Natural variation will establish ***process capability***. Process capability is the measure of a process's performance. Capability refers to how capable a process is of producing an item that is well within engineering specifications.

The process capability is established at process planning. Actually, the process planner, through his/her decisions, establishes the suitability of the process to the task and the anticipated scrap and rework percentage. Inherent capability of the process factor (CP) will indicate if the process is capable, the process is capable but should be monitored, or the process is not capable.

The product-allowed variations (tolerances) are compared to the allowances of the process capabilities. Both are regarded as normal distributions around the mean value, as can be seen in Fig. 2.8.

The tolerance interval of product demands, as well as the process capability, is regarded as $\pm 3\sigma$ of their normal distribution. The 3σ span indicates that 99.73 % of all parts will be within the tolerance interval. For the example shown in Fig. 2.8, 99.73 % of the parts, regardless of the product demands, will be within ±0.3, while the required tolerance is ±0.4; this gap means that (according to normal distribution tables) 99.994 % of the parts will meet product demands. The bigger the difference between the process capability and the product demands, the greater the chance of reducing production of reject parts until it becomes easy to predict.

The trend today is to work with **6σ or even 9σ**, the result of which is that the chance of producing a reject part is 1 in 100 million. Which range to select is up to the process planner.

Figure 2.9 shows the case in which the product demands are lower than the process capability. This means that the process planner deliberately (probably due to the available resources) plans to have a certain percentage of reject items. If the inspection reveals the same percentage of rejects, it means that all is functioning correctly and nothing should be done. Natural process variation may only be corrected by redesigning the part and the process plan.

Successful control requires action in the form of a monitoring system. A control chart may be used to record the average fraction of defective parts at a work station.

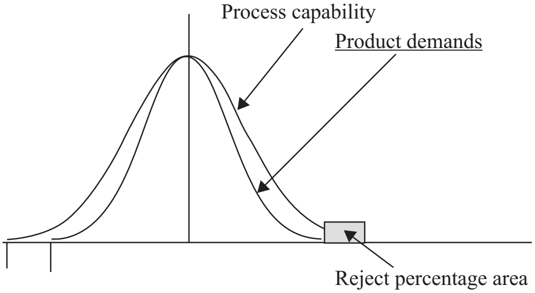

Fig. 2.9 Product demands and process capabilities

Through application of statistical techniques, problems are identified, quantified and solved at the source in an optimum time. Out-of-Control conditions become evident quickly, as does the magnitude of the problem. With this information, action can be taken before the condition becomes a crisis.

1.3.4 Management Control

Management should consult with the product designer and process planner, and make the decision as to what rate of reject is reasonable, i. e., decide which range of sigma (**3σ, 6σ, 9σ**) to adapt.

1.3.5 To Meet Geometric Tolerances

There are various causes of geometric inaccuracy. For instance, flatness, angularity and perpendicularity errors in milling can have one of several causes: machine tool geometric errors, work piece deflection, cutting tool deflection, tool eccentricity, tool flatness, and, in the case of producing the item in more than one subphase, refixturing of the item on separate surfaces.

Concentricity, run out and true position inaccuracies will occur when separate features are being machined on separate fixtures in more than one subphase. Each refixturing of the item introduces a large error. Machine tool errors, tool deflections and item deflections contribute to inaccuracies as well. In order to devise a process that meets geometric tolerance specifications, the following precautions should be observed:

- *Fixturing* When a geometric tolerance is specified, the only way to meet the specification is to machine the relevant surfaces in a single subphase, i. e., in one fixture.
- *Machine accuracy* Items can only be as accurate as the machine on which they are produced.
- *Tool accuracy*; similarly, items can only be as accurate as the tool used to produce them.

- *Tool deflection* Tools deflect under the load generated by the cutting forces, so these forces have to be controlled by appropriate cutting conditions.

There are many other factors, such as temperature influences, vibrations, material heterogeneities, kinematics, and so on. In spite of the accumulation of all these errors, it is possible to produce accurate items by careful choice of machine tools, machine conditions, appropriate tooling and accurate fixtures, and last but not least, an optimal choice of strategies for determining tolerance.

1.3.6 Management Control

Geometric tolerances greatly increase the processing cost of the product. Management should have control of such tolerances. They should supervise and instruct the product designer to be very frugal when assigning such tolerances.

Chapter 3
Process Planning

Abstract Process planning plays a major role in determining the cost of components and affects all factory activities; disappointingly, it is an art rather than a science. Process planning activities are predominantly labour intensive, depending on the experience, skill and intuition of the planner. Thus, it robs the manufacturing system of its natural flexibility.

This chapter advises two methods for managing this important task:

First, run seminars on how to improve process planning in which experience is transferred from one planner to the others. Include an understanding of the detail parameters of deciding upon a process plan. Use textbook data.

Second, redefine the process planner's task. A process planner should build a roadmap of alternatives, and let each user generate the suitable routing at the time of need.

1 Introduction

Process planning determines the method by which a product is to be manufactured; it defines, in detail, the process that will transform raw material into the desired form. The form is defined by the product designer, and is expressed in engineering drawings.

Process planning is an important link in the complete manufacturing cycle. It plays a major part in determining the cost of components and affects all factory activities; it is a crucial link between design and manufacturing and the economic management of an enterprise.

The management of an enterprise is overwhelmingly based on economic considerations. Managing requires making many economic decisions, such as the economics of manufacturing a certain product, capital investment and cash flow needs, type and number of machines needed, number of employees, due date of delivery, layout, etc.

The implementation of a decision has to be based on intuition, on partially estimated data, or accurate data. The better the data, the better the decision will be. In every case, process planning has to give the background for economic evaluation.

For example, in introducing a new product into a company, the finance department will want to know its manufacturing cost. To answer this question with rea-

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sonable accuracy, the bill of materials (product structure) for the product has to be broken down, giving a list of all required items and their quantity for a single product. For each part on the list, a process plan will be devised—listing the sequence of operations, the machines, the tools and fixtures used and machining time for each operation. The finance personnel will translate this data into costs.

Another example, in relation to the data from process planning, is the case where management would like to know what capital investment has to be made into the manufacturing facilities. To answer this inquiry, a procedure similar to that in the previous case has to be followed. Then, the data will be multiplied by the quantity of products to be manufactured per period. In the case of using the same facility for several operations, the total time required of each facility is summed up. When the total time per period is known, the number of required facilities of each type can be computed. Knowing the cost of each working station, management can transform this data into total investment.

Likewise, if management would like to know the working force required by profession, a similar evaluation must be made, but instead of summing of facilities, there would be a summing of employees required for each facility.

Almost any industrial inquiry concerning the manufacturing process (floor space, due dates, lead time, work in process, etc.) addresses process planning as a data source. Process planning is the basis for the optimization of the whole production scenario and its alternatives, and not only for simple operations.

Finally, it is important to emphasize that process planning is required at any manufacturing plant, regardless of plant size, part complexity or batch size. The oft-stated opinion that process planning is not suited for small batch sizes is misleading. The problem with small batch sizes is not a process planning problem, or a manufacturing one; it is an economic problem. The difficulty here is in finding a reasonable compromise between time of preparation (thinking time) and manufacturing time.

2 Process Planning and Product Design

Product design and process planning are the two most important tasks of the manufacturing process. They establish over 80% of the processing cost and 30% of the lead time. These two are interrelated and affect one another; therefore, they should work together in a complimentary fashion.

The purpose of process planning is to transform raw material into the form specified and defined by the engineering drawing. This task should be carried out for the assembly, and separately for each subassembly and individual item of the product. This stage is basically analogous to the engineering design stage, but here the nature of the objective is different.

Process planning is a decision making task for which the prime optimization criterion is to meet the specifications given in the engineering drawings. The secondary criteria are cost and time with respect to the constraints set by company resources, tooling, know-how, quantity required, and machine load balancing. Some of these constraints are variable or semi-fixed; hence, the optimum solution obtained will be valid only with respect to those conditions considered at the time the decisions are made.

The process planning and design are completely independent tasks, but, in many cases, an insignificant change in the design may significantly reduce the process plan cost and lead time. Therefore, there must be communication between these important tasks.

Product designers are not process planners. However, what they have in mind during the design stage considerably affects the manufacturing process and the process planning. There are many processes from which to choose, which can be broadly divided into the following categories:

- Forming from liquid—casting, molding
- Forming from solid by deformation
- Forming by joining items
- Forming by assembly
- Forming from solid by material removal
- Forming by material increase

The product designer should bear the manufacturing process that will produce the designed part in mind. Each category has its specific design roles in enabling or reducing manufacturing cost. As previously mentioned, the designer's job is to recommend an existing process, preferably one available in their own plant.

Items that were designed with a specific manufacturing process in mind that do not meet the capabilities of the proper processes might turn out to be very difficult to manufacture. In such cases, it should be remembered that items are designed subject to functional, strength or manufacturing constraints. Item drawing should always be seen as a constraint by the process planner, although it might be an artificial constraint if the manufacturing process is the controlling factor in the item design. Each manufacturing process has its advantages, capabilities and limitations. The cost of an item can be kept to a minimum if its features, dimensions and tolerances match the capabilities of one of the available processes. Otherwise, the cost might be excessively high or the production might even be impossible.

The product designer is responsible for meeting product specifications and controlling the strength and cost of the product. However, the process planning selected may offer several design options, and several design constraints.

Studies have indicated that the incurred cost of the engineering stages, i.e., product design, detail design, testing and process planning, is about 15 % of the product cost, while the production stage accounts for 85 %. However, since the committed cost of the product is about 90 % established in the engineering stages, it is worthwhile not to rush but rather to increase the thinking time in design before making decisions.

2.1 Selection of Primary Production Processes

There are many processes that can produce a product/part that will meet design specifications. Each primary process should result in an appropriate design that will meet the process capabilities and constraints.

The process planning of some of the primary processes is straightforward, as the tool produces the items. Therefore, the task of process planning is just to select the appropriate primary process.

The following design factors have bearing on the selection of an appropriate manufacturing process:

- Quantity
- Complexity of form
- Nature of material
- Size of item
- Section thickness
- Dimensional accuracy
- Cost of raw material,
- Possibility of defects and scrape rate
- Subsequent processes

The choice of process should be made initially with economic factors in mind. The difference in direct manufacturing time can be quite significant.

For example, the direct time for molding an item with moderate complexity with a metal die is about *25 s*; to produce the same item by material removal process might take about *an hour*.

However, the cost of the metal die is high, probably in the neighborhood of $ 25,000. Assuming that the direct labor cost of the material removal process is about $ 15/h (ignoring indirect hourly rate and setup costs, which will probably be higher for the molding process), the economic quantity should be at least 25,000/15 = *1666 pieces* in order to break even.

The quantity to be produced will be the major determining factor of process selection. It is clearly a ***management decision***. To assist the designer in designing for manufacturing, several guidelines are detailed in the following sections.

2.1.1 Forming from Liquid

The following are recommended design guidelines for manufacturing parts produced by forming from liquid (casting and molding). Exact recommendations are sometimes impractical, since variables such as component geometry, production process and individual part requirements may dictate certain design features.

Wall Thickness

Since a thinner section results in both weight and cost reduction, choice of wall thickness is an important consideration for successful component design. Typical section components are between 2 mm and 4 mm, though lesser thickness may be used over short flow distances and in small parts. There is, however, no universal optimum value; each component must be considered individually

Ideally, the nominal wall thickness should be constant throughout the component. When this is not possible, smooth transitions are recommended, since sharp

Fig. 3.1 Material flow

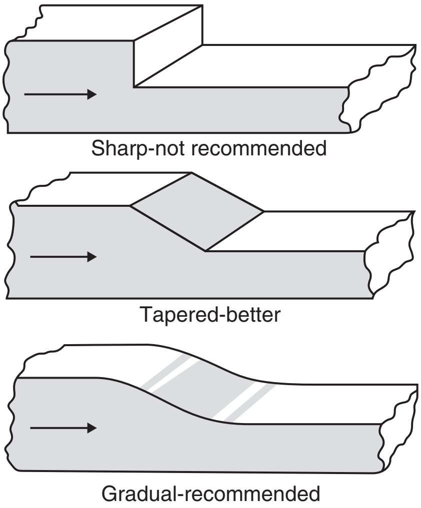
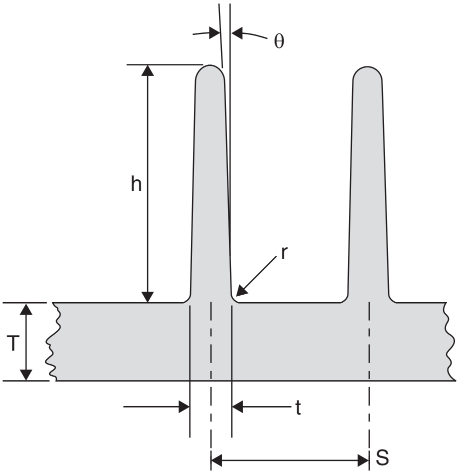


Fig. 3.2 Guidelines for ribs



transitions may cause cooling differentials and turbulent flow during molding. These can result in dimensional instability and appearance defects. Additionally, sharp corners act as stress concentrators and often lead to premature failure.

Where changes in thickness are involved, the design should make provisions for the material to flow from the thicker to the thinner section during the process. This procedure promotes higher cavity pressures, which minimize sink marks, and reduces the likelihood of short shots. A sketch of recommended section changes and flow direction is shown in Fig. 3.1.

Ribs Design

One method of increasing component stiffness without increasing the overall thickness or involving a large weight increase is the incorporation of ribs. See Fig. 3.2.

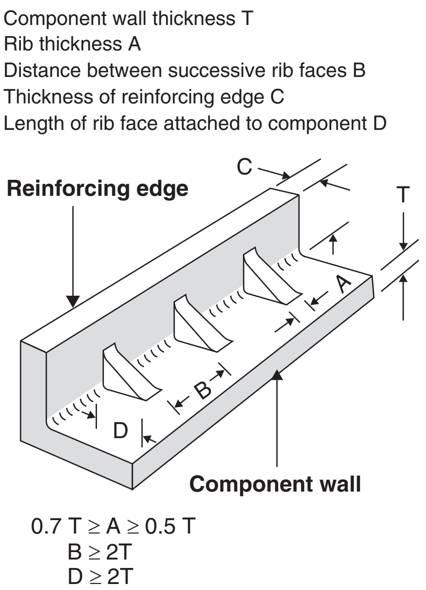


Fig. 3.3. Guidelines for introduction of support ribs

To achieve a successful rib design, the following guidelines are suggested:

- In order to reduce sink marks on prime appearance surfaces, the basic thickness of the rib should not exceed 60 % of the adjoining wall thickness; this, however, may be increased when appearance is less critical
- To reduce the possibility of overstressing, the height of the rib should not exceed three times the thickness of the adjoining wall; where increased strength is required, further ribs of the specified proportions are recommended in preference to an increase in height
- Rib spacing should be at least two times the nominal wall thickness
- Rib channels lying in the direction of material flow in the tool may be utilized advantageously during processing to feed extremities
- A draft angle of at least 0.5° on each side should be incorporated in order to facilitate release from the tool
- Care should be taken to ensure adequate tool venting where gas traps are likely

Support Ribs

Support ribs may be considered as a form of strengthening used in corners which may be encountered at such locations as side walls or bosses.

For the successful introduction of support ribs, the following guidelines are recommended (see Fig. 3.3):

- The thickness of the support rib should be between 50 % and 70 % of the component wall thickness
- The minimum distance between faces of successive support ribs should be twice the thickness of the component wall

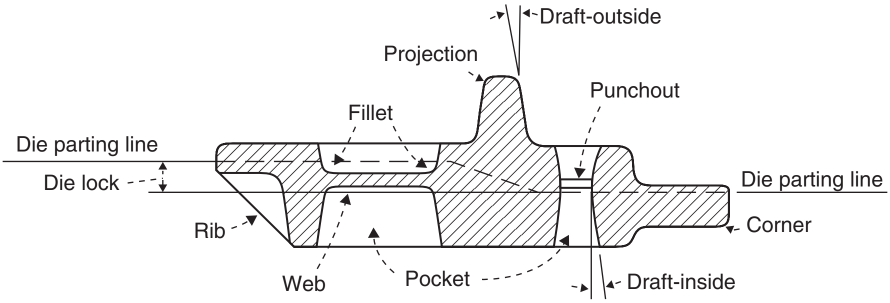


Fig. 3.4 Forging terminology

- The minimum length of the support rib face attached to the component wall should be twice the thickness of the wall
- Generous radii should be incorporated at the ends of the rib
- A minimum draft angle of 0.5 degree should be incorporated
- The minimum length of the support rib face attached to a boss should be four times the thickness of the wall

Forming from Solid by Deformation—Forging

The following are recommended design guidelines for manufacturing parts produced by forming from solid by forging. Figure 3.4 illustrates the fundamental terminology.

Proper design for forging will ensure a consistency of shape meeting the part specifications and long die life.

It is important to make certain that generous fillets or radii are added to sharp corners to improve die life. Ribs or other thin sections tend to chill more quickly during forging operations, thus limiting the flow of the metal being forged. To ensure that the impression is completely filled, it is beneficial to design generous fillet radii and abnormally large draft angles when deep ribs are included in the design of the forging. This practice must be accentuated as more difficult-to-forge materials are used. Deep pockets or recesses in the forging design require knobs or protrusions on the die that not only slow down metal flow but tend to heat up faster than the rest of the die and accelerate die wear at these points. Such die protrusions again necessitate generous draft angles and large radii.

2.1.2 Management Control

Management should make sure that the product designer and the process planner come to a consensus on the selected process. The selected manufacturing process affects product cost and processing time. It might also affect the mix of company resources, and thus, the company line of preferred products.

Such a decision depends on the quantity of orders, and thus, marketing, sales and finance should be involved.

Management should ask to review the protocols of the decision-making meeting and the finance papers in order to review whether the recommended product design meets the selected process category. One of the methods that management might use is the checklist. This method lists decisions that should be made and serves as a reminder to the designer, who must mark on the list that everything was considered.

2.1.3 Assembly Planning

In the mechanical and electrical engineering industry, about one half of the working force is employed in assembly. Costs and manufacturing times of many products are determined, to a large extent, by the assembly process. It is, thus, clear that a correct design for assembly is of tremendous importance.

The first objective of assembly planning is to assist the designer in considering design for assembly in an organized manner. Each aspect of the activity should be considered in a logical sequence, so that the implications of decisions made are both known and consistent with decisions which might have been made if someone else had carried out the study.

There are a number of reasons for considering assembly planning, but, generally, one is seeking a reduction in operation cost. Assembly technique can be done through several methods, including:

- Simple manual assembly
- Manual assembly with tools, i.e., automatic screwdriver
- Assembly by robot
- Assembly by automatic machine

Research shows the unit assembly cost of one component to be a function of batch quantity and assembly technique. It also shows that for small batch size, simple manual assembly is the most economic, while for high quantity; assembly by automatic machine is the best choice.

The other principal reasons are:

- The long lead time in an assembly department with a high product value
- The high personnel input, and, hence, the high labor costs
- A relatively large proportion of activities which cannot be counted as part of the actual assembly process
- To increase output of an existing product
- To improve consistency of quality and reliability
- To seek solutions for small batches that do not justify hard automation
- To reduce the problem of labor turnover, scarcity, or fluctuation in output due to minor labor disruption or absenteeism.

Most of the individual activities can already be supported with the aid of existing, conventional tools. Normally, the approaches consist of catalogues in which design guidelines are set out in the form of examples for various activities. These include, e.g., guidelines for assembly-oriented shaping in general.

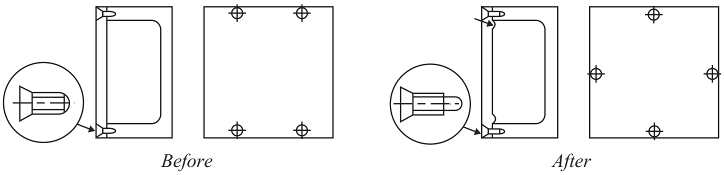


Fig. 3.5 Design of a box and cover

Design Dilemma

Engineering design is a specialized process of problem-solving. Although it has its own peculiar way, suited to a technological pattern, its process resembles that of problem-solving in general. There is always more than one solution to a problem, and rarely a single solution that is the "best". There are many factors that the designer should consider, such as:

- Design for functionality
- Design for reliability
- Design for maintenance
- Design for safety
- Design for convenience of use
- Design for operational economy
- Design for adequate duration of service
- Design for ease of assembly
- Design for ease of processing

Several of these parameters conflict with one another, and thus, a compromise must be made. The designer has to do his best in the limited time assigned for the problem (the design). In this book, we consider only the last two parameters, assembly and processing.

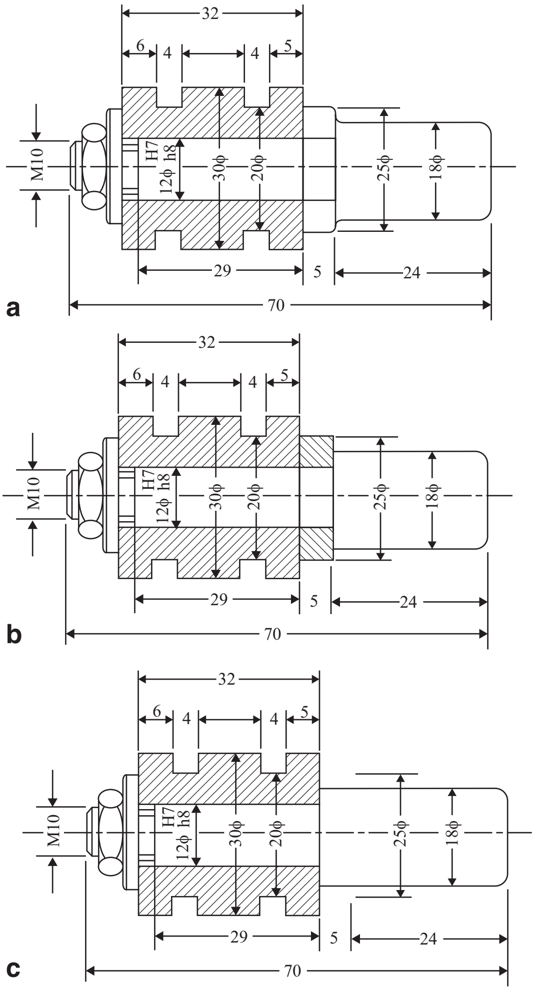
The designer might argue that, instinctively, he always has in mind how a product is to be assembled and that traditional design rules and common sense are sufficient. This may be so, to some extent, but surveys of a wide range of products show that in more than 90 % of all products designed for assembly, improvements could be made. Moreover, if a group of designers were given the same problem, they would inevitably produce a variety of designs each one of which would be considered easy for assembly by its maker.

A simple example of possible design improvement is demonstrated in Fig. 3.5. The designer's task was to design a box made to contain a certain amount of volume and a cover. The design in the figure meets the product objective. However, from an assembly point of view, it poses several difficulties.

The assembly task includes two operations: to position the cover in place and to fasten it with screws. As the cover is designed as a flat square, the positioning operation is just to lay it down on the box and adjust its sides to the box sides. In addition, the screw holes have to coincide with the threaded holes on the box.

The designer decided that four screws were needed to hold the cover and secure the content of the box in place. Therefore, he put two screws in the opposite sides

Fig. 3.6 Design of a pulley



of the square. Through this decision, the positioning of the cover has to be in two stages; first, put the cover on the box, then make sure that the holes in the box and the cover coincide; if not, the cover has to be turned by 90°, which calls for the attention and visual inspection of the assembler.

A better design would be to space the holes in a symmetrical way, which means that if the sides of the cover coincide with those of the box, the holes of the cover and the box match. This design improvement still calls for the assembler's attention in positioning the cover. To guarantee the positioning of the cover regardless of the attention of the assembler, a dent in the cover might assure that, if the dent falls in place, the cover is in the right position, and thus, the screws can be fastened. A further improvement is to use self-starting screws.

There are many factors that the designer should consider, and there is no one "best design". This is demonstrated by Fig. 3.6, which shows several designs of a pulley. Each one of the designs will meet the design objective; therefore, they are all good designs. However, from a standpoint of assembly and economics, each design has its own quite different consideration.

Design A is a traditional design. It saves assembly time but results in extra cost of raw material and machining time.

The assembly is straight-forward, all parts are assembled from one side, and assembly tools and features are standard items. However, from the machining and economic points of view, it results in a waste of raw material and machining time of the shaft. The raw material is 25Ø mm × 70 mm long. The shaft has to be turned to 18 Ø for a length of 24 mm.

Design B reduces the cost of raw material and machining but increases the cost of assembly.

In this design, the raw material is 18Ø mm x 70 mm long instead of 25Ø mm × 70 mm long. There is no need to turn to a 24 mm length from 25Ø to 18Ø mm. However, there is a need to add a washer of 5 × 25Ø with a hole of 12Ø mm. The assembly is from one side only, but with an added part (the washer) for the assembly operation.

Design C reduces the assembly and machining cost but increases raw material cost.

The task of the washer in design B and the shoulder in design A is to reduce the surface pressure (compression stress) and the wear of the moving parts. However, by choosing a more wear-resistant material, the shoulder may be reduced from 25Ø mm to 18Ø mm without affecting the life time of the pulley.

Design B increases the cost of assembly, as there are more parts to assemble, but the additional cost might be compensated by the reduction in the cost of raw material and machining.

Assembler Dilemma

Assembly is a collective term for a large number of very different technological steps. Assembly planning might use manual, automated, robotic, conveyor, or a combination thereof, with each method having its own potential obstacles, therefore making it difficult to guide the designer before the assembly method is selected.

Assembly has at least four stages: moving, locating, laying, and fastening. Each stage might pose different design constraints, and even conflicting demands between one stage and another.

Design encounters many different projects and objectives. Each represents different assembly problems. It is difficult to have an assembly-oriented theory that covers all potential cases. Engineering design is an innovative process, depending heavily on the designer's imagination, talent, and experience. Some designers regard themselves as artists rather than engineers. They may regard the assembly planning as an invasion of their territory. One may have to fight hard to gain concessions from product designers and, whilst they may appear to co-operate willingly, they often reserve the right to re-specify the components as the project progresses.

The main obstacles to automatic assembly are:

- The absence of an assembly-oriented product design theory
- The difficulties in handling individual parts
- The large proportion of adaptation and adjustment work
- The visual inspection during assembly
- The inadequate manufacturing precision of the individual parts

The influences of assembly-oriented product design in the production process are, by proportion:

30 %- the design is not assembly-oriented
26 %- difficult handling of components
20 %- high adaptation and adjustment activities
15 %- visual inspection during assembly
9 %- low precision of single components

If these points are considered more closely, it becomes evident that the poor handling aptitude of individual parts and high proportion of adaptation and adjustment work can be avoided by assembly-oriented product design. A survey also shows that if design-specific modifications were made, 60 % of the parts could be assembled automatically.

Assembly Techniques

Assembly systems can be grouped into three classes of assembly:

- Manual assembly
- Automated assembly
- Robotic assembly

Manual Assembly

In manual assembly, the observation, the control of motion, and the inherent decision-making ability of the assembly operator are far superior to those of even the most sophisticated machine.

Since the assembly operator has such controlled versatility, the tools required are generally much simpler and less expensive than those that are necessary for any form of automated assembly. The assembly operator can identify defective parts, thus making down-time due to poor part quality almost negligible.

The main advantage of manual assembly is that a human assembly operator can make intuitive judgments; the orientation and assembly of parts requires the most difficult combinations of motion.

Automatic Assembly

There are many reasons that justify automated assembly, but the overriding one is economic productivity by cutting down on assembly costs. Automated assembly is best applied to situations of high volume production of a product that has little or no product variations, involving labour-intensive assembly operations. It is under these circumstances that it offers significant potential benefits in terms of assembly cost minimization and increased productivity. The main point to note is the phrase ‘special purpose’; this implies dedication to a single function. This means assembling a single product with little or no product variation. It is significant to note the large batch size and high annual production rates which are economically suited to automated assembly.

Robotic Assembly

The place of robots in assembly has, for quite a few years, been the subject of vigorous research but reasonably little industrial application. This trend has now changed, and one of the largest growth areas of robotic applications has been in assembly operations.

By no means are all assembly operations suited to the use of robots. The versatility of robots is obviously not suited to mass dedicated production, but rather to applications where a variety of products are assembled. Where a number of varieties exist within a product family, a programmable assembly system can bring the benefits of automation to the assembly process whilst coping with the necessity of regular changeover through good software design and modular tooling.

Hybrid Automation-Manual Assembly System

The assembly process is the most complex process in modern manufacturing. While automation has made most part manufacturing very efficient and less dependent on manual labour, manual assembly processes are still the most used. This situation is apparently due to the complexity of products at the final assembly stage. It is also a function of the modern trend toward mass customization assembly. Even highly standardized products are offered in a suite of variants that lead to only small batches of similar products at the assembly department.

2.1.4 Design Constraints for Assembly

The importance of early consideration of product design for assembly is self-evident, the consequences of lack of consideration being reflected in high manufacturing costs and high labour involvement. Manufacturing engineers readily recognize the benefits of design for assembly; because they spend many hours resolving difficult assembly problems ***after*** the design has been approved for production. Post-approval design changes are difficult to achieve because of the high cost. It is for these reasons that a design/manufacturing interface should be established at the earliest possible stages if an optimal design is to be successfully developed.

The designer will normally concentrate first and foremost on getting the product to function within the economic limitations laid down, and then turn attention to the ability of the product to be assembled. The fact that assembly is intended to be carried out by machinery will have a fundamental influence on all aspects of the design. Although the main thrust will be assembly, the designer will have to bear in mind other design considerations to varying degrees.

During assembly-oriented design, there are many design constraints. On the basis of a detailed analysis of all these constraints, a generic set of rules can be established to which a designer should adhere whenever possible. There are over sixty design rules identified in detail in the appropriate literature. In addition, a number of design guidelines of a more general nature have also been developed. Some of those are detailed in the following sections.

Reducing Number of Components

One of the keystone rules for design for assembly is to reduce the number of components. For each component in a product, an automatic feeding device and at least one automatic work head or robot would be required. Obviously, reducing the number of component parts can significantly reduce the cost of assembly automation. Parts reduction is normally achieved by combining two or more parts together or eliminating redundant parts. Combining parts generally implies more complex components; however, it has been found that the cost of parts still reduces to such an extent that greater savings are made on parts than on reduction of assembly time. ***Management*** should make the call in any specific case.

Parts Variation

Most marketable products don’t just sell in one variety; there are usually a number of product styles, some with various additional or optional features. This variation is normally essential to cater to all envisioned customer requirements. Variations of this nature are desirable from a sales point of view, but create endless problems if the product is assembled automatically. It is essential to know all intended variations at the outset of the design in order to prevent major problems in assembly.

If product variations are unavoidable, then as many components as possible should be made common to all product variants. These common components, whenever possible, should contain all features that are used on each product variant, even to the extent of incorporating redundancy.

Minimizing the number of product designs, and consequently part designs, will mean that fewer part-feeders will be required. When product variants are unavoidable, then the part variants of the different products should be assembled as near to the end of the assembly process as possible. This means that a common core assembly containing all common parts is assembled initially, and then the parts for the different designs are assembled last. This assumes that the product variations are only in styles or accessories; if variations in basic operation exist, then different assembly lines will probably be necessary. This strategy for assembly is essential for dedicated automatic assembly in large volume production, although the strategy can be relaxed for robotic assembly due to its inherent flexibility, and assembly strategy should be structured toward reducing throughput time to a minimum in order to maximize production rate.

Placing the Component into a Product

In product assembly design, the product should be designed around a horizontal and a vertical datum which will provide references upon which the movements executed by any of the automatic placing or fastening mechanisms and any required calibration can be fixed; if no functional feature or features of the product can be used, then a non-functional projection or tooling reference may be necessary. Ideally, the major component of a product should act as a building nest for assembly. The rest of the components should then be placed and, if necessary, fastened into position in a natural sequence without previously assembled components causing any impediment.

Orientation

There is a danger that the product designer, who is used to designing products for manual assembly, will not fully appreciate the dexterity of even the most unskilled human operator in handling parts. Although machines can be made to simulate a human operator, the capital cost involved is usually prohibitive. In order to keep this cost to a minimum, the designer should, as much as possible, design the required components for minimum orientation.

Fastening

The methods commonly used to fasten components together can be listed in four categories.

a. Joining with no separate fasteners required
b. Joining requiring one separate fastener per joint
c. Joining requiring more than one separate fastener per joint
d. Joining by heat, with no separate fasteners

Joining with No Separate Fasteners Required Usually, the use of pressure is required, e.g., swaging, staking, crimping, twisting and spinning. Often, integral parts of the components themselves are used, i.e., integrally cast rivets, built-in clip-on mouldings, and tongue and slot joints. Pressure provides a simple, straight-action fastening method, and can be applied in numerous ways. The main danger in using pressure techniques is the possibility of dislodging other unfastened components or causing damage to the product. The method of pressure application should be selected accordingly, with the provision of clamps where necessary to avoid dislodging.

Joining Requiring One Separate Fastener per Joint

Examples: rivets drive nails, screws, and self-tapping screws. Adhesives can also be included in this category. A common argument used against these, and for threaded fasteners, is the ease required for dismantling for re-work. This is often valid, especially when routine servicing is required during the life cycle of a product. Frequently, however, threaded fasteners are used purely for a re-work capability during production.

Adhesives are a relatively new field in assembly and their potential has not yet been fully realized. The bonds formed are strong. The main problems encountered when using adhesives are during application. The danger of blocked applicators due to premature hardening of the adhesive is very real.

Development in this field is continual, and the product designer should be up-to-date with new developments in an area that, when fully developed, could provide the basis for major advances in assembly techniques.

Joining Requiring More than One Separate Fastener

The obvious example is the nut/bolt/washer combination. It is always preferable to feed the nut first and then drive the screw into it, and in many cases, it is safer to start the thread with light pressure at one station and transfer to a second station for final tightening. Combination fasteners should be avoided wherever possible in quantity mechanized assembly.

Joining by Heat

Welding and heat-sealing. Both processes require no additional material to make the joint and, as such, are ideal fastening methods, but require time and constant pressure applied at the electrode during the joining process. Unlike pressure jointing, welding cannot be done as a split operation, and if the time cycle required is short, two or more work heads operating simultaneously at one work station may be required.

Heat-sealing is used to fuse plastic components together under light pressure. As the use of plastic components continues to grow, heat-sealing will be used more and more.

2.1.5 Management Control

The task of product design requires two major mental states of mind. One stage is deciding the general concept of the design, for which designers must think big, letting their imaginations go wild, using their knowledge in engineering, mathematics, physics, chemistry, electronics, law, etc. It is an inspirational task and one of great satisfaction.

In the second stage, designers must contrastingly think small, deciding on little details of the design, such as corner radio size, what size of screw to use, what tolerance to define, etc.

It is very difficult to switch one’s state of mind between these two task requirements; potentially close to impossible. But it must be done. Management should not

Table 3.1 Comparison of 37 experts' recommendations

Operation	Number of experts	Time of machining (minutes)
Drill 30	9	0.13–0.58
Drill 28 + bore 30	9	0.22–0.65
Drill 20 + drill 30	7	0.49–0.84
Drill 15 + drill 30	1	0.81
Drill 10 + drill 30	2	0.78
Drill 5 + drill 30	1	0.81
Drill 8 + drill 28 + bore 30	1	0.86
Drill 8 + drill 18 + bore 30	1	0.77
Drill 10 + drill 20 + drill 30	2	1.04
Drill 10 + drill 28.7 + ream 30	1	1.07
Drill 10 + drill20 + drill 28 + bore 30	2	1.13
Drill 5 + drill 13 + drill 22 + drill 30	1	1.29

diminish the product designer's overall responsibility for the product as represented by the engineering drawings, but the final responsibility still belongs to management, which must determine a way to make that clear.

Changes in product specification might cost (relatively) 2% of product cost, while changes at the design stage might cost 5%, and changes during product processing might cost 10%. But after sales, changes might cost over 90%. It is for these reasons that a design/manufacturing interface should be established at the earliest stages of design if an optimal design is to be successfully developed

Management should ask to review the protocols of the decision-making meeting and the finance papers in order to make sure that all available options, as detailed above, were considered and debated. This is also another instance in which a checklist can be used to ensure thoroughness.

Management should take an active role in the design process.

2.2 Forming from Solid by Material Removal

Forming material removal is a very comprehensive process. There are almost an infinite number of combinations of machines and tools that will produce the part as specified by the drawing. However, the cost and machining time will vary substantially according to the selected process. Therefore, it requires a skillful handling of the operating conditions in order to arrive at an economic optimum. In this respect, the sensitivity of the machining conditions, in relation to time and cost of machining, can be demonstrated by the following examples.

To validate these statements, thirty-seven expert process planners were asked to specify a process for producing a hole 30 mm in diameter and 30 mm long, with a tolerance on the diameter ± 0.15 and a 7.5 μm Ra. The results are shown in Table 3.1.

The machining time range is 10:1, although all the recommendations are technically feasible. Such dispersion was invested in and it was discovered that it depends on the process planner’s previous working place, the resources available there, and years on the job.

The first process in the table was done by a young planner working with new 25 KW resources and/or working on large items, probably in a chemical plant.

The last process in the table was done by an elderly planner working with 2.5 HP resources and working on small items, probably for instruments.

Similar tests were conducted in which expert process planners were asked to specify a process plan for milling and turning items. It is of interest to note that, as the part complexity increases, the number of proposed process alternatives was reduced, but they were concentrated around a mean process plan.

Many more similar examples can be presented, stressing the point that a part can be produced by many alternate processes. The recommended process usually reveals the *past experience* of the process planner, but is also an outcome of the sequence of decisions made. A wrong sequence of decisions may result in artificial constraints, because, if the sequence of decisions were different, the constraints might not have existed.

For example, if the first decision is to select a machine, then its power, spindle torque moment, force, stability, available speed range and feed rates act as constraints in selecting the cutting parameters. If another machine is selected, another set of constraints would arise.

The first decision of selecting chucking location and type imposes constraints on the allowed cutting forces, and thus, on depth of cut, feed rate and machine size. Similarly, a selected tool imposes constraints on the maximum cutting speed, depth of cut, feed rate and tool life.

The real constraints should be technological constraints and should be independent of the sequence of decisions. For example:

- A boring operation cannot be the first operation in making a hole
- Twist drills have constraints on dimensional tolerance and surface finish of the produced hole
- There is a relationship between the exerted force on a part and its deflection
- The allowed deflection of the part during metal cutting is a function of the dimension tolerance
- The allowed cutting forces in a metal cutting operation are a function of the allowed part deflection
- Cutting forces are a function of cutting conditions
- There is a minimum depth of cut, below which there will not be a chip removal process
- There is a spring back in elastic bodies
- There is a relationship between feed rate and surface finish
- Tool wear is a function of cutting speed and cutting feed

In spite of the importance of process planning in the manufacturing cycle, there is no formal methodology which can be used or can help to train personnel for this job.

Process planning (routing) may be generated by an expert process planner or by CAPP—Computer Aided Process Planning, both of which will be described and evaluated in the following sections.

3 Process Planner Expert Method

Process planning activities are predominantly labor intensive, depending on the experience, skill and intuition of the planner, and, therefore, often preclude a thorough analysis and optimization of the process plan and nearly always result in higher than necessary production costs, delays, errors and non-standardization of processes.

Process planning is regarded as an art and not a science. Research into the method of process planning reveals that planners rely on their experience and intuition; as different process planners have different types of experience, it is no wonder that, for the same part, different process planners will devise different processes. Each process will ***produce the part as specified*** in the drawing, although different processes will have different machining time and costs.

Experience comes from practical work on the shop floor during production, where a process is defined and corrections are made. Experience is also gained from the rejected part and the problematic processes. Very little experience, or even the wrong kind of experience, can be gained from the "no problem" items. But the process planner often neglects other considerations, such as time and cost. The experienced process planner usually makes decisions based on comprehensive data without breaking it down to individual parameters; there is no time to analyze the problem, and the result is an empirical solution without justification.

Usually, a process planner will evaluate several alternate solutions, such as going to the shop floor to consult with the foreman with regard to machine load. Normally, the process planner applies innate knowledge, but, for the same machining requirements, there could be different process alternatives. This means that process planning is more or less an iterative rather than a straight process. The iterations are, however, "lost" when the routine (process plan) arrives at the production management stages.

Process planning is also a series of decisions, decisions that must uniquely specify the process, even if they are not mandatory to it. Once the process planner makes a decision, it becomes a constraint on all decisions that follow it. For example, a selected machine imposes constraints on the power available for the cutting operation, the torque at the spindle, the maximum depth of cut, the maximum cutting speed and the available speeds and feeds, the machining dimensions, the number of tools that can be used, the accuracy, the handling times, etc.

A single machining operation can be adjusted to comply with these constraints, but machining cost and time will be applied to the selected machine. Similarly, a selected tool imposes constraints on the maximum cutting speed, depth of cut, feed rate and tool life.

It is accepted that these constraints are artificial ones; they exist only because of the sequence of decisions made. Another sequence might result in a different set of constraints. Similarly, a decision made at the process planning stage will be a constraint on the production management stage.

In summary, if the technical data were available at the production management stage, savings in manufacturing a product mix could be realized.

Process planning is a key function in a workshop and the process planner is always overloaded. That is probably why a routing will usually last for several years. The routing is defined to meet the parameters set by the product design drawings. The quantity is not part of engineering but rather sales, yet it is one of the most critical parameters while defining a routing. Therefore, it should be revised when the quantity exceeds allowances set by management.

3.1 Process Planning Decisions

Process planning is a sequence of decisive activities which are a compromise between processing routings restricted by the drawings of the items and by management specifications (quantity). The decisions are:

1. Selection of processes and tools which are candidates for processing a part and its features by respecting the constraints imposed in the definition drawing.
   The process planner's first priority is that the routing will meet requirements; processing cost and time are secondary objectives. To make sure that this task will be accomplished, the planner will select the best resources and probably add some safety factors to ensure success. Scheduling and process planning are not a concern; in fact, they are not even defined at this stage.
   Thus, the defined routing might cause scheduling (bottlenecks) complexities, and probably increase processing cost.
2. Determination of production tolerances and setting dimensions that ensure execution of the design tolerances, while choosing production dimensions for reasons of commodity and capability of the manufacturing machinery.
   To make sure that the routing will meet this requirement, the process planner will choose accurate resources. However, it might be cost effective to use a mix of old inaccurate resources for the rough operations and the accurate resources for the finishing operations.
3. Selection of starting surfaces and datum surfaces to ensure precise execution of processing operations simultaneous to a selection of holding fixtures and the checking of the stability of a part through appropriate clamping.
   It is important that jigs and fixtures be designed in a modular method, in order to reduce set-up times.
4. Determination of processing conditions for every elementary operation that enables the computation of working times and costs to carry out an economic evaluation.
5. Grouping of elementary operations on the same resource so that operation time will be reduced, while respecting accuracy requirements.
6. Selection of resources to execute the technological operations, taking into account of resources to execute the technological operations, taking in account the number of work pieces to be produced. This selection creates item routing.
7. Editing of process sheets to be assembled in a comprehensive process planning file, which is transferred to the manufacturing department for execution.

3.1.1 Process Planning and Production Planning

It is customarily known that process planning cost is not a parameter in the planner's decisions. The planner's task is to define a routing that meets engineering drawing specifications. Normally, he/she does not inquire as to how and why such specifications were made.

The production planner's task is to follow the routing and schedule items and products to meet delivery date at the lowest cost possible. Again, how and why such routing was made is not normally questioned. Thus, the company objective of making a profit is upset.

Example: An item drawing calls for a plate with pocket and hole. The raw material must remove six mm and end with a tolerance of 0.1 mm. To meet these specifications, two cutting passes must be made; one rough and one finished cut. Therefore, the operations are:

Operation 010	Rough cut	19 KW	0.60 min
Operation 020	Finished cut	3 KW	0.94 min
Operation 030	Rough pocket	1.6 KW	0.90 min
Operation 040	Finished pocket	0.2 KW	4.86 min
Total			15.4 min

The process planning routing is;

Machine with 19 KW or more for 15.4 min per item.

The scheduler will have to follow this routing. The selected resource will be (15.4–0.60) 14.8 min of the cutting time under load, but this machine is restricted from other jobs that need high cutting power.

The process planner might propose selecting a 3 KW machine by reducing cutting speed of the rough operation. Thereby increasing processing time from 0.6 to 3.8 min and the routing will be:

Machine with 3 KW for 18.6 min.

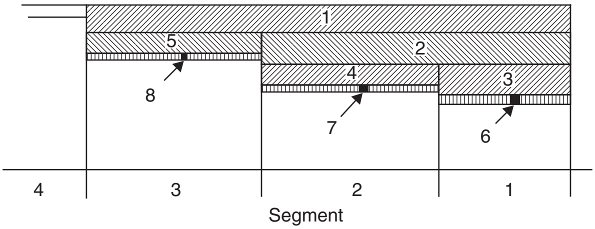
Increasing operation time by 3.2 min may release a high power machine for other jobs.

The process planner does not have any preference for the above routing. But it may solve several bottlenecks in shop floor scheduling if production planning is aware of such a possible selection. If the process planner delivers such alternative routing to production planning, it will add scheduling options.

A similar case is the decision as to sequence of operations. The process planner must make this decision even when he/she does not have any interest or technical priorities. Figure 3.7 shows eight operations required to produce a part.

It is clear that Operation 2 cannot be performed unless Operation 1 is done and clears the way for the tool. Similarly, Operations 3 and 6 must be made in that order. However, Operation 2 clears the way for the tool that processes Operation 5, and,

Fig. 3.7 Operations to process an item



therefore, Operation 5 may be processed after Operation 2. Operation 8 may be processed after Operation 5 and Operation 7 after Operation 4.

Thus, the allowable operation sequence might be:

1 2 3 6 4 5 7 8
1 2 5 8 3 4 6 7
1 2 3 5 8 4 7 6
1 2 3 4 6 7 5 8
1 2 5 3 4 6 7 8
1 2 5 8 36 4 7
1 2 3 4 5 8 7 6

There is incredible flexibility in process planning, but the method used prohibits the process planner from transferring it to production planner and management to benefit from that flexibility.

3.1.2 Management Control

Expert process planners usually makes their routing decision based on previous experience. Management must have faith that process planners are doing their best. However, as each process planner might propose a different routing, management should take steps to improve the knowledge of their process planners, to bridge the gap between art "expert" and science.

It is important that the process planner should understand the process and the effect of each individual parameter of the process plan. Such understanding and a methodic through process will improve the performance of the process planner.

Modern resources are DNC-computer controlled. Several have the capability to process items by introducing the drawing, certain parameters and the resource process of the item. In other words, the resources very clearly generate automatic routing. Management should consider carefully how and when to use this resource capability. They might wish to do their own routing and let the resource follow their instructions instead of its own resource, which is unknown to them. They should make sure that the automatic routing is better than their own.

The problem is that they chose a resource and not a process, as discussed before.

They should be aware that they might use an expensive resource to do what a simple, inexpensive resource could do, the latter thereby increasing plant throughput and reducing processing cost. This point is discussed in the section on production planning.

To improve performance, management might take the following steps.

- Force the process planner to consider several process options
- Make the process planner to reveal his ideas, options, intentions and imposed constraints (quantity, tooling, machinery etc.) in making their decision
- Make the process planner declare the nature of routing optimization; is it cost effective or process time effective?
- Have two separate process planners devise a routing for the same item; compare the processes; if they are not the same, let them discuss the differences and exchange experiences with one another
- Arrange a seminar of process planning theories
- Have technical meetings between process planning and production planning so that each can come to understand the problematic task of the other
- Set an “expiration date” of routing based on duration
- Set a quantity allowance (quantity range around the quantity used for the routing and the required order quantity); if exceeded, ask for a new routing to be defined
- Make sure that the designer of jigs and fixtures (if it is not the product designer) consults with production planning to design a fast and easy set-up on the shop floor; Determine the use of modular fixtures, SMED (single minutes change of dies, or pallets.

It is advised that management consider Group technology and SMED, which are described in the appendix.

3.2 CAPP—Computer Aided Process Planning

Production planning and control is one of the main users of process planning/routing. Traditionally, routing prescribes the flow of work in the plant and lists the sequence of workstations required to produce an item. Routing is unchanging and does not reveal or reflect the basic intentions of a process planner (seldom does it present alternatives), and, therefore, production planning does not result in an optimal production planning solution.

A process planner must be aware of the facilities in the shop and should know the load on the resources, although there is no way to ascertain which resource will be overloaded and which underloaded at the time of capacity planning, other than by estimates and assumptions. Usually, the process planner aims at a local economic process plan efficiency. Balancing resource loading is usually not the process planner’s responsibility or even one they have to consider. And yet, in fact, it is impossible to know the load if one does not know the process.

It is a loop problem, and, normally the process planner will simply select a “better” resource. Thus, about 30 % of the resources will be overloaded and the rest underloaded. This situation, together with added bottlenecks and other disruptions on the shop floor that need immediate solutions, makes production planning a complex task.

A variable routing approach will assist and make production planning a simple task

This situation has recently been reconsidered with a view that routing (the process plan) should be regarded as a variable. The process planner should transfer the roadmap (infinite alternative plans) to production planning, and the scheduler will make the decision as to which process to use in real time and consider the shop floor situation. Thus, manufacturing costs and throughput will be reduced.

3.2.1 Hybrid Process Planning—RCAPP

Process planning affects all factory activities. It is a crucial link between design and manufacturing and is considered a bottleneck of production today. Therefore, Computer Aided Process Planning (CAPP) has been recognized as an important research field. Although a tremendous effort has been made in developing many different CAPP systems in the last three decades, it still remains essentially in the conceptual stage and at an effectiveness that is far from satisfactory; thus, the benefits of CAPP in a real industrial environment are still to be seen. Many benefits are anticipated, but the path to follow has been unclear.

The difficulties in constructing a CAPP program have been analyzed and methods to overcome these difficulties have been proposed. One of the difficulties is that there is no formal methodology which can be used or which can serve as an algorithm for a computer program. It is a huge task to develop such a methodology and it takes years of research. However, due to the rush for immediate results, no such research was made. On the other hand, the task of developing a CAPP system gradually came to be thought of as a computer science problem, while the technology was regarded with secondary importance and was left for the individual user to set the rules.

A purely generative CAPP system can be constructed. However, it might take some time. The proposed method is a ***compromise between a pure CAPP and today`s trend toward an Expert System CAPP***. It proposes utilizing the expert process planner, but in a method that will introduce flexibility while preserving the technique of a pure CAPP.

The main problem in constructing a CAPP algorithm is deciding the sequence of decisions to be made, i.e., with which decision to start; once a decision is made, it imposes constraints on the following decisions. However, different sequences of decisions will impose different constraints. Therefore, it is regarded as an artificial constraint. For example, if the first decision is to select a machine, then its power, spindle torque moment, forces, stability and available speed range act as constraints in selecting the cutting parameters. If another machine is selected, another set of constraints would arise.

The RCAPP (Relational Computer Aided Process Planning) system must consider only real constraints. A real constraint is the part`s mechanical strength.

It is clear that if the force acting in the metal removal process breaks the part, the part cannot be produced. If the forces deflect the part to such a degree that it becomes impossible to keep the required tolerance, it is a real constraint.

However, if the forces exceed the part gripping forces, this might be an artificial constraint, meaning that the previous decision on gripping was not good and must be altered.

To overcome this problem and comply with dynamic requirements, the proposed RCAPP algorithm divides the process planning task into three stages: Technology stage; Transformation stage; Decision (mathematics) stage.

Technology stage: This stage requires an in-depth knowledge of manufacturing processes. Research shows that such a CAPP system may be developed; however, it will take a great deal of effort and time. This stage sets the base rules for the overall CAPP program. There is no time limit for this stage.

Theoretical Process (TP) is defined as the ***best process*** possible. It is **practical from a technological** point of view, i.e., it does not violate any technological or physical rule. It is theoretical from a specific shop viewpoint, i.e., the specific shop might not have the required resources, or the required resources are not available on the market.

In order to construct a RCAPP system that will be available for practical use in a short period of time, it is proposed that this stage be defined by a ***human expert process planner***, or a CAPP system, while assuming a theoretical, imaginary resource, ignoring all variable elements such as order quantity, handling time, set-up, etc. The capabilities of the imaginary resources are set according to present technological boundaries. The power is set based on the biggest electric motor that can be built anywhere in the world. This means no power constraints, no force constraints, etc. The imaginary tools are of the best tool grade, hardness and toughness possible by present-day technology, even if no one produces such a tool. Part rigidity is absolute and can be ignored.

Transformation stage: This stage transforms the individual operations specified in the theoretical process to practical operations, to fit any resource available in the plant. The available resources are handled one by one. Initially, the physical size of the machine is checked. In the case that the machine cannot accommodate the part, it is excluded from further consideration. Next, the machine accuracy and type are checked. In the case that a machine cannot perform even a single operation, that machine is excluded. Next, the processing time (cost) is computed by a simple computer program. The results are listed in a spreadsheet, as shown in Table 3.2.

The priority column indicates the code for sequence of operations

Decision (mathematics) stage. This stage specifies a routing to comply with the user request specifications, performing this task through a computer program in a split second.

The definition of the mathematical problem is as follows: Given a list of operations to be performed and a list of available facilities, a decision is required as to which machine (or machines) to use, which operation(s) to perform on each machine, what their sequence should be, and what cutting conditions to employ. The optimization criterion is either maximum production or minimum cost. The operations in the list are not arranged according to any reasonable machining sequence. However, some operations must precede others.

The RCAPP technique is to divide the problem into technological, transformation, and decision (mathematical) stages. The technological problems are the difficult ones; therefore, if one is reluctant to invest the time and effort to develop this phase, one may skip it by using an expert to generate the required data. The transformation is a straightforward task that can easily be developed and programmed.

The decision/mathematical stage has its own problems, but they can be solved. A roadmap solution was presented, but other solutions to the defined problem may be proposed. Hence, no technological breakthrough is needed to implement the proposed RCAPP system.

Through the RCAPP method, routing may be generated to meet the terms of the user in a split second. It is interesting to note that many production management systems use the matrix as a data generator.

The benefits of the proposed CAPP system are:

- It is easy to implement
- It introduces flexibility in process planning
- It may generate processes without human intervention
- It generates processes in less than a second
- It requires a moderate personal computer
- It can easily be integrated into many production management systems

Further details of RCAPP are given in the Appendix.

Management Decisions

Production planning and control is one of the main users of process planning/routing.

The expert process planner generates a routing to suit immediate requirements, which may not be optimal for other requirements.

RCAPP is a universal program that may serve all production planning and management needs**.** As already mentioned, it **can** generate a routing that meets the specifications of the user in virtually no time at all.

If it is proposed that the manager should decide to use the RCAPP method, the manager should be involved in the following decisions:

- Decisions on how to calculate an hourly rate for each resource
- Method for transforming results from processing time to processing cost
- Decisions in regard to the set-up, and how it may be added to each individual item and not to the batch
- Decisions of how to define and compute an all-embracing optimum
- Decisions on what programming parameters to set and how to treat them
- Etc

Note: The appendix includes flowcharts and examples to aid the system analyst and programming.

Table 3.2 Table of TP—Process Operation

No	Operation	Prio-rity	Tool Dia	Length (mm)	Depth (mm)	Feed (Mm/min)	Speed (m/min)	Power (KW)	Time (Min)
010	Rough milling	0	125	378	4.4	808	100	20	0.47
020	Rough milling	010	125	128	4.6	735	100	20	0.17
030	Semi- finish milling	020	125	278	0.4	905	148	2.2	0.31
040	Finish milling	030	125	378	0.2	200	165	0.39	1.89
050	Rough pocket milling	010	80	150	4.0	1093	102	20.6	0.24
060	Finish pocket milling	050	12	b	0.4	120	24	0.33	4.16
070	Center drill	020	3	3	-	0.05	14	0.025	0.03
080	Twist drill	070	7	21	-	0.16	15.7	0.3	0.22
090	Core drill	080	12	21	-	0.19	23.5	0.5	0.20

Table 3.3 Universal Roadmap

Operation	TP	PR	Rel.	R1	R2	R3			Rn
Cleaning									
Milling									
Turning							Ti, j		
Welding									
Riveting								Ci, j	
Any process									
Sheeting									
Bending									
Forming									

Appendix

Hyper—Rcapp Demo

The RCAPP concept divides the process planning task into three stages:

Stage 1. Technology stage; generates TP—Theoretical Process. It is the "best" possible process from a technological standpoint. It does not violate any physical law. It is theoretical from a specific shop viewpoint. This stage is done by a process planner, or a computer program, as shown in Table 3.2

Stage 2. Transformation stage; constructing an Operation-Machine roadmap, as shown in Table 3.3. It lists all required operations, as generated by the time in Table 3.2 (TP). It considers the ***available resources*** and transforms machining time of each operation to consider the constraints of each specific machine, and builds the content of the roadmap (Ti, j—The time to perform operation I, on machine j). The transformation may be done following the operation transformation flow chart, as shown in Fig. 3.8

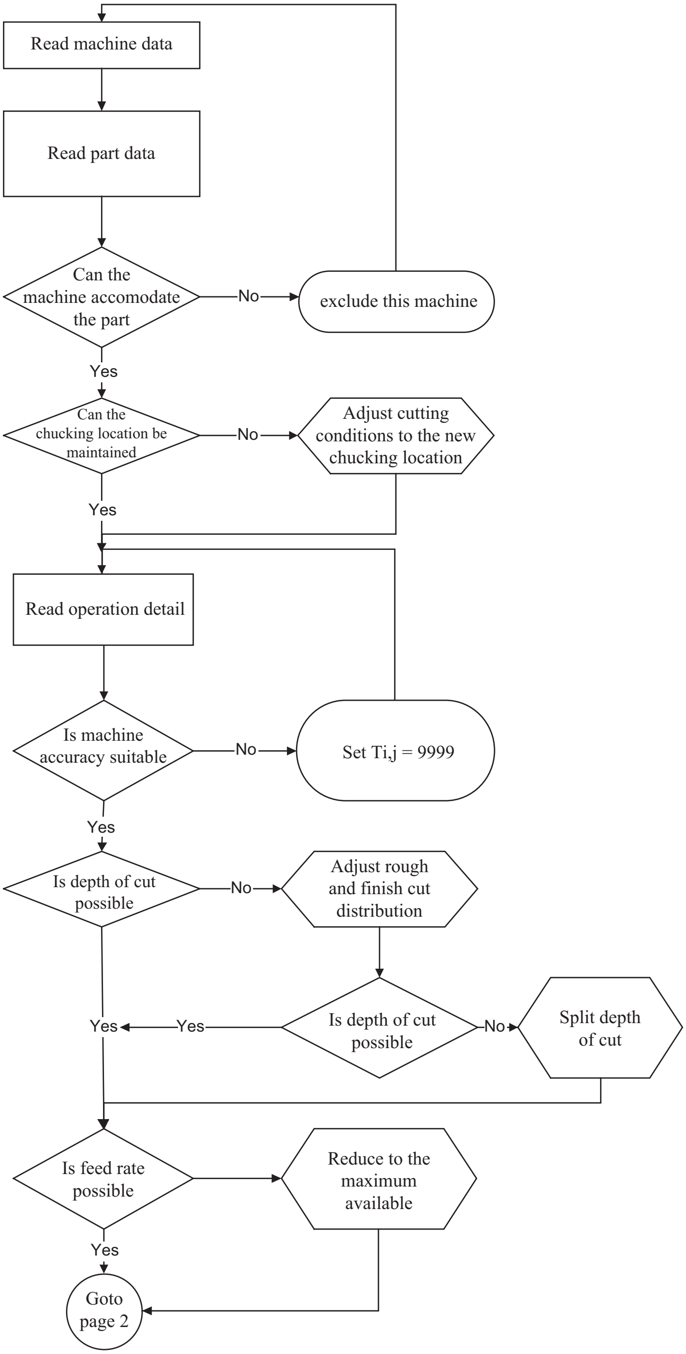


Fig. 3.8 Operation transformation flow chart

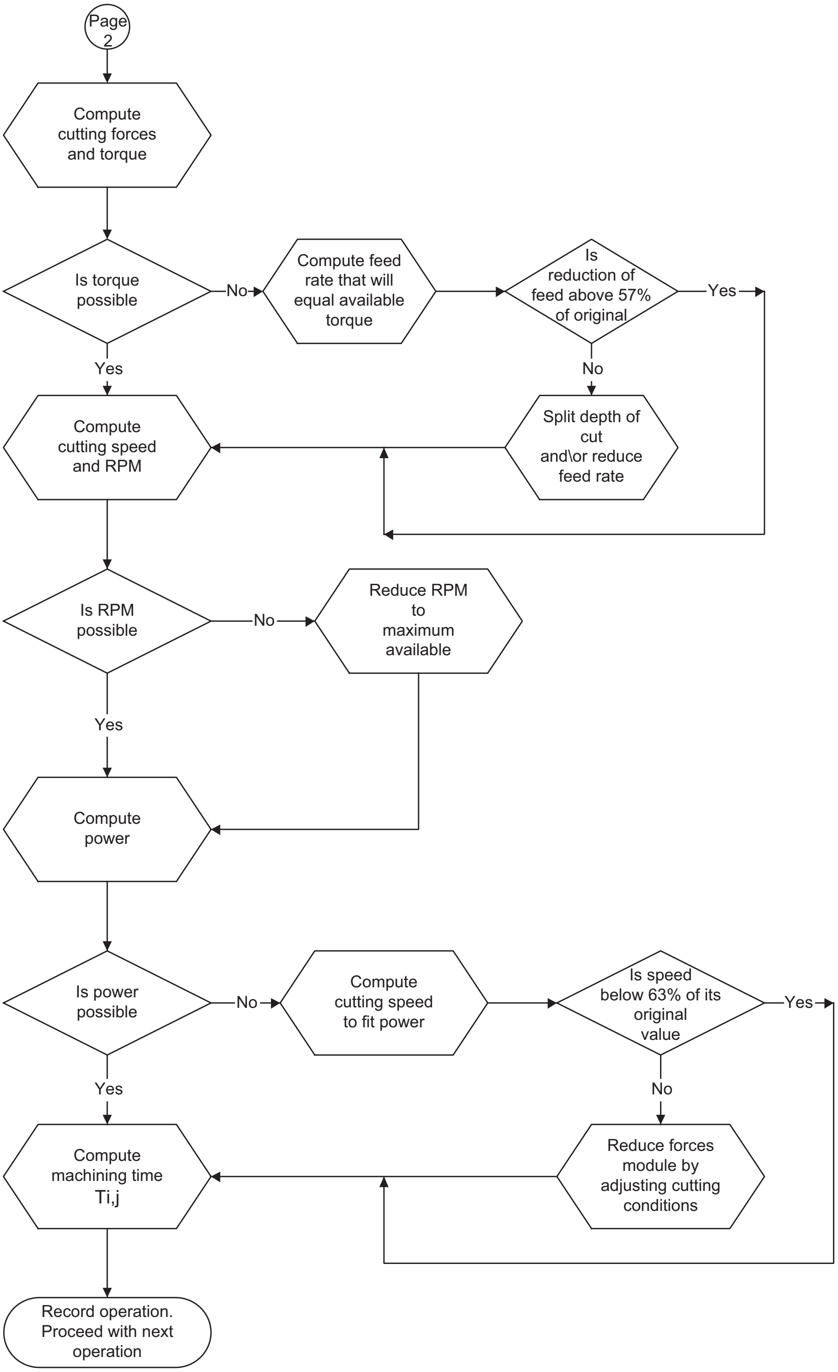


Fig. 3.8 (continued)

Table 3.4 Specifications of available resources

Resource Number	Resource Specifications	Power (KW)	Speed (RPM)	Handling Time (Min)	Relative Cost ($)
1	Milling Machining Center	35	1500	0.10	4
2	Large CNC milling	35	1200	0.15	3
3	Manual milling resource	15	1500	0.66	1.4
4	Small drill press	1	1200	0.66	1
5	Old milling resource	15	2400	1.0	1
6	Small CNC milling	10	3000	0.25	2

Table 3.5 Resource—Operation time roadmap

Op.	TP	PR	Rel	R1	R2	R3	R4	R5	R6
010	0.47	0	0	0.57	0.62	1.28	99	1.62	1.19
020	0.17	010	0	0.27	0.32	0.88	99	1.22	0.59
030	0.31	020	0	0.41	0.46	0.97	99	99	0.56
040	1.89	030	0	1.99	204	2.55	99	99	2.14
050	0.24	010	0	0.34	0.39	0.99	99	1.32	0.74
060	4.16	050	0	4.26	4.31	4.38	99	99	4.41
070	0.03	020	0	0.13	0.18	0.69	0.69	1.03	0.28
080	0.22	070	0	0.32	0.37	0.88	0.88	1.22	0.47
090	0.20	080	0	0.30	0.35	0.86	0.86	99	0.45
Total	7.69			8.59	9.04	13.92			10.82

Table 3.6 Resource—Operation cost roadmap

Op	TP	Pr	Rel	R1	R2	R3	R4	R5	R6	Min. cost
010	0.47	0	0	2.28	1.86	1.79	99	1.62	2.36	1.62 M5
020	0.17	010	0	1.08	0.96	1. 23	99	1.22	1.22	0.96 M2
030	0.31	020	0	1.64	1.38	1.36	99	99	1.12	1.12 M6
040	1.89	030	0	7.96	6.12	3.57	99	99	4.28	3.57 M3
050	0.24	010	0	1.36	1.17	1.39	99	1.32	1.48	1.17 M2
060	4.16	050	0	17.04	12.93	6.75	99	99	8.82	6.75 M3
070	0.03	020	0	0.52	0.54	0.97	0.69	1.03	0.56	0.52 M1
080	0.22	070	0	1.28	1.1	1.24	0.88	1.22	0.94	0.88 M4
090	0.20	080	0	1.20	1.05	1.20	0.86	99	0.90	0.86 M4
Total	7.69			34.36	27.12	19.50			21.64	17.45

Assume that six resources are being considered. A short list of specifications of these resources is given in Table 3.4.

Using a simple computer program, or human process planner, to transfer in Table 3.5, the time roadmap can easily be converted to a cost roadmap. This is done by multiplying the time by the hourly rate. Thus, the value of Ti, j is converted to Ci, j, where Ci, j represents the cost of performing operation i on resource j. The converted time-to-cost values are shown in Table 3.6

Stage 3. Decision (mathematics) stage; Roadmap solution. Compute the path and sequence of operations that will result in the optimum process plan according to the criteria of optimization.

The roadmap format represents an almost infinite number of possible processes. For a roadmap of N =10 operations and M =10 machines, the number of process combinations is

$$N!M^{N} = 3.6288 * 10^{16}.$$

Finding the appropriate process becomes a ***mathematical problem*** and not a technological one. The definition of the mathematical problem is as follows:

Given: Operation (i)—Resource (j) roadmap listing all operations and the process value for each operation on each resource (Vi, j). A decision is required as to which resource to use, which operation(s) to perform on each resource, and what their sequence should be. The constraints are indicated by Priority—which indicate operations that must precede others and certain Relationships that must tie operations to be performed on the same resource. Extra expenses and time should be added to cover extra set up, chucking, and transfer of parts between resources, additional complication in capacity planning, job recording and inspection, etc. These extra expenses are called a "penalty". Thus, the penalty for a batch is a function of the quantity to be produced. Naturally, in each case, the sequence of operations might be different.

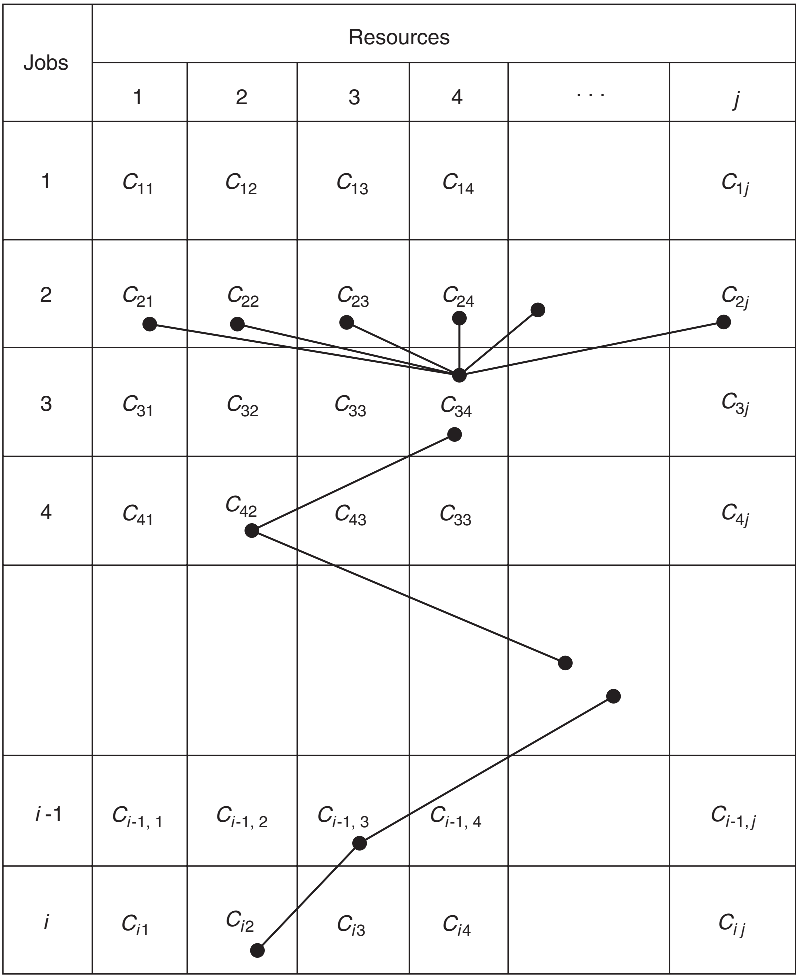
The solution might be solved by the basic feature of dynamic programming which is that the optimum is reached stepwise, proceeding from one stage to the next. An optimum solution set is determined, given any conditions in the first stage. This optimum solution set from the first stage is then integrated with the second stage to obtain a new optimum solution, given any conditions. Then, in a sense ignoring the first and second stages as such, this new optimum solution is integrated into the third stage to obtain still further optimum solutions, and so on until the last stage. It is the optimum solution that is carried forward rather than the previous stage.

This dynamic programming procedure is shown in Fig. 3.9. At an intermittent point in the series of decisions, it was decided that job 3 is to be performed on resource 4 (see Fig. 3.9). At this stage, we can ignore how and why we reached this decision. The problem at hand is: to where should we precede from this point, that is, on which resource should job 2 be performed? Thus, this procedure is a finite problem, and can be solved easily and quickly. The number of combinations to be solved is

$$N * M.$$

In the problem at hand, the stages are referred to as jobs (operations) and decisions are made by choosing the optimum path between any two jobs. However, since the sequence of operations listed in the roadmap is not fixed, this sequence can be changed. One of the problems to be solved is which sequence of operations will result in an optimum solution. Therefore, the general dynamic programming solution procedure has to be modified in order to handle the problem at hand.

The proposed solution is divided into two stages.



Jobs	Resources					
	1	2	3	4	. . .	j
1	C_{11}	C_{12}	C_{13}	C_{14}		C_{1j}
2	C_{21}	C_{22}	C_{23}	C_{24}		C_{2j}
3	C_{31}	C_{32}	C_{33}	C_{34}		C_{3j}
4	C_{41}	C_{42}	C_{43}	C_{33}		C_{4j}
i -1	$C_{i\text{-}1,\,1}$	$C_{i\text{-}1,\,2}$	$C_{i\text{-}1,\,3}$	$C_{i\text{-}1,\,4}$		$C_{i\text{-}1,\,j}$
i	C_{i1}	C_{i2}	C_{i3}	C_{i4}		C_{ij}

Fig. 3.9 Dynamic programming procedure

The first stage is from the bottom up, that is, from the last operation up to the first. It will proceed operation by operation, determining the optimum path (resource selection) for each operation independently of the previous operation. However, at each operation, a review of all previous optimum decisions is made in order to examine the effect of the sequence of operations. The sequence that results in a total path optimum is selected.

The second stage is from the top down, which is from the first operation down to the last. It reviews the optimum achieved by examining the effect of the sequence of operations from any operation up to the first operation. The sequence that results in a total path optimum will be used.

Chapter 4
Production Lot Size & Maximum Profit

Abstract This chapter deals with two topics that are traditionally outside the scope of engineering. By introducing flexibility to production planning integration, such disciplines can be improved.

Lot size; The term economic lot size comes from the theory of inventory control. The approach assumes gradual usage of items, which does not always hold true in manufacturing.

The flexibility of manufacturing may regard economic order lot size in terms of production. This chapter presents a lot size definition as a parameter of routing.

The maximum profit section proves that neither the minimum processing cost nor the maximum production criteria nor the higher selling price will result in maximum profit. A proposed method for arriving at the optimum selling price and selection of the appropriate routing is presented.

1 Production Economic Lot Size

The topic of inventory lot size is discussed in Chap. 8.

The processing lot size has an effect on plant load, and the work in process. The smaller the lot size, the more flexible capacity planning may be. Usually, an item requires several operations on different resources; these operations are made in a serial sequence, i.e., an operation may start only after the previous operation has finished. An operation, in production management terminology, is the processing made on a specific resource in one chucking. The operation time is the set-up time plus the elapsed time from the instant the item is inserted into the work station till the time that it is removed. The time of an operation is the time of a single operation multiplied by the batch quantity. The larger the batch sizes, the longer the operation time and the longer a specific resource is engaged with one processing operation. Research in scheduling theory has proved that giving priority to operations that have the shortest processing time (SPT) results in the following:

- Mean flow time is minimized by SPT sequencing
- Mean (and total) inventory is minimized by SPT sequencing
- Mean (and total) waiting time (where the waiting time of a job is defined as the time it spends in the system prior to the start of its processing) is minimized by SPT sequencing

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- Maximum waiting time is minimized by SPT sequencing
- Mean (and total) lateness is minimized by SPT sequencing
- Weighted mean flow time is minimized by SPT sequencing

Although the above results apply only to simple problems, they are important as possibly useful heuristic procedures or parts of good algorithms to be devised for a particular problem.

Simulation studies vary widely in their objective functions and job shop characteristics, constraints, and conditions. However, even under these varying conditions, the performance of the SPT dispatching rule continues to be impressive

All of the above research work never dealt with the question as to how to get a short processing time. This question was outside of their research topic, which was scheduling. In cases of scheduling problems, the solutions may be found by reducing queue waiting time, preparation time, post-operation time and transportation time, using dispatchers. Another method is splitting—the simultaneous processing of an operation on several machines; there is also overlapping—starting the subsequent operation before the preceding one has completed the planned quantity.

The lot size is the main factor in the operation time, and, therefore, should not be taken as an external decision, but rather as part of the production management problem.

In conventional production management methodology, routing is considered to be fixed data. It is determined by the engineering and technology department, at another time period. Production Management must consider the routing as unalterable. The task of production management is a very complicated one, as it has to deal with many unknown elements: disruptions during processing, change of orders, and many uncontrollable factors. Accepting routing as unalterable eliminates many of the possible solutions and forces management to come up with artificial solutions.

The obvious solution is that the routing may be variable, and thereby introduce flexibility into the task of production management, but this has always been considered a taboo.

Lately, the notion that a routing may be altered is gaining acceptance. Some methods propose generating alternate routings, which would require approval before being employed. This is a start, but it may introduce only those alternate routings conceived of by the engineer. Some suggest seeking out the process planner whenever the original routing causes problems, so as to describe the problem and ask them to generate another process. This is a good idea, but it calls for the process planner to be available at any instant during all operating shifts.

The roadmap method solves this problem, as it presents almost infinite possible routings, but leaves the decision as to which one to use to the user, whether production management or general management.

The roadmap method has transformed the process planning task to one of mathematics. Once the roadmap has been constructed, any discipline and function in the company may generate a process plan, whenever one is needed. Thus, it introduces flexibility to the tasks of production management.

However, this added flexibility introduces many new problems. In the conventional method, no one questions how and why the process planner decided to propose the one process that they did. It was a constraint that made life easier. By in-

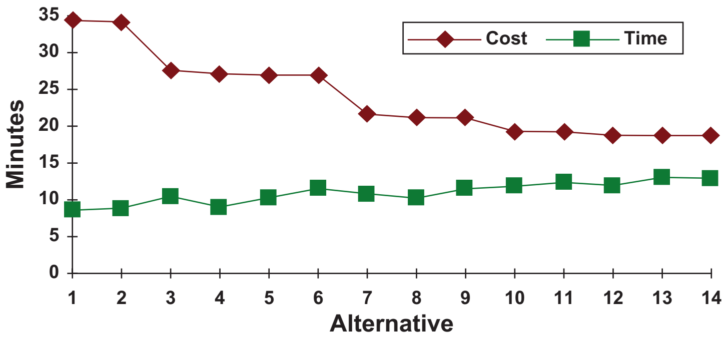

Fig. 4.1 Process planning alternatives

troducing flexibility, the user has to answer several questions, such as: what criteria of optimization to use in generating the process, should it be maximum production, or minimum cost, or maybe maximum profit (a criterion that is talked about but seldom used). The differences in processing time and processing cost are demonstrated in Fig. 4.1. The differences might be quite substantial, for example, in a case in which the time for maximum production criteria was 8.59 and the cost 34.36 while, by using the minimum cost optimization criteria, the time was 11.58 while the cost was 18.39. Many other process results fall between such limits.

Therefore, when talking about processing time in the roadmap method, era is of no meaning, unless the user defines what characteristics they wish the process to possess. But without the operation time, production management cannot operate.

1.1 Determining Lot Size

The term Economic Order Quantity (EOQ) comes from the theory of inventory control, together with the terms order point, safety stock, service level, etc.

The standard theory of the EOQ approach assumes a gradual usage of items, which does not always hold true in manufacturing; therefore, its use is not always recommended. The RPS (Requirement Planning System) method is basically intended for ***depended items***, i.e., items that are part of a product assembly. In such cases, the inventory demand is zero most of the time, and requires the entire quantity at the assembly planning period.

A part-period balancing (also known as least total cost) gives better results for most items so that their requirements are established by the time of the delivery order date, the product structure and the routing. A part-period means one part is held in inventory for one period. The total number of part-periods, then, is the number of parts held in inventory multiplied by the number of periods held. Each part-period incurs a certain carrying cost. Thus, whether three units are held for two periods or two units are held for three periods, the number of part-periods is six and the carrying cost is six times that for one part-period. When the accumulated carrying cost exceeds the order costs, an order is planned.

The Just-In-Time (JIT) manufacturing philosophy eliminates the question of economic lot size and relates it to the production plan.

The number of units to be manufactured in any one lot depends primarily upon the type of manufacturing involved. If the product is to be manufactured strictly to a sold-order, the quantity to be made will usually equal that required by the customer's order plus a certain overage or allowance for rejects during processing. It is customary, where the vendor manufactures quantity products specifically to the customer's order, for the customer to consider that the order is complete if the delivery quantity is within 10% over or under the purchased quantity.

Where manufacturing is set to a weekly or monthly schedule, the quantity to be manufactured for the period is based on the arrival or backlog of sales orders subject to any limitations in the manufacturing capacity during the period.

Where manufacturing is done to replace depleted inventory of stock, the lot size to be manufactured will usually be based upon the principles of economic lot quantities. Under this principle, the quantity to manufacture is that for which the sum of the set-up and other preparation costs and the cost of processing the article manufactured is at a minimum. Naturally, this theoretical quantity is frequently affected by such factors as the availability of plant resources.

Conventionally, the processing cost is regarded as independent of the set-up and other preparation costs. The roadmap method generates a process as a function of the quantity. For example, for a low quantity, the mathematics solution that generates the process will recommend using one machine, the one resulting in a minimum value per part. For very high quantity, the recommended process will select the best machine for each technological operation. For a medium quantity, the recommended process will be a compromise between the different machines.

The compromise should consider the extra processing cost compared to the extra set-up cost. To get such results, the set-up cost and other preparation costs (such as extra scheduling, inspection, transportation, interest on capital, inventory carrying cost, etc.) are computed per individual item, and regarded as the penalty to be paid whenever a change in machine is made. Its value is the total cost divided by the quantity.

Thus, the recommended process follows exactly the definition of the economic lot size, which is the quantity to manufacture as determined by the minimum cost for the sum of the set-up and other costs of preparing and processing the item.

1.2 Determining Lot Size by the Roadmap Method

Economic lot size can be formalized as: Given a required quantity, what is the economic quantity to be manufactured?

With a roadmap, a second problem is automatically presented: What is the best process to use?

These two problems may be solved by the same roadmap solution. In order to determine the economic processing quantity, a loop program is initiated in the roadmap for solutions with varying quantity, followed by simulation of the processes recommended.

Table 4.1 Resource—operations roadmap for part "PLATE"

Operation	TP	Priority	REL	M #1	A #2	C #3	H #4	IN #5	E #6	Min. cost
010	0.47	0	0	2.28	1.86	1.79	99	*1.62*	2,36	1.62
020	0.17	010	0	1.08	*0.96*	1.23	99	1.22	1.18	0.96
030	0.31	020	0	1.64	1.38	1.36	99	99	*1.12*	1.12
040	1.89	030	0	7.96	6.12	*3.57*	99	99	4.28	3.57
050	0.24	010	0	1.36	*1.17*	1.39	99	1.32	1.48	1.17
060	4.16	050	0	17.04	12.93	*6.75*	99	99	8.82	6.75
070	0.03	020	0	*0.52*	0.54	0.97	0.69	1.03	0.56	0.52
080	0.22	070	0	1.28	1.11	1.24	*0.88*	1.22	0.94	0.88
090	0.20	080	0	1.20	1,05	1.20	*0.86*	99	0.90	0.86
Total	7,69			34.36	27.12	19.50			21.64	17.45

For example, the roadmap for part "PLATE" is given in Table 4.1.

Assume that the set-up cost for each machine is 30 (costs may vary for each machine). For a quantity of one, the set-up cost exceeds the cost of using one machine, in this case, machine #3, which is 19.50.

Therefore, there is no sense in using the roadmap to search for the best compromise, and the total cost of processing this item in a quantity of one is the sum of the set-up and the processing cost, i.e., 30.00 + 19.50 = 49.50.

On the other hand, for a quantity of 10,000, the penalty for each machine change will be 30/10,000 = 0.003, which is negligible; therefore, one may consider that there is no penalty in changing machines and can select the best machine for each operation. In this case, the recommended process is as follows:

Machine 5	Operation 010	1.62
Machine 2	Operation 020	0.96
Machine 6	Operation 030	1.12
Machine 3	Operation 040	3.57
Machine 2	Operation 050	1.17
Machine 3	Operation 060	6.75
Machine 1	Operation 070	0.52
Machine 4	Operation 080	0.88
Machine 4	Operation 090	0.86
	Total cost	17.45

In this sequence of operations, nine set-ups have to be added, which amount to 9 × 0.003 = 0.027, for a total cost of 17.477. This total cost may be decreased by examining the priority column and the machines that appear more than one time. Machine 4 can perform operations 080 and 090 in one set-up. Operation 050 can be performed after operation 020 on machine 2 and, thus, the number of set-ups may be reduced to 7.

For a quantity of 10 PCs, the penalty will be 30/10 = 3. This penalty should be added even for one machine change, which means that, at most, the processing cost might be the minimum cost for each operation (17.45) plus one additional set-up (3.0), which adds up to 17.45 + 3.0 + 3.0 = 23.45. While using only one machine, machine 3, which gives the minimum cost, the total cost will be 19.50 + 3 = 22.50.

Table 4.2 The effect of lot size on total processing cost

Quantity	Machines	Total cost
1	3	49.5
2	3	34.5
5	3	25.5
10	3	22.5
20	3	21.0
30	3	20.5
40	3 & 6	19.98
50	3 & 6	19.68
60	3 & 6	19.48
70	3 & 6	19.34
80	3 & 6	19.24
90	3 & 6	19.15
100	3 & 6	19.08
125	3 & 6	18.96
130	5 & 6 & 3	18.94
150	5 & 2 & 6 & 3	18.80
200*	5 & 2 & 6 & 3	18.55
300*	5,2,6,3,1,4	18.25
500*	5,2,6,3,1,4	17.93
1000*	5,2,6,3,1,4	17.69

*Note that the increment of the quantity is changed

For a quantity of 50 PCs, the penalty will be 30/50 = 0.6. Checking the probability of using more than one machine indicates that, for two machines, the minimum cost (17.45) will be increased by 2 × 0.6 = 1.2 and the total will be 17.45 + 1.2 = 18.65. If using one machine (machine 3), the total cost will be 19.50 + 0.6 = 20.1. This means that it is worthwhile to solve the roadmap, by its mathematic algorithm, for this quantity.

To check the cost of processing part “PLATE”, the roadmap was solved with a loop program, which changed the quantity by an increment after each solution and recorded the results. These results are shown in Table 4.2.

It seems that as the quantity increases, the processing cost reduces. At a certain quantity, the decrease in processing cost is negligible, and it is recommended to consider this ***quantity as the economic lot quantity***.

The decision can be made automatically by specifying the rate of change or by management decision, while having the additional data as to number of machines involved in the process, the cost contribution of each machine, if needed, and the cost difference as a function of the quantity.

The processing cost will be reduced in a curve, as shown in Fig. 4.2.

For example, the economic lot size is regarded as the quantity for which the change in cost is less than 0.05. In this case, the economic lot size is 125 units. At this quantity, the cost is 18.96, while, for the next quantity of 130 units, the cost is 18.94.

The last four entries in Table 4.2 may cause confusion regarding the lot size decision, as it is greater than the automatic limits. This effect is due to the change in the increment of quantity from 10 to 50 units and then 100 units. Considering a constant increment, the decision is correct. These added four lines in the table are mainly for manual decision-making by management, giving them more comprehensive data in making a manual decision.

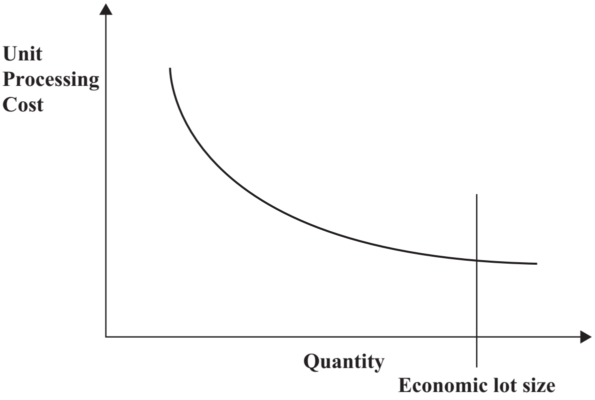

Fig. 4.2 Economical lot size determined by the roadmap

The computed economic lot size is merely a starting point and must not be regarded as an unalterable decision. It depends on the type of manufacturing. In manufacturing strictly to a customer order, the overall order quantity has to be delivered at the specified date. It must not mean that this quantity will be the manufacturing batch size.

If the ordered quantity is smaller or equal to the economic order quantity, the order quantity will be the batch size. However, if the order quantity is larger than the EOQ, then a check should be made as to whether it will be more economical to split it into several suborders. The number of suborders should be computed by Eq. (4.1).

$$\text{Number of suborders} = (\text{Confirmed order quantity}) / (\text{Economic lot size}) \quad (4.1)$$

The number of suborders should be an integer. It is recommended to round the mathematics result of Eq. (4.1) to the nearest integer, (i.e., 2.4 will become 2 and 2.6 will become 3)

The quantity in each suborder is computed by Eq. (4.2)

$$\text{Manufacturing batch size} = (\text{Confirmed order quantity}) / (\text{Number of suborders}) \quad (4.2)$$

The delivery date for the suborders is computed in such a way that the finished ordered products will be continuous; Fig. 4.3 demonstrates the delivery dates in the case in which an order was split into three suborders. Suborder 3 (the last one) keeps the delivery date of the original order.

The time for the last operation of the order, multiplied by the batch size (as computed by Eq. (4.2)), results in the offset time of the delivery dates for the suborders. Suborder 2 will be the delivery date as stated in the order minus the time to perform the last operation of suborder 3. Suborder 1 will be the delivery date of suborder 2 minus the time to perform the last operation of suborder 3. By this method, the flow of the order product will be continuous and uninterrupted. This method is similar to the overlap method of reducing lead time. By the creation of suborders, each with a

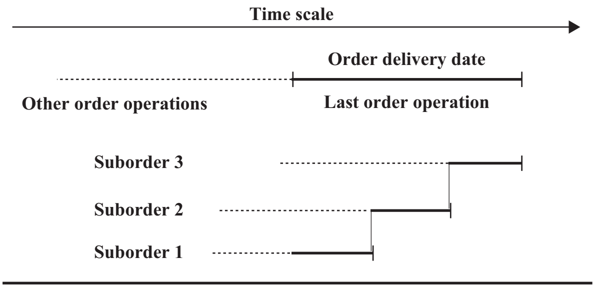

Fig. 4.3 Delivery date for suborders

batch size close to the economic order quantity, the SPT rule of scheduling theory has been followed, and scheduling will improve.

2 Maximum Profit Process Plan

Routing in the roadmap method is considered a variable, and is determined in the roadmap at the time of need. However, in some cases, a starting routing is needed. The expected criteria of optimization are maximum production or minimum cost. These two criteria result in completely different routines, as shown in Table 4.1. The question of which one to use is a management decision and not an engineering decision.

This question usually depends on the number of orders, plant load, and seasonal products, number of orders being the most likely. During a normal period, when there is ample time to meet a delivery date, using the minimum criterion of optimization makes sense. For rush orders, such as a product that is specific to a certain holiday (after which the product is usually unsalable), if the delivery date is in jeopardy, the maximum production criterion of optimization would be preferred.

Another consideration is use of the routing that solves a bottleneck, overloaded or under-loaded problem in the scheduling and capacity system.

It makes sense to use ***maximum profit*** criterion of optimization as a starting routing. However, this criterion is mathematically undefined and is subsequently seldom used. Maximum profit depends on the selling price of the product, and therefore, is not an engineering parameter.

The roadmap method allows use of the maximum profit criterion of optimization routing. This criterion is defined as the process plan that, in a certain period of time, will result in the maximum profit. As shown in Fig. 4.1, the process plan generated indicates the processing time and cost of each alternative. These two values are used to select the routing. If time is important, then the maximum production criterion of optimal routing is used. If the processing cost is important, then the minimum cost criterion for optimal routing is used. In the maximum profit criterion of optimization, both these values are considered.

The profit of a single item is the difference between the net selling price (Sale) and the processing cost (Cost). Single Item Profit (SIP) is therefore computed by:

$$\text{SIP} = \text{Sale} - \text{Cost} \tag{4.3}$$

where cost is the cost roadmap solution, $C_{i,j}$ (the sum of all operations $_i$ on any resource $_j$).

The total profit in a period is the SIP—Single Item Profit—multiplied by the number of items produced in the period (Quantity). The quantity that will be produced during the period is the number of minutes during the period (PM) divided by processing time in minutes to produce an item (RT), thus:

$$\text{Quantity} = \text{PM} / \text{RT} \tag{4.4}$$

where processing time (RT) is the solution from the time-roadmap.

The Total Profit in a Period (TPP) is then:

$$\text{TPP} = \text{Quantity} * \text{SIP}. \tag{4.5}$$

Equation (4.5) may be written as:

$$\text{TPP} = (\text{PM} / \text{RT}) * \text{SIP} = \text{PM} * \{(\text{Sales} - \text{Cost}) / \text{RT}\}. \tag{4.6}$$

Equation (4.6) indicates that the process alternative resulting in total profit per period (TPP) is actually independent of the length of the period, as it is a linear function of that length. The engineering variables in Eq. (4.6) are Cost and Time (RT) and the management variable is the Sales price. Therefore, in computing the maximum profit process plan, we may ignore the length of the period (PM) and use instead a fixed value of profit at a unit period which is a Relative Total Period Profit (RTPP):

$$\text{RTPP} = (\text{Sales} - \text{Cost}) / \text{RT}. \tag{4.7}$$

To demonstrate the effect of the process plan alternative on the profit, let us again use the roadmap for the part "PLATE", as shown in Table 4.1.

The roadmap is used to prepare 14 routing alternatives, 11 for cost criterion and 3 for time criteria, presented in Table 4.3.

Solving the roadmap for the recommended economic lot size of 125 units per batch, and a set-up cost of 30, results in a minimum cost optimization with item cost of 18.73 and processing time of 12.93 minutes.

Over a period of 8 hours, or 480 min, the quantity of items that will be produced is 480/12.93 = 37.123 items. If the selling price of each item is 50, then the daily profit will be: 37.123 * (50 − 18.73) = 1160.84.

Using the maximum production process with the above conditions will result in an item cost of 34.36 and a processing time of 8.59 min. The number of

Table 4.3 Process planning alternatives

Alt	Machines	Cost	Time
1	3,6 *Cost*	*18.73*	*12.93*
2	1,3,6	19.30	11.85
3	2,3,6	18.76	11.95
4	5,6,3	18.74	13.05
5	6,3	19.24	12.37
6	6	21.64	10.83
7	2,6	21.16	10.23
8	5,6	21.14	11.50
9	2,4	26.94	10.30
10	1,2,4	27.60	10.47
11	5,2,4	26.94	11.54
12	1 *Time*	*34.36*	*8.59*
13	2,1	34.18	8.88
14	2	27.12	9.04

parts that can be produced per day is 480 / 8.59 = 55.88 and the profit per item is (50 – 34.36) = 15.64; therefore, the profit per day will be 55.88 * 15.64 = 873.95.

Actually, neither of these processes gives the maximum profit.

The equation for computing the Relative Total Period Profit looks very simple; however, as shown in Fig. 4.1, the Cost and Time (RT) depends on the criterion of optimization used, and the alternatives selected. Each alternative results in a different cost and processing time.

Similarly, the sales price may be regarded as a variable to be determined by management. The question is whether management has a methodology for arriving at the “best” selling price.

The concepts relevant to the present problem are:

- Engineering stages are incorporated into production and management stages
- All stages of the manufacturing process work toward a single objective; each stage considers the problems and difficulties of the other stages
- Each decision is made by the qualified expert
- Each decision is based on real facts and not on assumptions

Engineering is not qualified to set the product selling price, and management is not qualified to generate a process plan. Engineering should supply data to management in order to make decisions based on real facts and not on assumptions. The system for determining the process that will result in maximum profit is therefore divided into three stages.

- The first stage is to generate data
- The second stage is market research
- The third stage incorporates the first two stages to determine the maximum profit process plan.

These stages are described in the following sections.

Table 4.4 RTTP as a function of selling price

					Sale pirice						
Alt	Machines	Cost	Time	30	40	50	60	70	80	90	100
1	3,6 *Cost*	*18,73*	*12.93*	0.872	*1.927*	2.418	3.192	3.965	4.739	5.512	6.285
2	1,3,6	19.30	11.85	0.902	1.747	2.591	3.435	4.278	5.122	5.966	6.810
3	2,3,6	18.76	11.95	*0,941*	1.778	2.614	3.451	4.288	5.125	5.962	6.798
4	5,6,3	18.74	13.05	0.863	1.629	2.395	3.162	3.928	4.694	5.461	6.226
5	6,3	19.24	12.37	0.870	1.681	2.491	3.306	4.110	4.920	5.730	6.539
6	6	21.64	10.83	0.772	1.695	*2.619*	3.542	4.465	5.389	6.312	7.235
7	2,6	21.16	10.23	0.864	1.640	2.510	3.379	*4.774*	5.752	6.729	7.707
8	5,6	21.14	11.50	0.770	1.640	2.510	3.379	4.249	5.118	5.988	6.857
9	2,4	26.94	10.30	0.297	1.268	2.239	3.210	4.181	5.151	6.122	7.093
10	1,2,4	27.60	10.47	0.229	1.182	2.135	3.089	4.042	4.995	5.948	6.902
11	5,2,4	26,94	11.54	0.265	1.137	1.998	2.865	3.731	4.598	5.464	6.331
12	1 *Time*	*34.36*	*8.59*	–	0.656	1.821	2.985	4.149	5.313	6.477	7.641
13	2,1	34.18	8.88	–	0.655	1.782	2.908	4.034	5.160	6.286	7.412
14	2	27.12	9.04	0.318	1.425	2.531	*3.637*	4.743	*5.850*	*6.956*	*8.062*

2.1 Constricting RTPP Table

The data are generated by running a roadmap and generating process alternatives. These alternatives are shown on the left side of Table 4.4, which indicates the alternative number, the machines involved in the process, and the cost and time for each process alternative.

The minimum cost process plan is alternative 1, and the maximum production process plan is alternative 12. If the sales price is unknown, different prices are examined, as shown on the right side of the table.

For each alternative, the relative total period profit is computed by Eq. (4.7); the results are given in Table 4.4. The alternative that results in the maximum relative total period profit appears in bold type in Table 4.4.

To calculate the total profit, the values in the table must be multiplied by the duration of the period. Following the example used earlier, the results can be computed by constructing a table of relative total period profit.

For example, the unit profit at a sales price of 50 for maximum production alternative 12 is 1.821. For a period of one day (480 min), the profit would be 480 * 1.821 = 874.08.

For minimum cost, alternative 1 would give a total profit per day of 2.418 * 480 = 1160.64 (the small difference in profit between the two examples is due to rounding).

Examination of Table 4.4 indicates that the "best" process plan for maximum profit criterion by selling price is as follows:

Product sales price	30	40	50	60	70	80	90	100
Recommended process alternative	3	1	6	14	7	14	14	14

This indicates that there is no pattern for predicting which process alternative will result in maximum profit. Therefore, a simulation should be done.

Table 4.5 Market research results

Product price	30	40	50	60	70	80	90	100
Quantity	10,000	9,300	8,200	7,000	6,000	4,600	3,500	2,500
Relative Quantity	1.00	0.93	0.82	0.70	0.60	0.46	0.35	0.25

2.2 Market Research

To determine the process that will result in maximum profit, the selling price must be known. Table 4.4 lists several possible selling prices (from 30 to 100).

This table provides data for decision-making. The task is to determine which process plan alternative (assuming that the optimum lies within these limits) should be selected.

Sales price affects sales quantity as well. Such data are obtained through market research. Because such research is beyond the scope of this book, we will use the results shown in Table 4.5. The table shows that, as the price goes up, the sales quantity goes down, which is reasonable. In order to work with relative values, the third row in Table 4.5 was added, showing the quantity at a selling price of 30 to be 100 %.

Which price to set in order to achieve maximum profit is determined by using Tables 4.4 and 4.5, and is discussed in the next section.

2.3 Setting Selling Price and Maximum Profit

The selling price that will result in the maximum profit per period is a function of the quantity required per period and the routing that result in the maximum profit per selling price. These two parameters act in opposite directions, as shown in Fig. 4.4. Therefore, there is an optimum selling price that will result in a maximum profit per period.

As these two parameters have different dimensions, they cannot be used to compute the optimum. Therefore, both are transformed into dimensionless values, called the index. The index is the ratio of the value of each selling price for maximum profit divided by the value of a selling price of 30.

These values are listed in Table 4.6 and shown in graphic format in Fig. 4.5.

The selling price and routing that will result in the maximum profit per period is computed using Table 4.6 as follows.

The first line indicates the selling price from Tables 4.4 and 4.5. The second line is a summary of Table 4.4, indicating which process alternative results in the relative total period profit.

The third line uses the maximum relative total period profit that refers to the alternate routing as indicated in the second line of Table 4.4.

The fourth line converts the relative total period profit into index numbers, assuming that the relative total period profit at a selling price of 30 is 100 %. This is

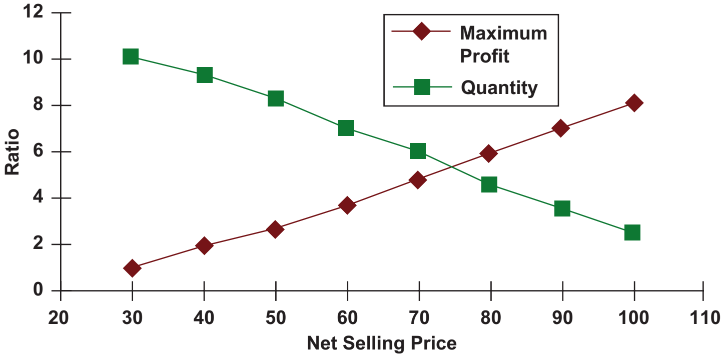

Fig. 4.4 Curve for quality and profit as function of selling

Table 4.6 Selling price and routing decision table

Selling price	30	40	50	60	70	80	90	100
Alternative process no.	3	1	6	14	7	14	14	14
RTPP—relative value	0.941	1.927	2.619	3.637	4.743	5.850	6.956	8.062
RTPP—relative index	1.00	2.048	2.783	3.865	5.073	6.217	7.392	8.567
Relative quantity	1.00	0.93	0.82	0.70	0.60	0.46	0.35	0.25
Result index	1.00	1.905	2.282	2.705	*3.044*	2.860	2.587	2.142

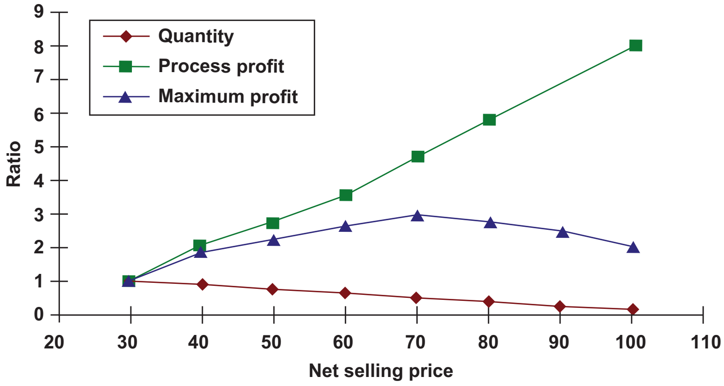

Fig. 4.5 Index of quantity and profit as function of selling price

Table 4.7 Profit as a function of selling price

Selling price	30	40	50	60	70	80	90	100
Alternative process no.	3	1	6	14	7	14	14	14
Cost of alternate	18.76	18.73	21.64	27.12	21.16	27.12	27.12	27.12
Quantity	10,000	9,300	8,200	7,000	6,000	4,600	3,500	2,500
Maximum profit	112400	197811	232552	230160	293040	243248	220080	182200
Result index	1.00	1.905	2.282	2.705	3.044	2.860	2.587	2.142

computed by dividing each relative value by 0.941—the relative total period profit at a selling price of 30.

The fifth line copies the relative quantity from Table 4.5.

The sixth line is the result index, and is computed by multiplying the relative index (line 4) by relative quantity (line 5). The object is to choose the selling price and process plan alternative to match the column that has the largest result index.

For the part "PLATE", as shown in Table 4.6, the recommendation is to set the selling price at 70 and use routing alternative 7.

2.4 *Testing the Algorithm*

The selling quantity per period at a net selling price of 70 is 6000 units. Alternative 7 calls for using machines 2 and 6; the processing cost would be 21.16 and the processing time 10.23 min. The profit per period would be (selling price—the cost) multiplied by the quantity, or

$$(70 - 21.16) * 6000 = 293,040.$$

Use of the same equation for the other net selling prices is shown in Table 4.7.

2.5 *Management Control*

This section proves that neither the minimum processing cost, nor the maximum production criteria of optimization, nor the higher selling price will result in maximum profit. A proposed method of how to arrive at the optimum selling price and selection of the appropriate routing was presented.

Chapter 5
Traditional Production Planning

Abstract The task of traditional production planning and control is to plan and produce the products according to management's orders and policy. It includes the following stages: master production schedule, material requirement planning, capacity planning, shop floor control, and inventory management and control. The market has put forward software to perform these tasks. Management may decide to prepare internal software or to purchase the software which is as close as possible to that which meets its managing policy.

This chapter describes the techniques of each individual stage and indicates the decisions that should be made by management that affect company performance. The "management control section" notes may be used in choosing vendor software.

1 Introduction

Manufacturing, as defined in the dual tasks of production planning and control, exists to meet the objectives defined by management. These objectives specify what products are to be produced, in what quantity, on what dates, and at what cost. The sources of these data can be confirmed customer orders, forecasts of future demand, or a combination of both.

The major objectives are:

- Meeting delivery dates.
- Keeping capital, tied down in production, to a minimum.
- Minimizing manufacturing lead time.
- Minimizing idle times on resources.

Theoretical production planning and scheduling is actually a very simple task. The plant gets orders that define the product, quantity and delivery dates. The resources of the plants are known, the product bill of material is known. The task of production scheduling is to make sure that the orders will be ready on time. That's all.

G. Halevi, *Industrial Management—Control and Profit,* Lecture Notes in Management and Industrial Engineering 1, DOI 10.1007/978-3-319-03470-6_5,
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1.1 Survey of Production Planning Methods

It seems strange that, in order to meet this simple task, over 110 complex production planning methods were proposed. Yet the search for "THE" method carries on. The following is a list of proposed methods, in alphabetical order (not order of importance).

Agent-driven approach The objective of this approach is to design a factory information system with the capabilities of computer-integrated manufacturing. The agent-based architecture interprets the components of a manufacturing system as humans associated with software agents. These agents are connected to message-conveying blackboards, each of which is associated with a manufacturing planning and control domain.

Agile Manufacturing The objective of this approach is to make the transition from mass production to agile manufacturing. Agile manufacturing can be defined as the capability to react quickly to changing markets, to produce high quality products, to reduce lead times, and to provide a superior service. The method is improvement of enterprise communications among all disciplines engaged in the manufacturing process.

Autonomous enterprise The objective of this approach is to manage autonomy, that is, to maximize freedom without letting the system devolve into chaos.

Bionic manufacturing This system is an architecture made up of totally distributed independent autonomous modules that cooperate intelligently, creating a future manufacturing system that responds to anticipated future manufacturing needs**.**

Cellular manufacturing This is a modern version of the concept of a group technology work cell. The objective of the cellular approach is for only the amount of product needed by the customer to be produced. It usually requires single-piece flow or, at the very least, small batch sizes. The method for meeting this objective is to form a family of parts, and, by rearranging plant processing resources, to form manufacturing cells.

Common-sense manufacturing (CSM) The objective of this approach is to regulate work in process, and enable the manufacturing line to meet the production goal. It allows operations teams on the shop floor to regulate and adjust the working plan.

Computer-integrated manufacturing This is the complete integration of all functional areas of the company into an interactive computer system, from engineering and manufacturing to marketing and management. Computer integrated manufacturing is a technology that combines all advanced manufacturing technologies into one manufacturing system that is capable of producing and distributing a diversified product through an innovative, flexible process that optimizes resources to achieve required standards of quality, constancy, cost, and delivery.

Cycle Time Management This is a manufacturing philosophy dedicated to reducing inventory and waste. Respect for workers is the vehicle that promotes continual improvement. For too long, factory workers have been misguided, misused, mismanaged and essentially treated as drones. Worker involvement in all aspects of CTM leads to manufacturing excellence.

Digital factory This is a revival of the early 1980s notion of "Factory of the future" and the "Unmanned factory", when robots were in their infancy. Today, technology enables us to achieve some of those dreams. The objective of this approach is to support the development of a product from its conception throughout its production. It uses computerized manufacturing resources and industrial robots as the tools for production. Digital factory is defined as a computerized solution that enables manufacturers to plan, simulate and optimize a complete factory, its production lines and processes at every level of detail.

Enterprise Resource Planning—ERP This approach is intended to improve enterprise communications among all disciplines in the company engaged in the manufacturing process, as well as with customers and suppliers. ERP is a revolution in the "production engine" of most manufacturers worldwide. By uniting numerous disparate systems under one software umbrella, companies are facilitating best practices and using ERP to drive dramatic cost reductions and increased efficiencies.

Flat organization This approach calls for simplification of the organizational procedures by removing any unnecessary level of line management. The number of organizational levels should be kept at a minimum to promote a faster and more cooperative response, where responsibility will be on the work force.

Flexible manufacturing system (FMS) The objective of this approach is to produce medium to low quantities with the efficiency of mass production. A flexible manufacturing system can be defined as a computer-controlled configuration of semi-independent work stations and a material handling system designed to manufacture more than one kind of part efficiently at low to medium volumes.

Fractal manufacturing This system, like bionic manufacturing (see above), is an architecture made up of totally distributed independent autonomous modules that cooperate intelligently, creating a future manufacturing system that responds to anticipated future manufacturing needs.

Global manufacturing system This is a computer-oriented manufacturing philosophy aimed at global optimization of the manufacturing process. It utilizes the power and capabilities of present day computers to meet the requirements of the manufacturing process.

Integrated manufacturing system (IMS) This is a system that recognizes and supplies computer services independently to each phase of the manufacturing cycle, while, at the same time, maintaining a database that serves as a single source of data for all company activities and applications. Basic data are maintained in an up-to-date and accurate condition so that information can be provided on demand.

Just in Time manufacturing This approach eliminates any function in the manufacturing system that burdens the company with overhead, impedes productivity, or adds unnecessary expense to the company's operating system. The biggest misconception about JIT is that it is an inventory control system. Although structuring a system for JIT will control inventory, that was not the major intention of the developers of the method. Simply put, just in time manufacturing means having just what is needed, just when it is needed. It means inventory and all other job auxiliaries.

Kanban ("tag") This is a production planning and scheduling system based on a pull instead of a push system, with an additional emphasis on the goal of eliminating waste. Kanban is a powerful force for reducing manpower and inventory, eliminating defective products, and preventing the recurrence of breakdowns.

Lean manufacturing The objective of this approach is to cut waste, shorten the total manufacturing lead-time for a product, and implement continuous improvement. In practice, lean manufacturing, TQM and JIT all use the same tool.

Optimized production technology—OPT This approach was developed as a scheduling system. OPT governs product flow in the plant. The rules of OPT are derived for capacity constraints, especially bottlenecks. Both capacity and market constraints should be handled by the logistical system.

Supply chain management The objective of this approach is to provide suppliers and customers with a window into their supply chain so they can reduce inventory, better utilize plant capacity and cut communication costs. The potential cost savings can be tens of millions of dollars to the bottom line.

Theory of constraints This is a general manufacturing philosophy based on an understanding of the manufacturing processes and identification of its constraints. A constraint is anything that limits a system from achieving higher performance versus its goal. Initially, the system was developed as a scheduling system called optimized production technology (OPT, see above).

Total quality management (TQM) The objective of this approach is to satisfy the customer. Total quality management is not only concerned with the final customer who wants to buy a product without defect. The product and customer are understood in a wider sense than is normally applied in manufacturing

Virtual manufacturing This is defined as the manufacturing system the functionality and performance of which is independent of the physical distance between system elements. Virtual manufacturing is aimed at reducing product development time. Many companies understand very well that reducing product development time is a highly effective way of improving return on investment.

World-class manufacturing This focuses on how a system operates. While methodologies exist that focus on a design approach, such as business process re-engineering (BPR), the key strength of world-class manufacturing is in demonstrating operational processes, which maximize efficiency, to designers. For example, work-teams are often cited as a useful way of organizing workers. Teamwork is about how a system can operate, and so, work-teams are an operational issue.

Workflow management This focuses on improving the effectivity and efficiency of business processes within an organization. Inter-organizational workflow offers companies the opportunity to re-shape business processes beyond the boundaries of individual organizations. Workflow management controls, monitors, optimizes and supports business processes with the explicit representation of the business process logic that allows for computerized support.

1.2 Production Planning Dilemma

A common shared rationalization is that production planning is a very complex task. The production environment is a dynamic one. Machines fail, tools break, employees miss work, orders change, parts are rejected and reworked, power failures occur, loads and available capacities prove mismatched, promised delivery dates prove unrealistic, etc.

Such complexity is a result of the traditional approach and not a built-in necessity. Most of the disruptions arise out of the stiffness of a system in which decisions are being made too early in the manufacturing process. Through a different approach, one that will introduce flexibility to the manufacturing process, most of the disruptions can be solved by elimination.

Both the traditional method and the flexible method perform production planning tasks in a systematic way through the following stages:

- Master production schedule.
- Material requirement planning.
- Capacity planning.
- Shop floor control.
- Inventory management and control.

The stages are the same but each employs different technology. These two technological systems will be detailed separately. This chapter is devoted to the traditional approach while the next chapter will be devoted to the flexible approach.

2 Traditional Method

The traditional approach to design of manufacturing systems is the hierarchical approach, the nature of which has been previously discussed.

2.1 Master Production Schedule

The master production schedule is a management tool with a “look ahead” feature—a tool that is needed in order to plan the future of the company. It provides simulations of capacity requirements for different marketing forecasts, purchasing of new equipment, and profit or loss forecasts. It indicates the necessary planning with respect to shop-floor space, warehousing space, transport facilities and manpower.

The master production schedule is the driving force behind more detailed production planning. However, it is also a management tool for controlling and planning the future of the company, such as:

- Resource requirement planning.
- Human resource requirement planning.
- Cash flow planning.
- Profit forecasting.
- Budget and management control.

The master production schedule transforms the manufacturing objectives of quantity and delivery dates for the final product, which are assigned by the non-engineering functions of the organization, into an engineering production plan.

The master production schedule is a coordinating function among manufacturing, marketing, finance, and management. It is the basis for future detailed production planning. Its main objective is to plan realistic production programs that ensure even utilization of plant resources—people and machines. This will be the driving input for detailed planning and will guard, as much as possible, against overload and underload of resources at all times. If formulated properly, the master production schedule can serve as a tool for marketing personnel in setting delivery dates.

The master production schedule is the phase where delivery dates are established for the production phases. Thus, it controls the relative priorities of all open shop orders. If the master production schedule is unrealistic in terms of capacity, many shop orders will be rush orders with high priority, and the entire capacity planning system will malfunction. To maintain valid shop priorities, the master production schedule must not exceed the gross productive capacity in any period.

Planning the master production schedule is a difficult task, since it normally covers a wide range of products and represents a variety of conflicting considerations, such as demand, cost, selling price, available capital for investment, and company marketing strategy.

It is not purely engineering work. The engineers supply information and can simulate different strategies, but the final decision lies with ***management***. In some companies, the sales department is responsible for preparing the master production schedule. In any case, production engineering must be involved in order to ensure a realistic program.

The importance of master production scheduling is becoming more and more recognized. It is now acknowledged as the key to the success or failure of the detailed production plan. However, all *mathematicians and economists* who develop economic models for production, such as sequencing, economic lot size, and safety stock, still tend to assume that there is a master production schedule. It is external to their area of interest, and the quality of the master production schedule does not actually matter to them; they are willing to build a whole theory on sand. It is a complicated problem, so let us leave it alone. The small amount of literature available on this subject merely states its importance and that it should be done; numerous articles have been published on inventory management, scheduling, and forecasting, but to the best of my knowledge, not a single one has been devoted to the topic of master production scheduling.

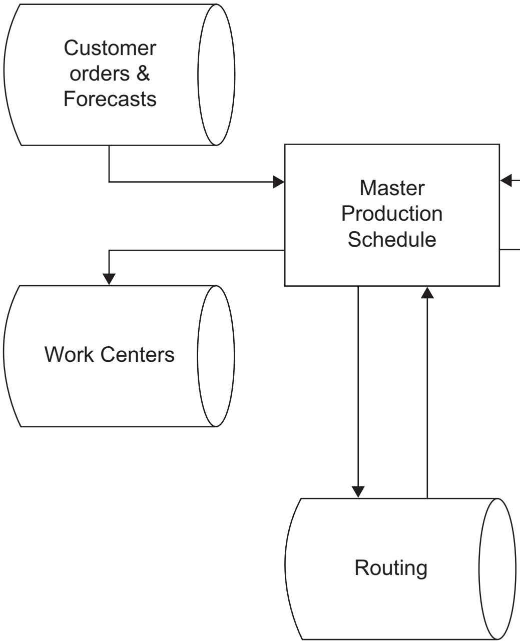


Fig. 5.1 Master production scheduling computation

It is recognized that it is impractical to try out all the possible combinations. Thus, human judgment is necessary to predict the most likely combination, and only that combination will be simulated by the system. Basically, from a capacity point of view, the master production schedule represents long range capacity planning. Suppose that the company plans to produce certain products in certain quantities with different delivery dates. The company needs to know the impact of the plan in terms of production capacity. The computations are as shown in Fig. 5.1. The computation system employs the following files:

- The order file—includes the details of all orders.
- The item master file—lists all available products and items.
- The product structure file—lists all the items constituted in the product, the relationship between them and the quantities for each assembly and subassembly.
- The routine file—indicates how each item and subassembly is being made; it tells in what work centers processing takes place and the sequence of operations, also providing such lead-time information as set-up time and standard machining time.
- The work center file—lists the available work centers and their available capacity.

By means of the data stored in these files, it is possible to break down each product in the order file to its components and accumulate the workload at each work center by time and period.

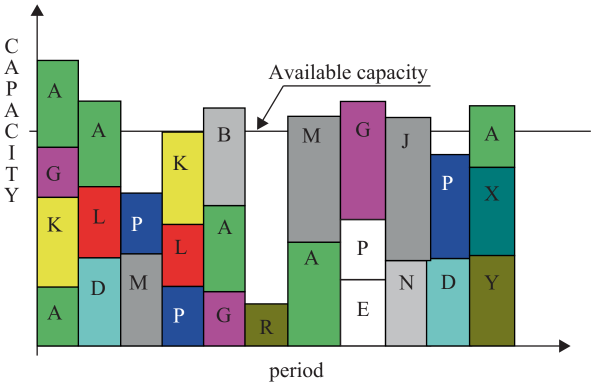


Fig. 5.2 Overall load company profile by items

We can now take a cross- section along different axes, in order to obtain useful information. Figure 5.2 presents an overall load capacity profile of the shop, which shows the profile of normal available capacity and total required capacity per period. This profile is for general knowledge only. If the required capacity is greater than the available capacity, it indicates that the sales forecast exceeds plant capabilities. On the other hand, if the required capacity is equal to or less than the available capacity, it indicates that the plant, as a unit, is underloaded.

However, in both cases, there might be some work centers that are overloaded and some that are underloaded.

To examine this, a work center load profile per period is developed for each work center in the shop in a similar manner as the overall shop load profile (Fig. 5.2). From these profiles, one can learn which work centers in the plant are overloaded and which are underloaded. One can also learn if the overload occurs at all periods and to what extent, or if there is a mixture of overload and underload periods and what the average load is.

These profiles provide the information necessary for such decisions as whether to purchase new resources for highly loaded work centers, whether to work extra shifts or overtime in moderately overloaded work centers, and whether to balance the load by working overtime or extra shifts at certain periods, changing delivery dates, changing lot sizes, subcontracting, or increasing the inventory buffer. Poorly loaded work centers can be eliminated by transferring their operations to other work centers.

If a decision is made to balance the load by changing product orders or lot size, information concerning the effect of each order on the total profile is needed.

Lot size in this context refers to the final product, not to its components. The existing models for lot sizing are usually single stage, taking into consideration the set-up cost, but ignoring the capacity of the work center. Using these models, the benefits gained due to economic lot sizing at one level of the product tree may be more than offset by its impact on other levels. Furthermore, these lot sizes are meddling with the master production schedule, since the previously balanced work center load is offset. These problems would not arise if the master production schedule took lot sizing into account.

The master production schedule is the driving force behind further detailed production planning. However, it is also a management tool for controlling and planning the future of the company, in such areas as:

- Resource requirement planning.
- Human resource requirement planning.
- Cash flow planning.
- Profit forecasting.
- Budget and management control.

2.1.1 Management Control

The load profiles, of all types, are a tool for management to make decisions. Routing is the dominant factor in constructing the different profiles, and can be optimized to result in maximum production or minimum cost. A maximum production routing is needed for resource planning and delivery dates. Minimum cost routing is needed for cash flow and budget. These two routings are extremely different in capacity.

Management must take an active role in making sure engineering has at least two types of routing and determining when they should use each one.

Period size might have an immense effect on the load capacity profile. A short period might highlight differences while a long period displays averages.

Period size must be a decision made by management, not engineering.

Lot size has an immense effect on the profile capacity per period, and on load balancing.

Lot size must also be a decision made by management and not engineering.

Management should direct engineering as to what type of load profiles they need and the shape they should take.

2.2 Requirement Planning System—RPS

A Requirement Planning System sets the goals for the production phases of the manufacturing cycle. It specifies what products are to be produced, the quantities, and delivery dates. Production activities are dependent on RPS; hence, they can be planned and are predictable. In addition, it includes activity planning in the area of purchasing, including the items needed, at what quantity and by which date. A third output is a list of items in inventory that are not needed at all (dead stock).

Production activities include plant shop manufacturing, as well as subcontracting operations to other shops, purchasing items, assemblies, subassemblies, and raw materials from external sources. At any point in time, numerous activities are underway in a working plant simultaneously. There are open shop orders, open purchase and subcontract orders, and items in storage between operations and activities. All of these activities must be considered when converting the master production schedule into production activities.

A working plant is a dynamic environment, subject to many changes and unplanned interruptions, which may lead to the accumulation of unused stock; these changes and interruptions might include:

- Customer orders being added or deleted; quantities and delivery dates being altered.
- Purchasing being restricted by package size, economic consideration, lot size, and changes in delivery dates.
- Interruptions in the shop causing early or late finish of jobs; reject rate being higher or *lower* than anticipated; these will cause imbalance in quantities of different items required for assembly, the controlling item being the one available in the smallest quantity; excess units of the other items are left over after assembly.

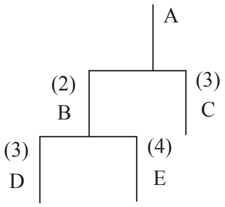
All of these factors lead to the accumulation of stock. This stock can often be utilized later in manufacturing. The objective of requirement planning is to plan the activities to be performed in order to meet the goals of the master production schedule, while accumulated stock is taken into account.

2.2.1 Manufacturing Activities Planning

Requirement planning is not a new concept, having gone previously under such different names as items balance sheet, activity planning, and inventory management. The logic and mathematics upon which it is based are very simple. The gross requirement of the end product for a specified delivery is given by the master production schedule. This requirement is compared against on-hand and on-order quantities and then offset by the lead time to generate information as to when assembly should begin. All items or subassemblies (lower-level items) required for the end product assembly should be available on that date, in the required quantity. Thus, the above computation establishes the gross requirement for the lower-level items.

The same computation is repeated level by level throughout the entire product structure, the net requirement of a level serving as the gross requirement for the lower level. Figure 5.3 shows an example of these computations.

The demand for product A is specified in the gross requirement row of the product A table. There are 40 units of product A in on-hand inventory, and there is an open order to assemble 40 units, which are scheduled for period 3. The demand for 20 units of product A in period 1 will be met from inventory. This will reduce the on-hand quantity to 20 units. The demand for 10 units of product A in period 2 will also be met from inventory, thus reducing the on-hand quantity to 10. An additional 40 units will be received in period 3, thus increasing the on-hand quantity to 50. The demand for 30 units in period 4 can again be met from inventory, reducing the on-hand quantity to 20. The demand for 30 units in period 5 will be partly covered by the 20 on-hand units, leaving a net requirement of 10 units. The demand for 30 units in period 6 is not covered; this results in an additional net requirement of 30 units. Since the lead time for assembling product A is two periods, the assembly of 10 units should start in period 3 and that of 30 units in period 4.



Product A

Lead time—two periods

Period		1	2	3	4	5	6
Gross requirement		20	10		30	30	30
Schedule receipt				40			
On hand	40	20	10	50	20		
Net requirement						10	30
Offset planned orders				10	30		

Subassembly B

Lead time—one period

Period		1	2	3	4	5	6
Gross requirement				20	60		
Schedule receipt							
On hand	90	90	90	70	10	10	10
Net requirement							
Offset planned orders							

Item C (purchased item)

Lead time—three periods

Period		1	2	3	4	5	6
Gross requirement				30	90		
Schedule receipt							
On hand	60	60	60	30			
Net requirement					60		
Offset planned orders		60					

Fig. 5.3 Manufacturing activity planning

Product A is composed of two units of subassembly B and three units of item C. Thus, there is a gross requirement of 20 units of subassembly B in period 3 and 60 units in period 4, while for item C, it is 30 units in period 3 and 90 units in period 4. There are 90 units of item B on hand, which covers the demand. Thus, there is no demand for items D and E. However, the 60 units of item C that are on hand, while totally covering the demand in period 3, will only partly cover that of period 4. This results in a net requirement of 60 items in period 4. Since the lead time for item C is three periods, the planned order must be offset to period 1.

Thus, the activities required to meet demand are:

1. Issue of a purchase order for 60 units of item C in period 1.
2. Issue of an assembly order for 10 units of product A in period 3.
3. Issue of an assembly order for 30 units of product A in period 4.

As one can see, the logic and mathematics amount to the simple equation:

$$\text{Net requirement} = \text{gross requirement} \; - \; \text{on} - \text{hand inventory} - \text{on} \\ -\text{order units.}$$

In spite of the fact that the logic and mathematics behind requirement planning are very simple, this phase of the manufacturing cycle is very difficult to implement. Figure 5.4 shows the relationship between requirement planning and other applications. The implementation calls for data from many applications and requires discipline in reporting.

The purpose of requirement planning is to plan manufacturing activities accurately by calculating the net requirement in conjunction with the production scheduling. However, if we treat each record of the master production schedule independently, the results will not be accurate: On-hand items will be allocated to orders that require them at a later date, while rush plan orders will be issued for the same items at an earlier date.

This situation is demonstrated in Fig. 5.5. Three end products are ordered: product A for period 9, product M for period 10, and product P for period 11. If we calculate the net requirements for each product independently according to ascending order of due date, we will start with product A. This product requires 100 units of item B in period 8.

Suppose that there is a free stock of 100 units of item B on hand. This quantity will be allocated to product A, and no net requirement will exist. Next, product *M* will be dealt with. This product requires 60 units of item B in period 7. Since the free stock of this item was utilized, a net requirement for this demand will result. Next, product P will be dealt with. This product requires 40 units of item B in period 6 and 40 units in period 9. Since there is no free stock, a net requirement will result.

These calculated results are unreasonable, since they call for planned orders of item B of 40 units in period 5 and 60 units in period 6 while keeping in stock 100 units not required until period 8. This could result in rush orders or in not meeting the due dates for products P and M. One would expect the calculations to allocate the free stock of 100 units as follows: 40 units to period 6 for product P, 60 units in period 7 for product M, and a planned order of 100 units scheduled to start in period 7 for product A.

The above example deals with only three orders that have common items. In practice, the number of such items might be much greater. In order to overcome this

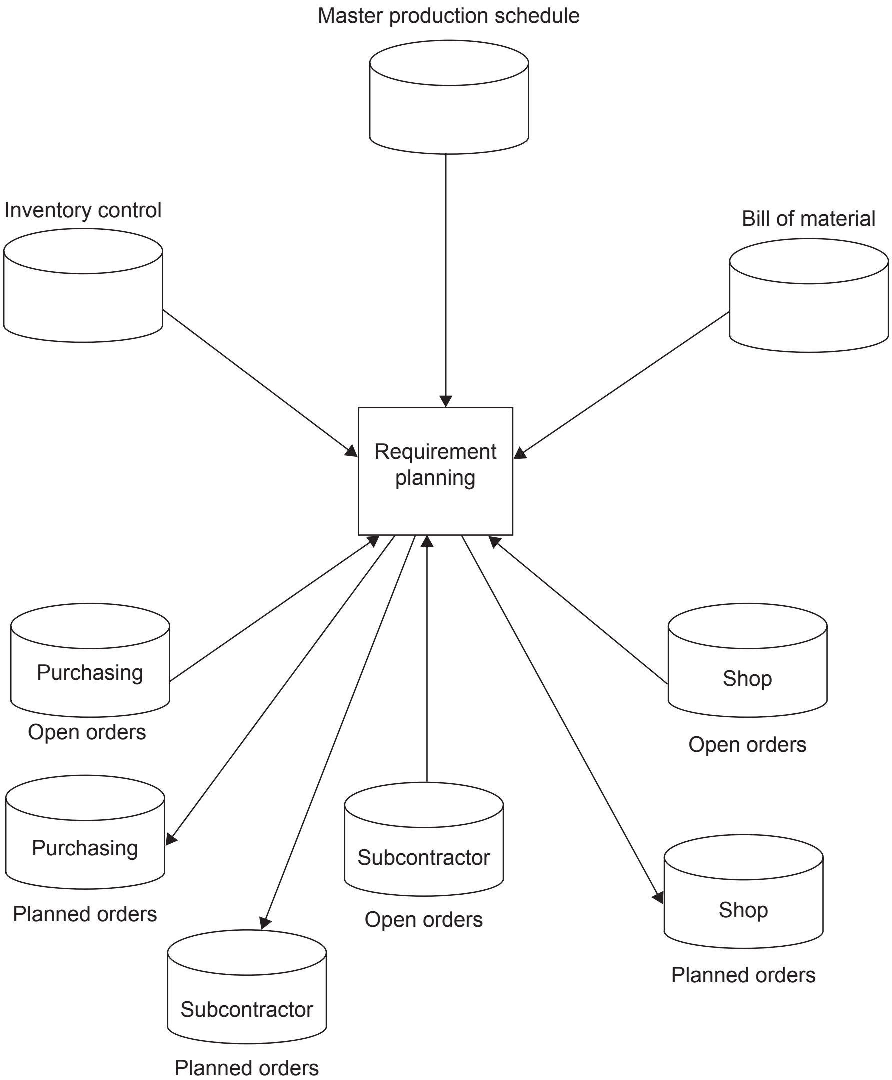


Fig. 5.4 The relationship between requirement planning and other applications

problem, the requirement planning calculations are carried out by using a low-level code and not by orders.

The low-level code is an indication of the lowest level at which an item is used in any products that have a low-level code of 00, or for spare parts, which might have any low level code.

The free stock (on hand) and schedule of received orders are also recorded in the bill of material file in the table of the appropriate item.

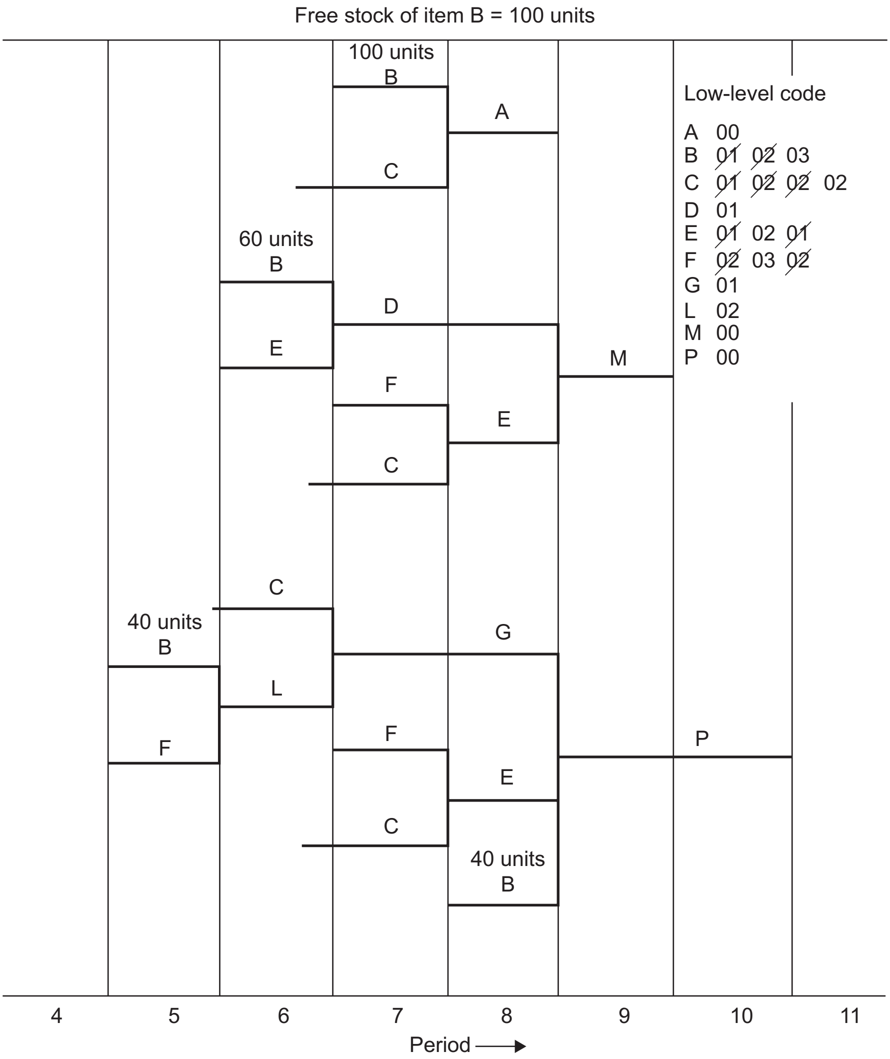


Fig. 5.5 Requirement planning for a number of products

The requirement planning starts with calculation the net requirements and planned orders (offset demand period by lead time) of items having a low-level code of 00.

The required planned orders are recorded as the gross requirement in the table of the appropriate item; this is done by using the product structure file and the quantity per assembly. When all items on file with a low-level code of 00 have been processed, the calculation will handle items with a low-level code of 01. This process will continue, level by level, until all items in the bill of material file have been processed.

Through this technique, item B of the previous example will be treated at level 03, at which point the gross requirements of all orders are recorded in its table. Thus, the allocation of the on-hand inventory will be logical and according to expectation.

2.2.2 Requirements Planning

Once again, the planning and execution in the traditional method, as described above, regards the routing as static and unalterable. Thus, the planning is simple, but it robs the shop of production flexibility and efficiency.

The scheduling in RPS for determining the required dates is based on ***unlimited capacity***. For purchasing or subcontracting, it might be tolerable. However, for in-shop processing, the schedule is unrealistic, and, in many cases, it cannot be done. The effect might be to increase work in the process and not meet due dates. Furthermore, the scheduling is of items (of all orders) and not of each order separately.

To improve the scheduling aspects, and other functions beyond material planning, inventory control and BOM control of RPS, an extension of this functionality is proposed. The extension is achieved by adding rough-cut capacity planning and pegging to restore order. It simulates scheduling with finite capacity, but only by simulation, and thus, improves the planning.

2.2.3 Management Control

See management control in section 2.1.1.

Additionally for management control,

Since requirements for planning horizons serve practical operation decisions, the requirement planning should be of a limited horizon. Thus, the number of periods (and size) should be decided by management, as should the offset periods.

2.3 Capacity Planning and Order Release

The objective of capacity planning is to set order releases for execution to the shop floor.

Requirement planning specifies the activities to be performed in order to meet the goals of the master production schedule. It plans both purchasing and production activities, taking account of requirements, but disregarding such manufacturing details as machine loading and shop dynamics. It sets objectives that must be transformed into a detailed loading plan for each machine or group of machines in the plant. As distinct from this, capacity planning is the planning phase for details; it is a scheduling and sequencing tasks. Finally, order release is the execution phase; on the basis of scheduling, it initiates productive activities by the issuance of orders to the shop floor.

Requirement planning specifies the manufacturing requirements of individual items; it breaks down the order or the product into its components through use of the bill of material. Although capacity planning might consider the individual items, this approach, sometimes called "build to stock," lacks the dynamics to overcome manufacturing divergences.

For example, if one of many items required for an assembly falls behind schedule, the due dates of the other items will be unaffected; they might still be a rush job in the shop, occupying overloaded facilities, only to have to wait in inventory for the missing item. A better solution is to use a network approach to capacity planning. The network in capacity planning need not be the same as the one specified in the product bill of material. The construction of a capacity planning network is done through the use of pegging and allocation of work-in-process, as assigned by requirement planning.

The time phase of requirement planning is a rough scheduling. Many features needed for accurate capacity planning are not available in today's requirement planning. It will suffice if one wants to plan and control merely at the item level, leaving the operation details to the foreman. However, when planning and control at the operation level are desired, capacity planning is the tool to employ.

2.3.1 Capacity Planning Objectives

The major objectives of capacity planning are:

- Meeting delivery dates.
- Keeping the capital tied down in production to a minimum.
- Reducing manufacturing lead time.
- Minimizing idle times *(machine out of work)* on available resources.
- Providing management with up-to-date information and solutions.

Some of these objectives conflict with each other. To minimize the capital tied down in production, the work should start as closely as possible to the delivery date; this will also reduce the manufacturing lead time. However, this approach will increase resources idle time in an environment in which resources are not continuously overloaded.

In the previous phases of the manufacturing cycle, the scheduling was done at the item level, disregarding available capacity. In such cases, the foreman has a priority list of all the jobs to be performed. The priority is assigned either on the basis of the due dates resulting from the requirement planning or on the basis of some external parameter defined by management or sales. Foremen, with their skill and experience, can undoubtedly load the shop efficiently. However, they lack the basic information as to when the job is scheduled to arrive at their departments and what effect their jobs have on the item and the overall assembly of the order. If they could know in advance about high-priority jobs due to arrive in their departments, they would not tie up machines with long-term operations that later have to be interrupted for more urgent work. Programming at the item level assumes, unjustifiably, that the work on the shop floor runs smoothly with no interruptions, no part rejections, and no machine breakdowns. Therefore, the scheduling of items, each carrying its own due date, is sufficient to meet the objectives. In some types of industrial operation, such as small job-shops, line production, or process production, there is no need to schedule operations. However, where a large number of interdependent activities must share the same limited resources, the scheduling problem exists.

Scheduling is the assignment of target dates to operations in order to define when they must be completed if the manufacturing order is to be ready on time. Some people think of scheduling as a science, and many papers have been published on the theories of job-shop scheduling. On the other hand, some people think of it as an art and believe that only the skill and experience of the foreman can effectively load the shop. In fact, scheduling is probably somewhere in between a craft and a trade, whereby the target dates are calculated according to certain rules, but the sequence of manufacturing is determined by variable factors that differ as a function of local experience.

Scheduling is simply a forecast and, as such, will often be subject to errors. The capability of any scheduling system is measured by how well it can respond to changes, that is, how efficiently it can reschedule and reload the work in response to what is actually happening at any given time.

The tendency is to try to avoid operation scheduling by releasing work very early and then, with shortage lists, expediting the urgent orders. With this method, all orders become urgent at some time or else they are forgotten. The result is an increase in the capital invested in work-in-process because lead times are increased. With increased lead times, the priority of orders becomes vague, and, hence, much time is spent working on orders that are not currently required, which further aggravates the overload condition. This problem can be controlled only by considering all resources and analyzing decisions with respect to them.

The capacity planning system encompasses the following:

- Planning the capacity required at each work center and helping to allocate the machines and manpower required to meet the goals of the master production schedule.
- Controlling the level of work-in-process by regulating the rate at which orders are released to the shop floor.
- Helping to reduce manufacturing lead times by reducing the time a job must spend waiting for a machine.
- Planning and minimizing queue lengths to help ensure that machines and personnel will not run out of work.
- Determining how much work can be transferred to alternate work centers in an effort to reduce overloads or fill idle capacity.
- Analyzing remaining overloads and underloads to determine which orders can be subcontracted without causing idle time in other work centers.
- Assisting in making short-term capacity adjustments by planning overtime, adding temporary extra shifts, or releasing work to subcontractors.

- Leveling the planned load on each machine center (in certain instances), thus reducing idle time, overtime, subcontracting, and amount of manpower movement between work centers.
- Determining which orders should be released earlier to prevent idle time.
- Accurately estimating the completion time for every shop order and customer order.
- Planning the sequence of operations to be performed at each work center and providing a work sequence list for the foreman and for other phases.

Capacity planning is dynamic, since changing conditions call for new plans. The life of a production schedule depends on the environment in the shop. It is probable that after a few days or, at most, a week, the schedule will no longer be realistic, and thus, a new plan is required. When a large number of operations are involved, the problem can rarely be solved satisfactorily by means of manual techniques. Although it can be analyzed by means of a manual system at any point in time relative to a given resource, under normal conditions, this technique cannot be used to review the resulting decisions in terms of the full time range and with respect to all other resources. In addition, a satisfactory solution in one area may cause an unexpected problem in another area.

Thus, a computer program should be employed for capacity planning, since it can reschedule all shop operations in a short time. The logic of capacity planning computer programs today is similar to that of manual techniques; it merely utilizes the speed of the computer.

The following data are required for capacity planning:

- *Orders*—The manufacturing program as specified by the requirement planning phase or by management; this list includes individual items, product network, quantities, and due dates; in the case of a network, only the product or order due date is required.
- *Routing*—The operations and sequence required to produce each item or assembly; this includes the machine number and operation time.
- *Machines*—A list of all machines, including available capacity time per period.
- *Parameters*—Dependent on the option used.

Scheduling must consider many parameters, such as machines, tooling, jigs and fixtures, materials, and operator skill. It calls for sequencing in many dimensions, which is very difficult to accomplish. Today's capacity planning programs mainly consider machines, whereas tooling and materials are treated as external data. Allocating machine operators to a job is external to the program, unless they are defined as facilities to be loaded, for the purpose of the program.

2.3.2 Capacity Planning Terminology

Capacity planning normally applies backward scheduling. This term and others are illustrated in Fig. 5.6.

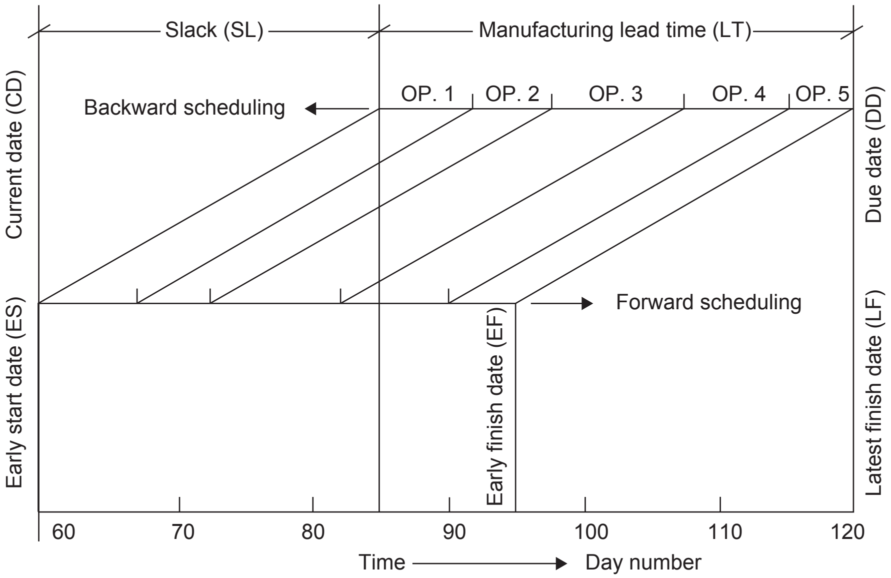


Fig. 5.6 Capacity planning terminology

Capacity planning uses a working day calendar instead of regular calendar dates to keep track of time, although the two are interchangeable. The working day calendar counts and assigns numbers to working days only. The day the scheduling is done is considered the current date (CD). In Fig. 5.6, the CD is day number 60. Suppose that there is an order for an item requiring five operations; in this case, the due date (DD) is day 120. From that date backward, the operations are laid out as shown in Fig. 5.6. In order to finish this item on time, the latest date on which to start operation number 1 (OP. 1) is day 85. This is called the latest start date (LS) for OP. 1. The latest date on which the item can be finished is its DD, that is, day 120. This day is called the latest finish date (LF) for OP. 5. These LS and LF correspond to the item (or order); each operation is also assigned its own LS and LF. For example, the LS of OP. 3 will be day 97, while its LF will be day 107. The LF of an operation is the LS of the preceding one; the use of "latest" means that any delay in starting the operation on its LS will result in a delay in the DD; however, in the example of Fig. 5.6, there is a slack (SL). The starting date of the operation is in the future, but manufacturing of the item can begin on the CD; this day is also called the early start date (ES) of the item or of the first operation. If this is carried out, the item will be completed on day 95, which is called the early finish date (EF) of the item or of the last operation. Each operation has its own ES and EF, corresponding to item scheduling. For example, the ES of OP. 3 is day 72 and its EF is day 82. Thus, the above item has a slack (SL) of

$$SL = LS - ES = LF - EF = 85 - 60 = 120 - 95 = 25 \text{ days.}$$

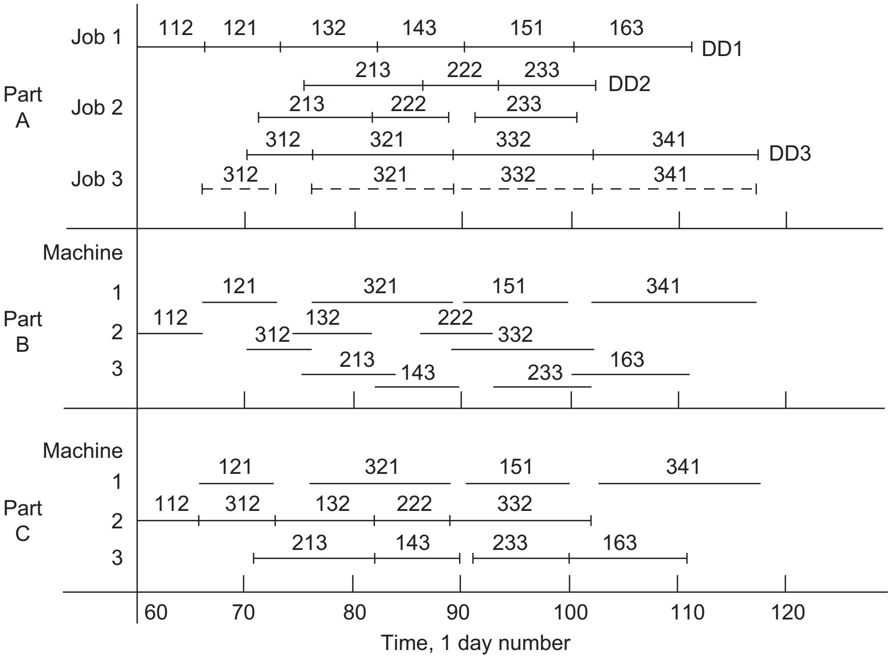


Fig. 5.7 Scheduling of three items (jobs)

This SL is for the item as a unit, but can be used on any individual operation.

Figure 5.7 shows the scheduling of three items (jobs). Each operation is marked by three digits: The first designates job number; the second, operation number; and the third, machine number. Initially, all three items are backward scheduled. The full lines in part A give a cross-section of order status.

Part B of the figure gives a cross-section of the machine load for the backward scheduling of Part A. It shows that on days 73–76, machine 2 is overloaded; jobs 1 and 3 require the machine at the same time. A similar situation occurs on that machine on days 89–93 and on machine 3 on days 82–86 and 100–102. To balance these loads, the SL time may be used. Since job 1 has no SL at all, any change in its LS will result in a late delivery. Job 2 has an SL of 15 days and job 3 of 10 days.

Part C of the figure shows the machine load cross-section after the overload has been resolved by pulling jobs forward. It is based on LS loading and considers available capacity.

The dashed lines in Part A show the planned cross-section of the jobs.

Job 1 does not have an SL and is, therefore, unchanged. In such cases,

$$ES = LS = CD \text{ and } EF = LF = DD.$$

Job 2 used 4 days of its SL in order to balance the machine load. It has a new SL of 11 days, the LS being on day 71. The job is scheduled to be finished on day 100, two days before the DD.

In scheduling to finite capacity, an item's operations and machines are linked and the meaning of the SL is changed: the item SL and operation SL do not coincide. In the example shown in Fig. 5.7, the scheduled LS of task 213 is day 71. However, machine 3 is unoccupied, and this task may start on CD = ES = day 60. Hence, this operation has ES = 60 and LS = 71.

The second operation (task 222), due to the fact that machine 2 is occupied, can start only on day 82, which is its ES. It is scheduled to be finished on day 89, two days before the required date. Hence, this operation has ES = 82, LS = 84, EF = 89, and LF = 91.

The third operation (task 233) has scheduled LS of day 91. However, checking machine loading, one can see that machine 3 is not occupied on day 90, and hence, the operation can be pulled forward to start on day 90. The result is

$$\mathrm{ES} = 90,\ \mathrm{LS} = 91,\ \mathrm{EF} = 99, \text{ and } \mathrm{LF} = \mathrm{DD} = 102.$$

The SL value may be positive, zero, or negative. A zero SL is sometimes referred to as critical, while a negative SL is called a delay. When working with networks, there is a third type of SL—network SL.

The overall elapsed manufacturing time is referred to as the manufacturing lead time (LT). Scheduling of the items in Fig. 5.7 was done manually. One looks at the diagram and tries as many loading combinations as needed to obtain a satisfactory result. The terminology that has been introduced enables scheduling to be treated mathematically, thus allowing a computer to be employed.

2.3.3 Capacity Planning Technique

The capacity planning logic and programs are composed of several stages. The first stage involves examining the feasibility of meeting the DD (unlimited capacity scheduling).

For each item or network, a DD and an ES are assigned. The ES may be explicitly defined by such constraints as the availability date of materials and tools. If the ES is not explicitly defined, the CD is substituted. Both the item LT and the available manufacturing time span (TS) are computed, and the two are compared.

Example:
Due date (DD) = day 170
Early start date (ES) = current date (CD) = day 110
Daily working hours = 8 h
Manufacturing lead time (LT) = 400 h
Compute available time span (TS):
$\mathrm{TS} = (\mathrm{DD} - \mathrm{ES}) \times 8$
$\mathrm{TS} = (170 - 110) \times 8 = 400$ h

Therefore, the slack (SL) is

$$SL = TS - LT = 480 - 400 = 80 \text{ h}$$

This indicates that the first operation should start, at the latest, 80 h (10 days) later than day 110 in order for the last operation to be completed on day 170. In this case, the part does not experience a delay, but an SL time of 10 days. That is to say, theoretically, the DD may be adhered to.

When the SL results in a negative value, that is, the TS is less than the LT, a delay might occur if normal manufacturing procedures are followed. An attempt is made to overcome the delay by the following methods.

Reduction of Indirect lead Time (LT)

The LT includes interoperation time (IT) as well as operation time (OT). The IT covers the following time elements:

- Queue time (i.e., time spent waiting to be assigned to a machine)
- Pre-operation time (i.e., time for cleaning, etc.).
- Post-operation time (i.e., time for inspection, etc.).
- Wait time (i.e., time spent waiting for transportation).
- Transport time (i.e., time required for transportation to the next work center).

For normal manufacturing procedures, a generous allowance is made for these interoperations. It reduces expediting and preplans transport and inspection. However, in case of delay, expediting may be applied and initially allowed IT reduced. The same effect can be expressed in mathematical terms and calculated on a computer.

Splitting

Splitting is the simulated processing of an operation on several machines. By this means, a reduction in operation duration is achieved.

The technical number of splits is determined by the number of similar machines or tooling sets available. This number is the upper limit for the number of splits possible. The economical number of splits is a function of set-up time and operation time. The longer the set-up time, the less economical the simultaneous use of more machines.

The plant must work out an economical algorithm.

Overlapping

Overlapping is starting the subsequent operation before the preceding one has completed the planned quantity. The result can be a considerable saving in lead time.

Overlapping must be tightly controlled because it involves additional effort in coordination. One must consider at least three aspects that constrain the practicality of overlapping.

- *Minimum overlap time*—This value ensures that a minimum overlapping of two operations can be achieved; if it does not, overlapping is not practical, since a saving in lead time is not balanced by the additional coordination effort.
- *Minimum time before overlap*—The overlapping operation may start only when the overlapped operation completes a given quantity and required interoperation time has elapsed; the set-up of the overlapping operation may start in parallel, so that operation time (OT) can begin immediately after the item is received.
- *Minimum overhang*—This is similar to the minimum time before overlap except that the data refer to the end of the overlapping operation instead of the beginning of the overlapped operation.

Computations can be performed in order to decide whether and how to plan overlapping. If overlapping is worthwhile, the preferred form can be computed.

2.3.4 Management Control

There are several programs and techniques and alternatives for solving this difficult task. One of several was presented. Management must consider and be actively involved in the selection of the most suitable capacity planning program for their plant.

Points to consider are:

- Period size.
- Lot size.
- Technology employed.

The term **lead time** used in scheduling (as described before) is a critical one, as can be demonstrated by Fig. 5.8.

Management should control these time elements, as they might cause artificial overload on the system and they serve as safety factors for schedulers.

2.4 Order Release

Order release is the link between planning and implementation. It initiates the production activities by issue of orders to the shop floor according to the program prepared in the finite capacity planning stage.

The previous stages of the manufacturing cycle, requirement planning and capacity planning, do not impose any actual activity; they are planning phases. Order release, on the other hand, releases jobs for both the shop floor and also for purchasing and subcontracting. (It is good practice to preplan these activities through

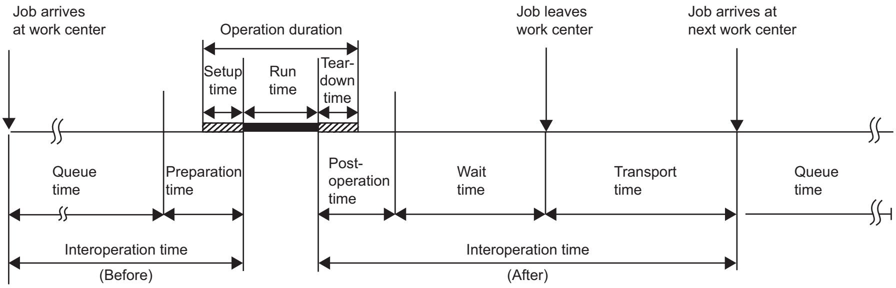


Fig. 5.8 Elements of Lead Time (LT)

capacity planning as well. Thereby, if a network is shifted, more accurate due dates will result than would from the requirement planning system). These planning phases do not impose any commitments. Each period (one week), a new requirement planning and capacity planning are prepared, while the old ones become obsolete. In the implementation phases, an order is a commitment of resources and material and cannot be overlooked in the next period. The shop floor phase is dynamic, as the purchasing phase often is, since reality seldom resembles planning: Suppliers fail to deliver on time, machines break down, tools break, and items do not pass inspection. Therefore, before authorizing release, a check should be made that material and tools are available.

Capacity planning schedules periodically according to available capacity. Each operation, item, and assembly is assigned a starting date. Jobs should be started in the shop on these dates. The actual starting date is up to the foremen. They know best what is going on in their departments: the open job orders, the workers and their skills, the machines and their foibles, material and tools available, and the set-up of each machine. Their responsibility is not only to complete jobs on time, but also to keep their operators occupied; they try to optimize operations in their departments, but, at the same time, keep operators satisfied. From their standpoint, sequencing operations by similar set-up, for example, is highly economical. They are also exposed to pressure from the operators to assign "good" or easy jobs, if incentive systems are employed. However, the foremen can function and make good decisions only within the range of the information they possess. They do not know which operations will arrive in their departments; moreover, they do not know, and thus, cannot possibly take into account, the effect of their decisions concerning job selection on the delivery date of an order. Therefore, the amount of work released to a department should be kept to a minimum. Theoretically, jobs should be released on their starting date. Thus, optimal decisions (from their standpoint) made by the foremen and bad decisions from the network standpoint cannot cause much damage. Practically, there are some preparatory actions to be taken before the job starts on the machine: Material and tools have to be issued and transferred from stock; the machine has to be set up; and alternate jobs should be made available for emergencies. Thus, the foremen should be notified in advance of jobs due to arrive in their departments as well as of the approximate (or planned) arrival date.

Plant management should specify rules on when to release orders to the shop and what offset to use for the capacity planning program. These rules have to correspond to the plant environment, discipline, and the nature of production.

One should bear in mind that the act of job release serves two purposes. It transfers the control of this job from the planning stage to the implementation stage (open orders or open purchasing) and is an early warning to the foremen stating that this operation will, in the near future, be scheduled for production. The short-term scheduling (one day) will sequence the above operations in the shop floor stage.

From a systems standpoint, it is advisable to release items and not operations. For example, job release rules are as follows:

- Jobs for which the first operation starting date falls within production range (e.g., three weeks) are released.
- Critical items should be allowed extra time.
- Items with a large number of operations should be released at an earlier date.
- The production range for items scheduled by early start is reduced.
- The production range for items with postponed operations is reduced.

The basic functions of job release are:

- Checking of the physical availability of material and tools required for the initial operation; only those orders that have all material and tools available are released.
- Preparation of shop order documentation; a printed order that includes item routing is sent to all departments involved in manufacturing the released item; drawing number, special inspection demands, and additional descriptive text are printed on the job release form.
- Attachment of the job-card for job recording (for operation level of control, one card per operation).
- Attachment of the material and tool requisition forms.

The order is recorded in the shop open order file and assembly demand file. Both files are required for requirement planning and inventory control. The data in the open order file are used for operation scheduling and shop control

2.4.1 Management Control

Plant management should specify rules on when to release orders to the shop and what offset to use for the capacity planning program. These rules have to correspond to the plant environment, discipline, and the nature of production planning horizons allocated for unplanned interruptions and urgent jobs.

2.5 Shop Floor Control

The objective of capacity planning is to make a decision on what jobs should be released to shop floor planning and control.

Capacity planning is a simulation of what is likely to happen on the shop floor. It attempts to schedule the jobs with respect to the existing production plan, manpower and machines. Its design is good for the purpose of ***releasing orders*** to the shop floor, and its planning horizons are for several weeks or months; however, it cannot take into account any unplanned interruptions that occur, such as urgent orders. To overcome this problem, the *available* capacity can be reduced to 75 % of the working hours in a day. Although this holds true as a rule, it is not sufficiently accurate for actual job assignment on the shop floor. Usually, the life of a schedule is no longer than a day. After a week, a capacity plan will probably not resemble reality at all. In the shop, unplanned occurrences take place: along with the familiar pitfalls in regard to machines, tools and workers, actual operation time may not work out as planned, the previous operation may not finish on time, a lot may be rejected, or the foremen, for their own reasons, may change the planned sequence. All of these cause changes in the implementation of the capacity planning program.

The capacity planning simulation disregards the unplanned interruptions, that is, an operation is available for scheduling when the latest finish and the interoperation time of the previous operation is due. In practice, an operation can be loaded only when all previous operations have been completed and the components are available in the queue of the machine.

The actual allocation to the individual machines is made by the shop floor foremen. They know best what is going on in their departments, the particular skill of each operator, the tolerances on the machines, and so on. Many companies, therefore, leave the daily scheduling to the foremen. On the other hand, some companies do daily scheduling by computer, while others might establish dispatching rules, both to guide the foreman. In any case, the system must know what is going on in the shop.

The information is vital for daily sequencing and for capacity planning. It is the basis for many other applications, such as cost, salaries, incentive pay, and absentee control. The frequency of receipt of this feedback is a function of the application. For daily scheduling, it must be processed daily or hourly, while for salary and cost, a week or even a month will probably suffice.

However, for reliability purposes, it is recommended that it be processed daily or even in real time by the data collection equipment.

2.5.1 Short Term Capacity Planning

Capacity planning considers all company orders over a long period of time, its main purpose being to trigger order release to the shop. These orders to the shop are considered as information or an early warning to the foremen with respect to what jobs might arrive in their departments in the near future.

The foremen must make all necessary arrangements to handle these jobs on short notice. Thus, these orders do not represent a signal to begin processing. The short-term capacity planning provides the actual order to start manufacturing. To be practical, it may, for example, be scheduled daily, but it normally covers a period of two to three days. This is done to compensate for computer down time and any unplanned interruptions that might occur. Input to the short-term capacity planning comes from the open order shop file, which establishes a realistic start date for each operation based on order priority and capacity limitations. Medium or long-range capacity planning is processed at greater intervals, for example, every 10 days, and updates the open order shop file.

The method of sequencing is based on operation priority together with certain special considerations, such as grouping jobs with similar set-up and tool availability. The sequencing of operations is performed in three steps:

4. Establishing the hours available at a work center (on a machine).
5. Sequencing work from the queue.
6. End-of-shift routines.

The basis for establishing the hours available at each work center (on each machine) is to specify the particular hours of the day that it will be available. Staggered working hours can be shown by varying the start/stop times for a work center (machine).

When sequencing operations, the system uses an internal 24-hour clock to simulate the actual scheduling of operations in the plant. Specifying actual start/stop times for each machine enables better sequencing decisions to be made. For instance, the sequencer would not plan to do a heat-treat operation at the end of the shift if the subsequent operation had to be performed within two hours and the next work center was working on a one-shift basis.

During processing, the clocks simulate the time of day and indicate when each machine will be available for the next job. The system keeps track of idle time expected between successive jobs on a machine because of unavailability of another job. The total idle time expected for the day or shift can be shown on the work sequence list.

The principle of sequencing is that all work centers may be cyclically processed in turn. During one cycle, all jobs queuing at a work center are considered for assignment. Work is assigned for a specified period of time ahead (20 min, 1 h, 2 h, 4 h, etc.). When all work centers have been processed, the clock is moved forward and processing is repeated for the next cycle.

During each cycle, work expected to be completed at a work center becomes available for processing at the next work center after interoperation time, shift length, and so on are considered.

Work center sequencing

The work centers themselves can be loaded in any sequence. In most industries there are certain “gateway” or first-operation departments (material cutoff, foundries, turret lathes, etc.) that ought to be sequenced first because they release work to later work centers.

At the start of processing, the first work center queue is checked for all operations available for sequencing. An operation is available for sequencing when all previous operations have been completed and components are available.

The operation priority is now calculated for all jobs in the queue, and the job with the highest priority is loaded into the first machine. The next highest priority job is loaded into the second machine, and so on, until every available machine in the work center has been assigned one job.

The clock for each machine is incremented by the operation time (set-up time + run time per part + tear-down time).

The next job is now loaded into the first available machine in the work center, and so on, until the capacity within the cycle period is used up or until all available jobs meeting the operation priority criteria are sequenced.

After an operation has been sequenced into a machine, the completed job is made available for sequencing at the next work center. The availability date and time are determined by using the interoperation time calculated earlier. The queue time is excluded because the actual queue is being simulated by this process.

The next work center is now loaded in a similar manner from the available jobs in its queue.

When all work centers have been sequenced, the clock is incremented and processing starts again at the first work center. Sequencing then goes on for each machine from the time it left off.

The next time around, the queue contains operations previously available but not sequenced, as well as new operations available as a result of just being completed at other work centers. The sequencing is continued to cover a period of one or more days, as required.

When work has been sequenced up to the end of a shift, the system sets the clocks to coincide with the start of the next shift. It also checks for any scheduled jobs that will be delayed beyond their start date; these jobs have not yet been sequenced, and their start date will now be later than that planned in the order release phase.

The system checks back through the shift to see what work could have been sequenced into alternate work centers. The operations that are running late are scheduled, if possible, for alternate work centers where capacity is available. Each work center will be looked at in turn, in a predetermined sequence, for work to offload.

Work centers having idle time above a specified figure can also be checked to see whether work can be offloaded from other work centers. Alternate operations or routings are evaluated during the sequencing process.

The level of overtime necessary to meet the schedule has been determined by *management* as a result of capacity requirement planning and order release planning. Operations are sequenced up to the specified level of overtime above the normal working hours.

Dispatching rules

Theoretically, capacity planning has scheduled the work to the last detail, and the foremen simply have to carry out this plan by assigning jobs to their operators. In practice, it never works this way. In spite of the fact that the load was balanced and all the competition for capacity resolved, the foremen still face the problem of jobs competing for capacity.

When a machine becomes free, a decision must be made in regard to its next operation. Short-term capacity planning attempts to solve this problem by considering only those jobs that are ready for processing. The priority rating is used to sequence these jobs.

Another approach is to construct a simple practical rule that the foremen will use in sequencing the jobs waiting in the queue of a machine. The rule must be simple, so that the foremen can use it without the need for elaborate computations. They must also possess all the relevant information. For example (there are over 60):

SPT	Shortest processing time
FCFC	First come, first served
SIMSET	Similar setup time
Random	Selection by random process
LV	Has the largest value

Following this line of thought, the question arises as to whether any priority decision rule (dispatching rule) works better than the others, and whether any decision rule is significantly superior to another (some say that the random is just as good as anything else).

2.5.2 Management Control

Several examples of shop floor scheduling were presented above. Management must decide which one to use. Such a decision is quite difficult, as we actually do not know what the objective is. How do we measure and define good scheduling? What are we actually trying to accomplish? There are many criteria by which one can define the goals of scheduling, such as:

- Minimum level of work-in-process.
- Maximum number of processes completed.
- Maximum number of jobs sent out of the shop.
- Minimum number of processes completed late.
- Minimum average lateness (tardiness) of all jobs in the shop per period.
- Minimum queue wait time of jobs in shop.

- Minimum number of jobs waiting in shop.
- Maximum shop capacity utilization.
- Minimum number of jobs waiting in queue for more than one period.
- Minimum size of jobs waiting in queue for more than one period.

It is impossible to satisfy all these objectives. Management should set a priority list according to importance to the company.

There is no one best scheduling method.

Management should make a decision as to which method it prefers from those mentioned above.

The scheduling must be based on management decisions in regard to the basic system such as:

- Number of hours in a working day.
- The length of the cycle period, which can vary from minutes to days.
- Number of shifts per day.
- When to use overtime and when to use shifts.
- Scheduling of each resource or work center.
- Setting of a reliable information system.

Chapter 6
Flexible Production Planning

Abstract Production planning is, by nature, a very simple task. However, traditional production planning systems and notions have made the system very complex and unproductive, as decisions are made too early in the manufacturing process.

This chapter presents a different approach, one that introduces flexibility to manufacturing in which routine is a variable and treats each order as a unit. Therefore, bottlenecks cannot be created and disruptions are solved automatically; thus, processing time and productivity increases.

1 Introduction

Because the traditional approach to production planning regards routing as static and unaltered, the routing that a process planer defines is used without knowing when it was done, what mode was used, and what the intentions and optimization criteria were. The RPS method breaks down the product into items, and optimizes item scheduling. Then, it calls for a sophisticated program to assemble the items into a product. Therefore, such a method robs the production of flexibility and efficiency.

Flexible production planning, while having the same objectives as the traditional method, is based on quite different notions, which are:

- Routing is a variable.
- The task of a process planner is to create a roadmap and not routing.
- Production planning treats each order independently, not each item.
- The system creates a working product structure based on product levels.
- Priority in production planning is given to critical orders.
- The system loads for available capacity.
- The system eliminates or rectifies bottlenecks in production planning.
- Shop floor control is maintained through resource searches for free operations.
- It enables alterations in production plans at any point in the process.

Production planning flexibility imitates human behavior, i.e., decisions may be altered if conditions change. For example:

If one plans to go from point A to point B, then one studies the map and plans the optimum route to take. This is the present time decision. However, at another time,

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when you have to move the same way, for example, at night, you might change the route. In winter, you will probably look for a route with maximum shelter from inclement weather. In summer, you might choose a route that protects you from the sun. In springtime, you might choose a route with a nice view.

Despite any original decisions as to routing, if you run into disruptions, such as a blocked road (bottleneck) or a traffic jam, you might decide that, instead of waiting, it is better to consult the road map (GPS) and change the route. Such change is done at each junction. It might be a longer route but it will be faster in regard to time. The original decision must not prevent one from adapting the new route.

A similar strategy can be applied to production management. The presented manufacturing system proposes supplying each manager with a “roadmap” stored in the company database, allowing him to deviate from the original plan while accomplishing the production program and target objectives assigned. The proposed method will introduce flexibility and dynamics, thereby increasing company efficiency and customer satisfaction.

The task of the process planner is to select what appears to be the most economical process out of the tremendous number of alternatives. He/she will naturally do their best based on individual experience; however, there are several criteria of optimization: maximum production, minimum cost, and maximum profit. Each one of these will result in a different routine. However, the process planner is neither an economist nor a production planner; therefore, they should not make decisions that are beyond their field of expertise. Furthermore, there are several criteria of optimization that are affected by routing, such as:

- Optimization of a single operation.
- Optimization of an individual item.
- Optimization of production of a product.
- Optimization of production of a product mix.
- Optimization of factory business.

Single routing in a company database cannot accommodate all these criteria; only the roadmap method can do that. Thus, the process planner’s objective is to create a two-dimensional spreadsheet (roadmap) of resources *vs.* operations containing the time/cost of performing each required operation on each resource, not to make a routing decision.

2 Production Planning

The objective of this stage is to plan the activities in a manner that ensures that order delivery dates will be met. The outcome of this planning is the order release being given to the shop floor for execution. The order release must be practical; otherwise, the shop floor will not be able to follow the given plan. If unrealistic job orders are released to the shop floor, one cannot expect that all jobs will be finished on time. From the released list of jobs, the foreman will select which job to execute, on the basis of available employees and their expertise. The foreman’s decisions as to job execution may not always coincide with those of the planning department.

To arrive at a practical plan and job release, the planning must be the same, or at least very similar, to the scheduling of jobs on the shop floor. It must be able to show the shop floor personnel the exact schedule, and prove that all the released jobs may be done the planning period. The shop floor may use any scheduling it desires, but it must complete all released orders on time.

Thus, the planning must consider: the available resources (planning with finite capacity in mind); the product structure (for example, in case of delay of an item, the ability to shift the planning of all other dependent items to the time that it is really needed); and the available flexibility in selecting the routing, (considering the routing as a variable).

The roadmap method of planning keeps in mind finite capacity and the use of the product structure (BOM tree). The detailed capacity plan is transformed into a real schedule. The schedule is the basis for dispatching the jobs to the shop floor and serves as explanation of how and when the released product mix has to be produced. However, the shop floor is still free to produce the product mix by any other routing which facilitates the solution of problems caused by disruption, with the restriction being that the released product mix, as specified for the period, must be completed in time.

The planning steps are as follows:

1. Determination of stock allocation priorities.
2. Stock allocation.
3. Adjustment of quantities as the result of economic considerations.
4. Capacity planning—machine loading.
5. Job release for execution.
6. Shop floor control.

3 Stock Allocation

The strategy here is to allocate the stock to the critical order, where critical is defined as the order in which the low level item has to start at the earliest time.

3.1 Determine Allocation Priorities

The objective of this step is to ***set priorities*** for stock allocation, i.e., to which order and item to allocate the available stock.

The strategy is to allocate the stock to the critical order, where critical is defined as the order that its low level item has to start at the earliest time. The earliest time for the order's low level item to begin might be in the past, or at the future date. To affect this strategy, the first step is to build the product structure on a ***time element scale***, instead of on ***level base***.

Figure 6.1 shows three products, A, B, C, and the items that are in each product at each level. Level 0—is the product (or order) for which the lowest level in this

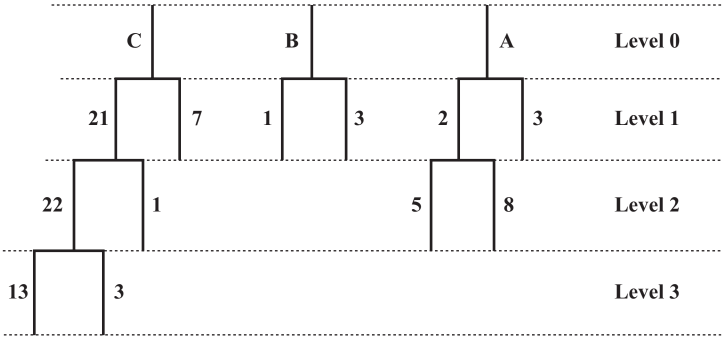

Fig. 6.1 Level-based product structure

figure is on order C and level 3, also referred to as the “low level” item, and items 3 and 13 are referred to as low level items. The connecting lines represent the relationship between the product, its subassemblies and the items, and do not represent the time to process the item.

In order to determine which order is the critical order, the level-base product structure is converted into a ***time-based product structure***. The name of the order is retrieved from the level-based product structure (level 0) and the roadmap is utilized to generate a process based on the order quantity for that item.

3.1.1 Time-Based Product Structure

The conversion of a level-based to a time-based product structure starts with the order delivery date down to the lower levels. The roadmap is utilized to compute the assembly time of the product (level 0) multiplied by the quantity, the value of which is converted to the delivery date units. This value is reduced from the delivery date. The result is the starting time for processing the level 1 items. Again, the time for processing each item and its quantity on level one of that order is reduced from the previous level end point.

The processing time of such a process is given for each single item. The total processing time is computed by multiplying the quantity by the processing time of a single product. Convert the computed total length of time to the time scale (let us say, in days) and subtract it from the delivery date of the order. Draw a line starting from the order delivery date backward, at the computed length. The end point of this line indicates the date at which the assembly (processing of the order) must start in order to meet the delivery date. Record this line on the time-based product structure.

Next, address all items of level 1 of the same order one by one, regarding the ‘start processing’ date of level zero as the delivery date of each item on level 1. Use the roadmap to generate the economic process, compute the total time and convert it to the scale time, and draw the connecting line by this length. Repeat this process for all levels of the order, and for all orders in the file.

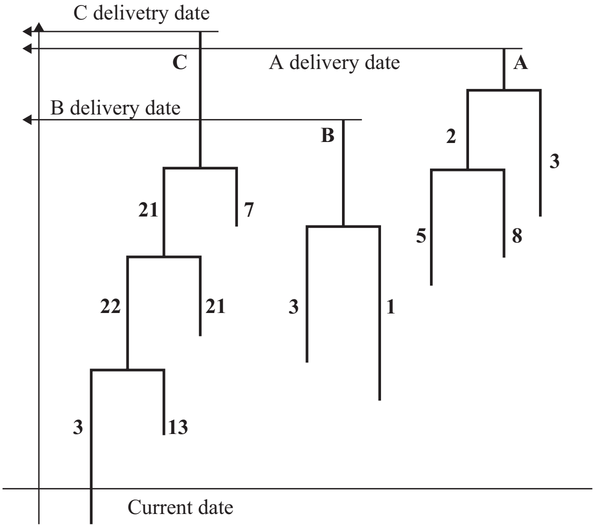

Fig. 6.2 Time-based product structure

Example: Fig. 6.1 shows three orders for products A, B and C. The computation may start with any order. For example, suppose it starts with order A. The assembly of order A is treated first, and the roadmap issues the time for assembly to begin. This time is indicated by the length of the line, from the delivery date of order A backward in time.

Next on the product A structure is subassembly 2. The quantity is computed by the order quantity multiplied by the number of subassemblies 2 in a single product A. The system turns to the roadmap and retrieves the time for assembling subassembly 2. The assembly ends at the beginning of assembly A and starts at the due date minus assembly of subassembly 2.

Next, subassembly 2 is composed of items 5 and 8. Their due date is the beginning of subassembly 2. The quantity of item 5 is computed by multiplying the quantity of item 2 by the number of items 5 in assembly 2. The system turns to the roadmap and retrieves the time to produce item 5. The processing due date is at the beginning of subassembly 2 and ends at this date minus the processing time of item 5. A similar process is made for each item.

The due date for item 3 is the beginning date of order A. The process duration is supplied by the roadmap. Note: the quantities of each item will consider the scrap factor.

Figure 6.2 shows the time-based product structure of three orders, each with a different delivery date.

The level-based product structure is regarded as a master structure, and refers to all company products, while the time-based product structure is a working structure and refers only to the company's open orders. The time-based product structure represents the activities that should be undertaken in order to supply the customer orders.

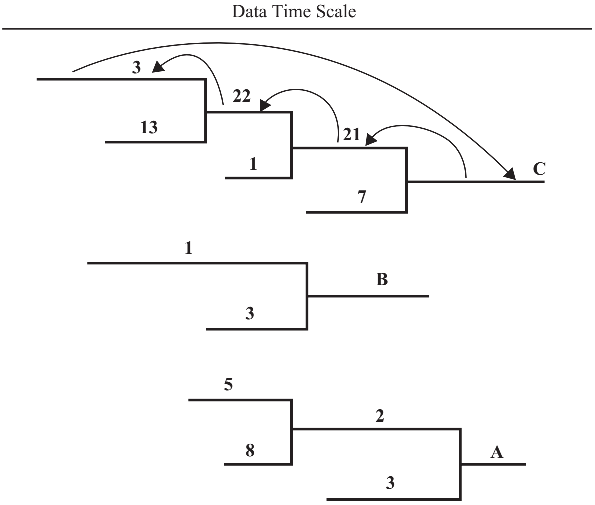

Fig. 6.3 Stock allocation sequence of priorities

3.2 Stock Allocation Method

The objective of this method is to allocate the available items in inventory to the available orders and adjust the early starting dates of each item accordingly. It is done by scanning all the orders and finding the critical item. A ***critical order*** is defined as the order the lowest level item of which has the earliest starting date for all orders, (i.e., the item with the earliest starting date.).

When the item with the earliest starting date is determined, the product structure for this item is examined in order to find the product and the order (i.e., the level 0) (see Fig. 6.3). The inventory is checked to see if this level 0 product is available in stock. If available, it is allocated to this order. The quantity of this order is reduced by the available quantity, and the product structure is rebuilt with new quantities per item and new starting dates. In this case, the starting time of the lowest level item will be changed and another order might become the critical one. The procedure is repeated by scanning all orders to find the "new" critical item. If the ordered product is not in stock, the availability of the next level item is examined using the same procedure.

For example: examining Fig. 6.3 reveals that item 3 of product C has the earliest starting date; therefore, it is regarded as the critical item. However, the allocation priority should be given to the level 0 item of the critical item, since there will be no need for that item if higher level items are available in stock. The chain of the critical path is: items 3—22—21—C. Therefore, the system checks the inventory for availability of product C.

In the case that item C is not in stock, or only in partial quantity, such a quantity is allocated to item C and the quantities of all items in the tree are adjusted accordingly, followed by construction of a modified time-base. The allocation proceeds, as described, to items on the lower level.

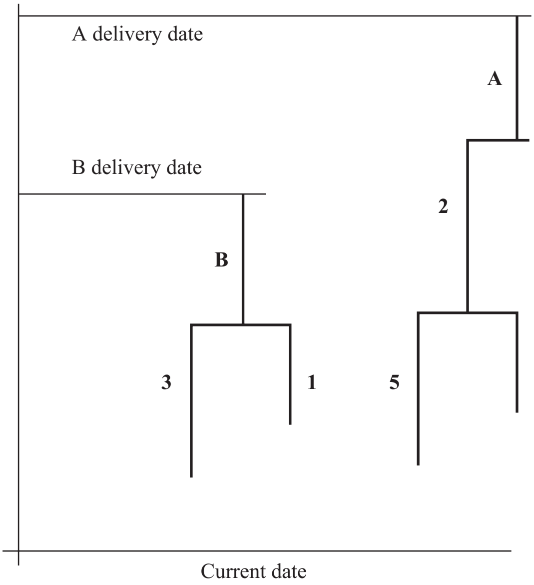

Fig. 6.4 Time-based product structure during the allocation process

Suppose that item C is available in stock for the entire quantity; then, the entire product structure of C is marked as available, and is erased from the time-based product tree. In this example, only products A and B are considered.

After each allocation, a check is performed to find the current critical item. In this example, item 1 is the new critical item (see Fig. 6.3). The path to the low level item is: 1—B. The system checks to determine if item B is in stock. If it is, it is allocated. If item B is not available in stock, a check is made to determine if item 1 is available. If it is, it is allocated to item 1 of product B. In case of partial quantity, the remaining quantity is reduced, and thus, the time to produce item 1 is reduced. Item 1 of product B is marked as "treated" to make sure that it is not considered again as the critical item. Such an intermittent state is shown in Fig. 6.4. In the next step, examining the time product structure indicates that item 5 of product A is the critical one. The process continues till all low-level items are marked as treated.

This method assures that allocation does not consider the delivery date of an order, but, instead, makes sure that the critical items get priority. This point is illustrated by the time structure shown in Fig. 6.3. Item 3 appeared in orders for product A, B and C. The early delivery date is for product B, followed by product A, and then product C. However, the critical sequence of allocation should be, according to the state indicated in Fig. 6.3, product C, then B, and then A.

At the end of the stock allocation step, the product structure includes only those items that have to be produced or purchased. The working product tree is not similar to the master product tree, as some items might be missing altogether and others might have a different quantity.

3.2.1 Management Control

The priority model is determined by product structure and the roadmap. Product structure is set by product design, and management may only control it at that stage.

Computing processing time of items requires use of the roadmap. The setting of a routing depends on management control to define the optimization desired. It can be maximum production, or minimum cost, or a combination of both. Each defined optimization will result in a different routing, and thus, different priorities and stock allocation.

Managers usually prefer to use minimum cost. Stock allocation with this option may result in the latest start of scheduling operations, thus leaving space for solving disruptions.

Using maximum production will result in short routing time planning that might solve period overload by scheduling with the maximum production option. **It is up to management to make such decisions.**

Available stock is defined as items in inventory, items being processed on the shop floor, and items on order in purchasing.

Management must make sure that company procedures will eliminate cases in which available items in the plant will not be considered in stock allocations. Such items might be purchasing items that arrived, were deleted from the purchasing files, but not yet entered into the inventory system. This might occur in a case in which the storekeeper has to count and compare the invoice for inspection on behalf of the quality department before it will be recorded as a receipt in inventory records. Similarly, shop-produced items may have been deleted from the in-shop list, but not yet recorded in inventory records.

Stock allocation gives priority to critical orders, which are defined as orders the lower level items of which must begin being processed at the earliest date. It is a distinctive definition. However, it is a mathematical optimum and must not be considered a practical optimum. In many cases, the difference between several starting dates is the result of negligence. For example: one should start order #1 at day 33.04 and order #11 at day 33.07, meaning that order #1 will get priority in stock allocation.

Management should have the tools to interfere with unreasonable decisions generated automatically. Management should be able to set priorities for plant orders, and set limits on negligence different from mathematical minimum decisions. In such cases, the program for setting preferences should be according to management desires and not to mathematics.

When the allocation stage is finished, some items may be left over. This means that no available order had any use for them. It can be considered **dead stock**.

Management should define clear roles as to when to define items as dead stock, and how to treat them.

3.3 Capacity Planning: Resource Loading

The working product structure lists the items that have to be processed. It is based in a format that provides a connecting link upward to the parent item. Pointing any individual requirements to their specific source is a significant feature; it provides an upward tractability from component to parent item, all the way up to the end item requirement. It is used to:

- Check the source of requirement.
- Trace the effect of component delay on the delivery date of the finished product; for example, if a process operation cannot meet its due date, all forward process operations will be scheduled at the realistic due date of the previous operation; resource loading considers the order with all its items, and not according to any individual item.
- Examine the validity and significance of a system-generated request to change the delivery date of the order.
- Discover the effect of a pending engineering change on a customer's order or trace upward to the product serial number at which point the change will become effective.
- Maintain the customer's identity down through the lower-level component order.

Resource loading employs a Table (spreadsheet) in which each available resource is represented by a column and each period is represented by a row. The data in each cross-section slot representing resource and period indicates the state of the resource at that period. If the content of the slot is a datum, it indicates that the resource is occupied at that period, processing a specific operation of a specific item. If the slot is blank (empty), it means that the resource is idle at this period.

Resource loading is forward planning. When a job is allocated to the resource, the appropriate position(s) in the column hold(s) the order and the item code. Empty positions indicate idle resources.

A critical planning path is defined as the path beginning at the low level item in the working product structure with the earliest starting date, moving through its subassemblies up to the product. The critical path will have priority in resource loading. However, all the items for the subassembly have to be available before the assembly can start, i.e., all independent items that go into the critical subassembly will have a priority greater than the subassembly.

The priority of such items is related to their starting date. Through this method, the critical product has loading priority. The items in the critical path of the critical product have even further loading priority. This method ***resolves the problem of competition of jobs over resources***. It guarantees the loading will be assigned to the most advantageous job. In a case in which a job requires a time slot at a certain period, and the resource is occupied by another job, it means that the other job had priority over the present one, since it was treated earlier.

If the required resource is anticipated as becoming available in a short period of time, then the job in the queue will wait. However, if the number of periods the job has to wait in the queue is large, then the system will use the roadmap to search for an alternate process. An economic model will be used to determine if it is more economical to wait and delay the operation, or to use another resource (process).

The routing is regarded as a variable, and is generated at time of need. The roadmap feature of forced process planning (which forces the roadmap solution to use an indicated resource, in this case, a resource that is idle at the required period) is

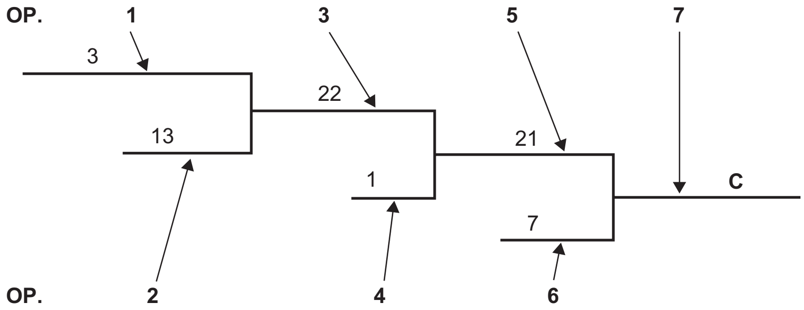

Fig. 6.5 Sequence of resource loading

used. In many cases, the difference in time between the "best" process and the first (and second) alternate process is negligible. By this method, *no bottlenecks* in production will result, and no bottleneck resolution procedures will be needed.

3.3.1 The Loading Procedure is as Follows

Scan all the low level items of the working time-based product structure and find the item with the earliest starting date. Search the product structure to find the product and the order, as shown in Fig. 6.5. This order has priority in resource loading. The loading is done from the low-level item, beginning at its first machining operation and forward. Subsequently, use the roadmap to find the item name and quantity and retrieve a process. The retrieved process indicates the number of resources, the name of each resource and the time required for the operation (including set-up and penalties).

Start with the first operation, multiply its time by the quantity (the real quantity and not the bill of material quantity) and divide by the period scale of the row. Determine how many periods are needed for this operation. Scan the column of the appropriate resource and search for an idle period. The search starts at the operation's earliest start period (depending on the previous operations and the product tree).

When an idle period is found, the name of the item is inserted into the row. In the case that the earliest available idle period is too far ahead of the earliest start period, the roadmap will be used to generate an alternate process. The alternate process will attempt to reduce the waiting time by employing a different resource that is idle at the required periods and that it is economical to change. The initially proposed process plan roadmap solution is based on the maximum profit criteria of optimization. However, in many cases, the difference between the alternate process plans is negligible. Blocking the occupied resource (using the "machine blocking" feature) and resolving the roadmap will generate the next alternate routing. If a known resource is idle, the "forced process plan" feature will be used and the economics of using that process plan will be examined. This process may be continued until an available space is found.

The sequence of items to be loaded is shown in Fig. 6.5. Assume that item 3 of product C has the earliest starting time. Therefore, product C with all its items is the critical path and has priority. The critical path is items: 3 22 21 C. Therefore, item 3 is the first one to be loaded. The roadmap for item 3 is used and the process plan is retrieved. All its operations are loaded. Next on the critical path is item 22. However, as it is a subassembly, it cannot be assembled without processing item 13. Therefore, item 13 will be treated and loaded next, before item 22. Next on the critical path is subassembly 21. However, it cannot be assembled without processing item 1. Therefore, item 1 will be treated and loaded next. Next on the critical path is assembly C. However, it cannot be assembled without processing item 7. Therefore, item 7 will be treated and loaded next. The sequence of loading will therefore be: 3 13 22 1 21 7 C. Note that items 13, 1 and 7 are independent items. Their starting period might be the same first period as item 3. If there is competition over resources between these items, the sequence will automatically assign the resource according to product priorities. If the slack between the start of subassembly 22 and the end of processing item 13 is too large, the starting date of item 13 will be delayed. In such cases (including the delivery date of the product), safety periods will determine the finish period for item 13 and it will be loaded backward from this period. Initially, the loading is done on a temporary basis. The loading is marked on an auxiliary resource period table that supplements the actual table. This temporary loading checks if the delivery date of the order is met, and what ***the slack*** is, if there is any. In a case in which the delivery date is not met, the temporary loading is erased, and a new attempt is made, this time using the maximum production criteria of optimization to generate a process from the roadmap.

At the end of loading product C, it will be marked as loaded. The process will repeat itself for the remaining orders on the working product structure, until all its products are marked as loaded.

Carrying out the planning actions as described above, results in:

- Minimum processing lead time.
- Meeting the delivery date.
- Resource utilization.
- Minimum work in process.
- Minimum capital tie-down in production.
- Elimination of bottlenecks in production.

3.3.2 Management Control

The loading scale period must be specific to the minute. The number of minutes defines a period. Period size is not of extreme importance. And yet, management should be involved in its definition.

Management should specify what is a “short period of time” to wait until a resource will become available and when an alternative should be sought.

However, if the number of periods for which the job has to wait **in the queue is large**, then the system will use the roadmap to search for an alternate process.

An **economic model** will be used to determine if it is more economical to wait and delay the operation, or to use another resource (process).

Management should **define the length of time** before an alternate process is sought.

Management should develop an economic model to determine when to wait and when to use an alternate routing, which, by definition, will have a processing time longer than the one that has to wait in the queue. (A proposed model might be to compare the alternate routing processing time minus waiting time to the original routine processing time. Data can be supplied by the system).

In cases of slack (i.e., the processing of an item is finished before its due date; as an example, see Fig. 6.5: item #13 is finished before item #3, both of which are required to assemble item #22), management should establish rules as to the size of the slack required for a search for alternatives to begin, or the minimum slack that is tolerable.

Stock allocation and capacity planning are valid for a short period of time and must be re-scheduled at defined periods. The decision as to period length is up to management. Some companies have been known to run it every day (if they have a reliable data collection system). The maximum period length should be once a week.

3.4 Job Release for Execution

Capacity planning establishes the jobs to be carried out in the plant so that customer orders can be met. It is a long-range plan. The actual processing is done on the shop floor, requiring a short-term production plan. The objective of capacity planning is to determine which job to release to the shop floor for execution. Different companies may have different strategies regarding the length of the period for which the jobs are released to the shop floor. Too long a period might result in exceeding the delivery dates, while too short a period might cause idle time at the shop floor level. A period of 1–6 days is commonly used.

Capacity planning is a very important planning task, bridging the gap between long- and short-term planning. To carry out the production plan, jobs have to be released to the shop floor for execution. The jobs in the capacity plan relegated to the earlier periods are to be released to the shop floor for execution.

Before job execution can start, some auxiliary jobs have to be performed. The auxiliary jobs are:

- Fixture design and building.
- Tool preparation.
- NC program generation.
- Material preparation (inventory management and control).
- Material handling (transport).
- Quality control (preparation of method and tools).
- Set-up instructions and set-up.
- Job instruction.

Therefore, jobs for performing these auxiliary jobs have to be released for production to the appropriate department. The jobs for medium range periods, the length of which depends on the specific factory procedures, are used to alert the auxiliary job departments of the jobs that are going to be released for production.

One can distinguish two main strategies in dispatching auxiliary jobs. The first one, which is to be preferred when the execution of auxiliary jobs takes a relatively long time, deals with a release as early as during capacity planning. In this case, the main job is released for execution only after the auxiliary job has been reported ready. The second strategy, which is preferred when the execution of the auxiliary job takes a relatively short time, releases these jobs at the beginning of the scheduling period.

3.4.1 Management Control

As a result of the potential problems laid out above as to overly short or overly long periods, management should specify the length of the period for which the jobs should be released to the shop floor, using the standard of 1–6 days. Too long a period might result in exceeding the delivery dates, while a too short period might cause idle time at the shop floor level. A period of 1–6 days is commonly used.

4 Shop Floor Control

The job release stage deals with the release of jobs that ***must*** be done on the shop floor.

This stage is generally affected in the office under stable conditions. However, conditions on the shop floor are dynamic. Therefore, the decisions on the shop floor must consider the immediate shop floor status, adding flexibility and dynamics to the shop floor control.

The proposed system would involve a shop floor control method that does not plan the routine for each released job in advance, and therefore, bottlenecks cannot be created and disruptions are solved automatically. It is allowed that the process be altered when necessary.

The roadmap method, as previously stated, is a tool that can generate a process that considers the immediate state of the shop floor within a split second.

Shop floor control (SFC) proposes a method that introduces flexibility and dynamics, and thus, simplifies the decision-making in production planning. The SFC method, which is a module of the production management system, proposes that, in order to introduce flexibility, routings should be regarded as a variable. Each expert will generate a routing that meets his needs at the time of need, thereby dramatically increasing manufacturing efficiency.

4.1 Concept and Terminology

The shop floor control approach is based on the concept that whenever a resource is free, it should search for a free operation to perform. A ***free resource*** is defined as a resource that has either just finished an operation and the part has been removed, or is idle and can be loaded at any instant.

A ***free operation*** is defined as an operation that can be loaded for processing at any instant. An example would be the first operation of an item for which the raw material and all auxiliary jobs are done. An intermittent operation is one for which the previous operation has been completed and the part has been unloaded from the resource

The term ***operation*** has a different meaning for production management and scheduling than it has for technology. A ***production management operation*** considers an operation as a set of all the activities done on one resource, from loading to unloading. It does not give any indication as to what the operations are. Production management operations (routing) are used for production planning and scheduling, while technological operations are used for resource set-up and preparing work instructions. A ***technological operation*** is an individual processing operation. The term 'open operation' in the proposed shop floor control approach refers to a technological operation.

The scheduling cycle starts by scanning all resources in search of a free resource. The free resource scans all free operations and lists those it finds. The best operation for a resource can be based on the performance objective, such as minimum processing time or cost. This scanning results in a list of candidates for scheduling.

If the list contains only one entry, then that operation is loaded onto that resource.

If the list contains more than one entry, then the system allocates the operation with the biggest time gap for processing it to another resource.

If the list is empty, this means that there is no free operation available for processing on that resource. Hence, the resource becomes idle, waiting for an appropriate operation. Idleness is a waste of time and such time may be used to process a free operation. Despite increasing processing time, it might be economical. Therefore, the system searches for a free operation that the idle resource can perform for economic reasons, despite not being the best resource for the job. One method to compute the economics of using an alternate resource is to compute the difference in time between the "best" and the alternate operations, and comparing it to the time that the free resource will otherwise be idle.

As an example: suppose that the quantity is 100 units, and the best processing time is 5 min. The alternate resource processing time is 6 min and the waiting time is 150 min. Subsequently, the economic consideration is as follows:

1. To produce the operation with the best resource, it will take $5 \times 100 = 500$ min;
2. To produce the operation with the alternate resource, it will take $6 \times 100 = 600$ min, out of which 150 are replacing the waiting time.

Therefore, the actual processing time is $600-150=450$. Hence, using the alternate resource and working “inefficiently” will save $500-450=50$ min of elapsed time.

If this next operation is more economical or better in terms of performance for this resource, meaning that its processing time (or cost) minus a transfer penalty is equivalent to or lower than the best time of that operation, then the following operation is allocated to that resource.

A ***transfer penalty*** is defined as the time/cost it takes to transfer a job from one resource to another. It includes set-up time, inspection, storage, material handling, etc.

In case of resource breakdown, no special treatment is needed. It will be marked as busy, hence, with no scanning cycle; it will be regarded as a free resource.

In the case of an item being rejected, the product structure is consulted to determine if it will hold assembly. If so, not all items required for that assembly are needed and will be removed from the list of released jobs for the period.

4.2 Algorithm and Terminology

Shop floor control starts with a list of jobs that should be processed in the relevant period. Such a list may be compiled from the roadmap production planning module, or from any other source. The list contains:

1. Job number and name.
2. Quantity.
3. Sequence priority.
4. Order bill of materials.

These jobs are free for execution. However, before job execution can start, some auxiliary jobs have to be performed.

Each of the free jobs retrieves the two dimension process plan roadmap from the company’s database and constructs a 3D roadmap process plan, as shown in Table 6.1 (3D: Resources—Operations—Items).

The algorithm is based on the following records:

The ***resource status file*** records the status of the resource throughout the scheduling period. The data stored is:

- Resource number.
- The loaded item and operation.
- Quantity.
- A link to the bill of materials.
- Resource counter.
- Sequence number of entry in the history file.

The ***resource counter*** is a counter that indicates the time remaining for processing the item. When loaded, it is set by multiplying the quantity by the processing time, as indicated by the 3D roadmap, and is updated at each scan cycle by the time elapsed from the last scanning cycle.

Table 6.1 3D roadmap status when R4 is idle

Op	PR	R1	R2	R3	R4IDLE	R5	R6	BEST	Δ
	I	T	E	M		#3			
10	X	12.5	9.51	5.15	99	4.02	6.54	5	
20	X	5.04	3.93	2.55	99	99	2.82	3	
30	X	6.28	4.86	2.98	2.53	2.47	3.44	5	
40	*00*	*6.38*	*6.12*	*7.05*	*5.78*	*5.93*	*6.83*	*4*	*1.27*
50	40	8.24	6.33	3.67	2.96	2.62	4.42	5	
60	50	5.15	99	4.02	4.86	2.98	2.53	6	
	I	T	E	M		#5			
10	X	3.12	3.17	4.02	3.27	99	99	1	
20	*00*	*13.9*	*10.3*	*10.8*	*9.95*	*12.5*	*99*	*4*	*3.95*
30	20	4.86	2.98	2.53	4.86	2.98	2.53	3	
40	20	6.04	4.68	2.90	99	99	3.32	3	
50	40	5.76	4.47	2.8	99	99	3.18	3	
	I	T	E	M		#7			
10	X	3.12	3.17	4.02	3.27	99	99	1	
20	X	6.15	4.2	8.05	9.3	99	99	2	
30	*00*	*8.34*	*8.92*	*7.58*	*7.23*	*8.76*	*8.12*	*4*	*1,69*
40	30	2.06	2.11	2.96	2.21	99	99	1	
	I	T	E	M		#9			
10	X	4.6	3.60	2.39	99	2.05	2.60	5	
20	X	5.96	4.59	2.87	99	99	3.28	3	
30	*00*	*11.5*	*12.8*	*11.9*	*11.4*	*13.1*	*99*	*4*	*1.7*
40	30	99	99	99	99	1.45	1.72	5	

The ***history file*** keeps track of the actual performance on the shop floor. It keeps the following data:

- Sequence number.
- Resource number.
- Product, item and operation.
- Start time.
- Finish time.

The objective of the history file is to store data for management and production control reports. It can be used to compare planning to actual performance, to arrive at the actual item cost, resource load, etc.

The scheduling module is based on a ***sequence cycle* loop** that examines all resources listed in the ***resource status file***, loads the free resources, and updates the resource counter. The sequence cycle loop starts whenever processing of an operation is finished. At this point, the resource becomes idle and a decision has to be made as to the next assignment.

Sequence cycle time is the elapsed time between present time and the previous sequence cycle loop. The time is retrieved from a ***running clock*** that starts at the beginning of the scheduling process and advances through the working time.

Free resources identify free operations, as per the central concept of SFC, by scanning the "PR" column of the process plan's 3D roadmap. Any operation with PR = 0 is a free operation. A free resource is identified by the resource counter being equal to zero (0).

The sequence cycle loop scans all resources and checks the field resource counter.

If the counter is zero, it means that it was idle in the last scanning cycle, and will be treated as such (see next case).

If the counter is not zero, the sequence cycle time is deducted from the resource counter. If the result becomes zero, it means that the process of the present operation is finished. In this case, the priority field (PR) of this operation is marked by an X, and the priorities of all operations with this operation number are changed to 00.

The next operation on that item automatically becomes free and gets priority in processing, if it is economical to do so. This means that this resource is the "BEST" for this operation or that its processing time/cost minus a transfer penalty is equivalent to or lowers than the "BEST" time of that operation. The operation is allocated to that resource, its resource status file is updated, and its counter is set to the new operating time.

As an example: Table 6.1 represents the shop floor status at a certain time. Operation 20 of item #7 was just finished. It was processed on R2, and operation 30 became free. The best resource for this operation is R4 with 7.23 min per item. A check is made as to whether it is economical to process this operation on R2 in order to save transfer time. The process time on R2 is 8.92. The increase in time is $8.92 - 7.23 = 1.79$. Assuming a transfer penalty of 25 min and a quantity of 40 units, the increase in time is $40 \times 1.79 = 71.6$ and the saving will only be 25 min. Subsequently, it is not economical.

Another case: Operation 20 of item #9 was just finished. It was processed on R3, and thus, operation 30 became free. The best resource for this operation is R4, with 11.4 min per item. A check is made as to whether it is economical to process this operation on R3 in order to save transfer time. The process time on R3 is 11.9 min. The increase in time is $11.9 - 11.4 = 0.4$. Assume a transfer penalty of 25 min and a quantity of 40 units, the increase in time is $40 \times 0.4 = 16$ min and the saving will be 25 min. Subsequently, it is economical, and R3 will process operation 30.

If it is not economical to process the subsequent operation on the previous resource, or if the resource was idle from the previous sequential cycle, then the system scans the matrices of all parts in this particular resource column, and lists all free operations with a best mark on them. This list includes all free operations that the specific resource has been proven to do best.

If the list contains only one entry, then this entry (operation) is allocated to the resource, its resource status file is updated, and its counter is set to the new operating time

If the list contains more than one entry, then the system allocates the operation with the biggest time gap for performing it to another resource. This value is determined by scanning the operation row in the relevant roadmap, and computing the difference between the processing times of the best resource and the alternate resources. Each free operation will be tagged by this difference value. The free operation with the highest tag value will be the one that will be allocated on this sequence cycle to the idle resource.

Table 6.1 demonstrates this algorithm: R4 is idle, and there are four free operations for which it is the best resource. The system scans these operations across all resources and computes the difference between the minimum time (BEST) and the time on each resource. The maximum difference value is in the column marked by $\underline{\Delta}$. In this case, the difference between the BEST resource and the resource processing time of item 5, operation 2 is the biggest ($13.9-9.95=3.95$). Therefore, this operation will be allocated to the R4 resource. Its resource status file is updated and its counter is set to the new operating time.

If the list is empty, a ***"look ahead"*** feature is used to determine the "waiting time" for the best operation to become "free". This search is done by scanning the idle resource column for a free operation. When such an operation is encountered (if it is not the best for that resource), the BEST field of this row indicates which resource is the best for that operation. The entry in the field *resource counter* of the *resource status file* indicates the waiting time for that resource.

An example of this procedure is given in Table 6.2, which shows the status of the 3D roadmap at this stage. R5 is idle and searches for a free operation. The free operations are (PR = 00). A scan of the "BEST" column of the table finds that none of the free operations calls for resource R5. The BEST resource for free item 3, operation 40 is R4. Consulting the *resource status file* in the resource R4 row indicates that operation 40 is in process and will take another 25 min to end, which means that waiting time for operation 40 is 25 min.

The system checks as to whether it will be economical to use the idle resource to process the free operation. One method is to compute the difference in time between the BEST and the alternate operation, and compare it to the time that the free resource would otherwise be idle. If the time spent is lower than the time gained, it is economical to do so. The computation is as follows:

Processing of the free operation, item 3, operation 40 by resource R4 takes 5.78 min per unit. However, resource R4 will become idle after only 25 min. Processing this operation on the idle resource R5 takes 5.93 min per unit. Suppose that the quantity is 100 units; subsequently, by working "*inefficiently*" and increasing the processing time by $(5.93-5.78)\times 100=15\text{min}$, a savings of $(25-15)=10$ min in throughput time is achieved.

Table 6.2 Status when R5 is idle

Op	PR	R1	R2	R3	R4	R5IDLE	R6	BEST
	I	T	E	M		#3		
10	X	12.5	9.51	5.15	99	4.02	6.54	5
20	X	5.04	3.93	2.55	99	99	2.82	3
30	X	6.28	4.86	2.98	2.53	2.47	3.44	5
40	*00*	*6.38*	*6.12*	*7.05*	*5.78*	*5.93*	*6.83*	*4*
50	40	8.24	6.33	3.67	2.96	2.62	4.42	5
60	50	5.15	99	4.02	4.86	2.98	2.53	6
	I	T	E	M		#5		
10	*X*	*3.12*	*3.17*	*4.02*	*3.27*	*99*	*99*	*1*
20	*00*	*13.9*	*10.3*	*10.8*	*9.95*	*12.5*	*99*	*4*
30	20	4.86	2.98	2.53	4.86	2.98	2.53	3
40	20	6.04	4.68	2.90	99	99	3.32	3
50	40	5.76	4.47	2.8	99	99	3.18	3
	I	T	E	M		#7		
10	X	3.12	3.17	4.02	3.27	99	99	1
20	X	6.15	4.2	8.05	9.3	99	99	2
30	*00*	*8.34*	*8.92*	*7.58*	*7.23*	*8.76*	*8.12*	*4*
40	30	2.06	2.11	2.96	2.21	99	99	1
	I	T	E	M		#9		
10	X	4.6	3.60	2.39	99	2.05	2.60	5
20	X	5.96	4.59	2.87	99	99	3.28	3
30	*00*	*11.5*	*12.8*	*11.9*	*11.2*	*13.1*	*99*	*4*
40	30	99	99	99	99	1.45	1.72	5

Resource Status File

Res.	Item	Op.	Q	Link	Counter	Hist.
R4	*#2*	*40*	*60*	*22*	*25*	*66*
R1	*#7*	*03*	*100*	*23*	*87*	*68*

Checking the other three open operations indicates that this is the best alternative. Therefore, item 3, operation 40 is loaded on R5.

If the finished operation was the last one in the processing of an item, the data of that item is removed from the 3D roadmap, freeing the bill of material for another item. The data of the new item (item name and quantity) are recorded and its process plan from the two dimensional roadmap master file is introduced into the 3D roadmap.

In case of disruption, the *finish time* in the *history file* will list the time of the interruption, and the *resource counter* of the *resource status file* will be set to 99, which will be set back to zero when the resource is in working condition again. A new job for that operation (item and operation number) is opened with the remaining quantity. This procedure is for a single or multi-resource disruption.

To validate the flexibility of the proposed system and to check the execution time, a demonstration program was prepared. The demonstration program can handle several orders and parts. However, for simplicity and clarification of the system, 2 orders, 12 items, 35 operations, and 15 resources were considered in the example.

See Appendix—Shop Floor Planning and Control

4.2.1 Management Control

Management should make the decision as to whether to use a Time or Cost roadmap or a combination of both in shop floor scheduling. In the first stages of production planning, it is recommended to use minimum cost roadmap data, because it allows for planning with a longer time element, and thus, leaves a span for emergencies.

Additionally, in the scheduling stage, the method takes care of the disruptions, thus also recommending its use.

The term "penalty" defines the extra time/cost for loading and unloading an item from a resource.

Management should decide how to assign a value to the penalty. It may use a fixed value, or an algorithm depending on: quantity, item processing time, fixtures required, etc.

Scanning for a free resource may result in a list of candidates for scheduling. If the list contains more than one entry, then a decision should be made as to which operation to load.

Management should set the rule (algorithm) for this decision. It is proposed that one should allocate the operation with the largest time gap for processing it to another resource.

If the list is empty, this means that there is no free operation available for processing on that resource. Hence, the resource becomes idle, waiting for an appropriate operation.

Management should define acceptable idle time, in such a case that the resource should remain idle. Over a longer time, management should set economic rules for selecting an operation that eliminates idle time and becomes economical.

In the case that processing of an operation is finished, the next technical operation on that resource should be selected. Each operation may require set-up and payment of a penalty; however, if the next operation is on the same item, no penalty is required, even if it is not the optimum resource for that operation.

Management should define an economic algorithm to decide whether to move the next operation to be processed to the best resource, or to keep processing it at the original resource (so as to avoid paying a penalty).

Flexible production planning treats each order individually. (As opposed to the conventional system, in which items of all orders are combined so as to increase the quantity). However, in the scheduling stage, a rule allowing the combination of jobs can have an advantage in a number of cases.

Management should define the appropriate rules. An example of such a rule might be: Jobs of different orders can be combined into a single batch if they call for the same item for different orders, and:

1. The processing time of the batch is less than (let us say) 60 min.
2. If they are free operations in the same time cycle.
3. Similar items can be handled independently but will have priority for being loaded in union with one another.

Appendix

Shop Floor Planning and Control

The shop floor control (SFC) method introduces flexibility and dynamics, and thus, simplifies the decision-making in production planning. The SFC method, which is a module of the production management system, proposes that, in order to introduce flexibility, routings should be regarded as a variable. Each expert will generate the routing that meets their needs at the time of need, thereby dramatically increasing manufacturing efficiency.

The Strategy

Shop floor control is based on the concept that whenever a resource is free, it searches for a free operation to process. The scheduling module is based on a ***sequence cycle loop*** that examines all resources listed in the ***resource status file***, loads the free resources and updates the *resource counter*, thereby enabling free resources to search for free operations, as per the central concept of SFC.

The resource status file keeps the status of the resource throughout the scheduling period. The data stored in this file is:

- Resource number
- The loaded item
- Quantity
- A link to the bill-of-materials
- Resource counter
- Sequence number of entry in the history file.

The resource counter is a counter that indicates the remaining time for processing an item. When loaded it is set by multiplying the quantity by the processing time, as indicated by the 3D roadmap, and is updated at each scan cycle by the elapsed time from the last scanning cycle.

The history file keeps track of actual performance on the shop floor. It keeps the following data:

- Sequence number
- Resource number
- Product, item and operation
- Start time
- Finish time

The ***sequence cycle*** *loop* starts at the beginning of the session and whenever processing of an operation is complete. At this point, the resource becomes idle and a decision has to be made as to the next assignment. The ***sequence cycle time*** is the elapsed time between present time and the previous sequence cycle loop. The time is retrieved from a **running clock** that starts at the beginning of the scheduling process and advances through the working time.

If the counter is zero, it means that it was idle in the last scanning cycle and will be treated as such.

If the counter is not zero, the sequence cycle time is deducted from the resource counter. If the result becomes zero, it means that the process of the present operation is finished. In this case, the priority field (PR) of this operation is marked by an X, and the priorities of all operations depending on this operation number are changed to 00.

The next operation on that item automatically becomes free and gets priority in processing, if it is economical to do so. This means that this resource is the "BEST" for this operation or that its processing time/cost minus a transfer penalty is equivalent to or lower than the "BEST" time for that operation. The operation is allocated to that resource, its resource status file is updated, and its counter is set to the new operating time.

If the list is empty, a “look ahead” feature is used, as detailed in section 4.2.

Example

Items planned by a job release model to be processed are released to the shop floor for processing. In this example, the selected items are: 1008 903 401 701 405 907 1004 706.

A roadmap of all selected items, including order quantities, is presented in Table 6.3:

The first columns present the resource number, part of the 3D roadmap
Column 16 holds the operation status code Zero (0), meaning a free operation
Column 17 holds the part name and code
Column 18 holds the number of the ***best resource*** for the job
Column 19 holds the quantity
Column 20 holds the modified combined quantity

Combined jobs rules: Jobs for different orders might be combined to a single batch if they are the same item for different orders and:

- The processing time of the batch is less than (let us say) 60 min
- If they are free operations in the same time cycle
- Similar items can be handled independently but will have priority for being loaded in union with one another

In the present example:

Item 707 with its 5 units is combined with item 703, and its quantity is increased to 58 units.

Table 6.3 List of open jobs

R#7	R#8	R#9	#10	#11	#12	16	17	18	19	20
2.86	3.12	99	99	99	99	0	1008	7	20	
2.03	2.33	2.57	99	99	99	0	903	7	49	
99	99	99	7.8	6.6	12.2	0	401	11	70	
99	99	99	7.8	6.6	12.2	0	702	11	53	58
99	99	99	7.8	6.6	12.2	0	405	11	20	
2.03	2.33	2.57	99	99	99	0	907	7	20	
2.86	3.12	99	99	99	99	0	1004	7	52	
99	99	99	7.8	6.6	12.2	0	706	11	5	0
1.91	1.85	99	99	99	99	0	903	8	49	
1.45	1.72	1.96	99	99	99	0	803	7	69	

Item 907 with a quantity of 20 units is below the minimum time, and it is combined with item 903 for a total quantity of 49 + 20 = 69 units.

Such a check is made whenever new items are released for processing, i.e., become free operations.

Start loading. The clock is set at zero and a sequence cycle loop begins.

R#7 is the first resource that finds a free operation—item 903-1.

Its processing time is 69 × 2.03 + 30 (minutes handling time) = 170 min.

It is recorded in the history file and resource counter.

R#11 finds item 401 free. Processing time is 462 min. It is loaded and recorded. (See Tables 4.12 and 4.13.)

As the best resource cannot be found for operations, a second round is done looking for alternatives.

Item 702's best resource is R#11– it is busy; the second best is R#10, which is free. It increases processing time by 70 min., but saves waiting time of at least 170 min. T = 58 × 7.8 + 30 = 482. The system decides to use the alternative and records it.

The best resource for Item 1004 is R#7, which is busy; the second best is R#8, which is free. It increases processing time by 12 min., but saves waiting time of at least 170 min. T = 52 × 2,86 + 30 = 192. The system decides to use the alternative and records it.

All free operations are loaded. Therefore, the second sequence cycle loop will start when the time left (Table 4.12) is at a minimum, in this case, clock time 170 when operation 903-1 is finished.

The remaining time for all resources is reduced by 170, as can be seen in Table 4.12. This sets R#7 as having zero remaining time, and thus, makes it a free resource.

The completion of Item 903-1 releases item 903-2 (second operation) and makes it a free operation.

R#7 is ready to load. The processing time is:
$T = 69 \times 1.91 + 30 = 162$. Thus, it will be finished at $170 + 162 = 332$.

#R No.	Item No.	Start time	Time left initial	T. left initial	Remaining time
7	903-1	0.0	170	0	0
8	1004	0.0	192	22	0
9					
10	702	0.0	487	317	295
11	401	0.0	462	292	270

Chapter 7

Quality Control: SQC & SPC

Abstract Quality control is a process through which management seeks to ensure that product quality is maintained or improved and manufacturing errors are reduced or eliminated. This is done through product inspections.

This chapter presents two statistically popular methods; statistical quality control (SQC) and statistical process control (SPC).

SQC is a technique for error detection and removal of reject items in order to meet quality specifications as specified.

SPC is a technique for error prevention rather than error detection.

1 Introduction

The goals of quality control are to:

- eliminate nonconformities and their consequences
- eliminate rework and wasted resources
- achieve these goals at the lowest possible cost

Quality control is a process through which management seeks to ensure that product quality is maintained or improved and manufacturing errors are reduced or eliminated.

A major aspect of quality control is the establishment of well-defined controls. These controls help ***standardize both production and reactions to issues of quality.***

An **inspection** is, most generally, an organized examination or formal evaluation exercise. In engineering activities, inspection involves measurements, tests, and gauges applied to certain characteristics in regard to an object or activity. The results are usually compared to specified requirements and standards for determining whether the item or activity is in line with these targets. Inspections are usually non-destructive.

It is imperative that manufacturers verify that the products manufactured, shipped and distributed under their brand name meet industry standards, government regulations or their own specific requirements. Quality inspections can help manufacturers:

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- Ensure product safety prior to shipping
- Minimize the amount of defective merchandise
- Reduce customer complaints due to inferior products
- Detect merchandise containing non-standard or non-compliant components
- Eliminate late shipments

Production inspections are ideal for shipments of substantial quantities; product lines with continuous production; strict requirements for on-time shipments; and as a follow-up if poor results were found during Pre-Production Inspection. Normally, Production Inspections are carried out when 10–15 % of the merchandise has been completed.

2 Statistical Quality Control—SQC

SQC Online offers easy-to-use calculators for various popular quality control procedures, based on the International Standards Organization (ISO) and other widely used standards. The standard that is adopted by most companies is ISO 2859. This standard provides tables that give inspection plans for sampling by attributes for a given batch size and acceptable quality level (AQL).

- Rectifying vs. non-rectifying sampling plans: Determines what is done with nonconforming items that were found during the inspection; when the cost of replacing faulty items with new ones, or reworking them, is accounted for, the sampling plan is rectifying
- Single, double, and multiple sampling plans: The sampling procedure may consist of drawing a single sample, or it may be done in two or more steps; a double sampling procedure means that if the sample taken from the batch is not informative enough, another sample is taken; in multiple sampling, additional samples can be drawn after the second sample

An inspection plan includes:

- the sample size/s (n)
- the acceptance number/s (c)
- the rejection number/s (r)

The single sampling procedure with these parameters is as follows:

Draw a random sample of **n** items from the batch. Count the number of nonconforming items within the sample (or the number of nonconformities, if more than one nonconformity is possible on a single item).

If the number of nonconforming items is **c** or less, ***accept*** the entire batch.

If it is **r** or more then ***reject*** it.

In most cases $r=c+1$ (for double and multiple plans, there are several values for the sample sizes, acceptance, and rejection numbers).

The standard includes three types of inspection: normal, tightened, and reduced inspection. The type of inspection that should be applied depends on the quality of the last batches inspected.

At the beginning of inspection, ***normal*** inspection is used. The other types of inspection differ as follows:

- Tightened inspection (for a history of low quality) requires a larger sample size than normal inspection
- Reduced sampling (for a history of high quality) has a higher acceptance number relative to normal inspection (so it is easier to accept the batch)

2.1 Management Control

Management should be the one to decide which one of the available standards to adapt.

Management should decide when to use normal inspection rules, or tightened inspection, and when to reduce sampling size.

3 Statistical Process Control—SPC

SPC products, having been manufactured under a system of error prevention, will be of the required quality because they are manufactured properly and not because they are inspected. Thus, the method increases productivity by reducing scrap and rework and providing continuous process improvement. Other methods—such as flexible manufacturing systems (FMS), computer integrated manufacturing (CIM, and just-in-time (JIT), TQM—that are aimed at increasing productivity concentrate on hardware flexibility, integration of information flow or reduction of inventory. Seldom has a system used technological flexibility to produce ideal products.

SPC is accomplished through technological means, using statistics for detection and technology for prevention.

3.1 Introduction to SPC

SPC is statistically based and logically built around the notion that variation in a product is always present.

There is a natural variation inherent in any process due to wear of tools, material hardness, spindle clearance, jigs and fixtures, clamping, machine resolution, repeatability, machine accuracy, tool holder accuracy, accumulation of tolerances, operator skill, etc. Variation will exist within the processes. Parts that conform to specifications are acceptable; parts that do not conform are not acceptable. However, to control the process, reduce variation and ensure that the output continues to meet the expressed requirements, the cause of variation must be identified in the collected data or in the scatter of data. Collection of these data is characterized by a mathematical model called ‘distributions’, which is used to predict overall performance.

Certain factors may cause variation that cannot be adequately explained by the distribution process. Unless these factors, also called 'assignable causes', are identified and removed, they will continue to affect the process in an unpredictable manner.

A process is said to be in statistical control when the only source of variation is the natural process variation and 'assignable causes' have been removed.

SPC identifies changes between items being produced over a given period, and distinguishes between variations due to natural causes and assignable causes. Corrective action may, therefore, be applied before defective products are produced. A properly conducted SPC program recognizes the importance of quality and the need for a never-ending search to improve quality by reducing variation in process output. Parts will be of the required quality because they are manufactured properly, not because they are inspected. SPC is basically in opposition to methods involving part sorting, such as sorting of conforming parts from nonconforming ones.

Variations that are outside of the desired process distribution can usually be corrected by someone directly connected with the process. For example, a machine set improperly may produce defective parts. The responsibility for corrective or preventive action in this case will belong to the operator, who can adjust the machine to prevent recurring defects. Natural variation will establish process capability.

The process must be under control in order to apply SPC. A process under control has its upper and lower control limits, which establish the suitability of the process to the task and the anticipated scrap and rework percentages. The inherent capability of the process factor (Cp) will indicate if:

- the process is capable
- the process is capable but should be monitored
- the process is not capable

Natural process variation may only be corrected by redesigning the part and the process plan.

Successful SPC control requires action in the form of a monitoring system and feedback loop, in a corrective and preventive action plan. A control chart may be in place to record the average fraction of defectives at a work station, but it is only of marginal value unless the people responsible for the process know what action to take when the process moves out of control.

SPC eliminates subjectivity and provides a means of comparing performances toward clearly defined objectives. The control chart used to identify variability and the existence of assignable causes will be used to track process improvements.

Through application of statistical techniques, problems are identified, quantified and solved at the source in an optimum time. Out-of-Control conditions become evident quickly, as does the magnitude of the problem. With this information, action can be taken before the condition becomes a crisis.

Immediate feedback is the key to the success of any SPC system. SPC is not solely a quality department function. The responsibility for control is in the hands of the producer. This provides the dual advantage of giving the operator a better understanding of what is expected, as well as providing a means of detecting undesirable conditions before it is too late.

3.2 Goals and Benefits of SPC

The goals of an SPC program are consistent with typical company goals of:

- Improved quality
- Increased profit
- Enhancement of a competitive advantage

SPC analyzes and controls the performance of the activities performed on given inputs to produce resultant outputs, i.e., manufacturing processes. A controlled process offers many advantages to both the producer and the consumer.

The producer will attain lower production, rework and scrap costs. In addition to these economic considerations, effective process control may justify a reduction in the amount of inspections and tests performed on the final products.

Specific goals of SPC are as follows:

- *To improve the quality and reliability of products without increasing cost* This objective is not simply an intrinsically 'good' thing to do, but is a necessity for an organization that wants to remain competitive; steps taken to improve a process will result in fewer defects and, therefore, a better quality product delivered to the consumer
- *To increase productivity and reduce costs*—Application of SPC can produce immediate improvements in yield, reduce defects and increase efficiency, all of which are directly related to cost reduction
- *To provide a practical working tool for directing and controlling an operation or process*—Implementation of SPC creates a high degree of visibility of process performance; the same statistical technique used to control the process can be used to determine its capabilities
- *To establish an ongoing measurement and verification system*—Measurements will provide a comparison of performances toward target objectives and will assess the effectiveness of solutions to problems
- *To prioritize problem-solving activities and help with decisions in regard to allocation of resources for the best return on investment*—SPC directs efforts toward a systematic and disciplined approach to identifying real problems; less time and effort will be spent trying to correct non-existent or irrelevant conditions
- *To improve customer satisfaction*—The program ensures better quality and reliability and better adherence to the schedule

Effective process control will enable the producer to fulfill the responsibility of only producing products that conform to standards and delivering them on time, as well as lowering assorted costs and reducing the need for inspections through the detection of out-of-control processes.

The consumer receives products of the required quality and on schedule. Additional benefits are: improved quality, resulting in lower maintenance, repair, and replacement cost, less inventory of spare parts, higher reliability, better performance and reduced time lost due to defective products.

SPC's focus on *defect or error prevention rather than just merely detection*. This means more machine up-time, less warranty costs, the avoidance of unnecessary

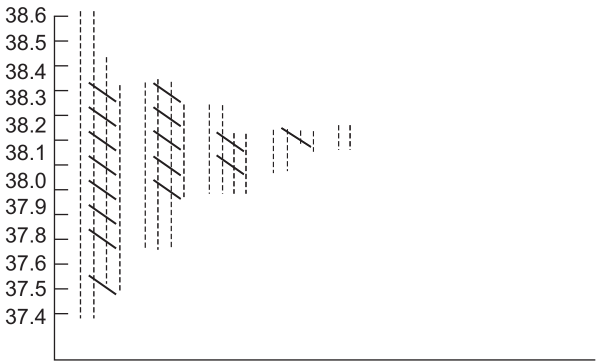


Fig. 7.1 Frequency distribution diagram

capital expenditures on new machines, an increased ability to meet cost targets and production schedules, and increased productivity and quality.

Additionally, SPC has been used as a basis for product and process design. With detailed knowledge obtained from SPC on product variability in regard to process changes, designers have the capability to design and produce items of the required quality from the first piece. Therefore, SPC control not only helps with design, but results in reduced start-up, debugging efforts and cost.

3.3 Basic Statistical Concepts

Statistics has been defined as the science of organizing and analyzing numerical data for the purpose of making decisions in the presence of uncertainty. In SPC, statistics are employed to identify changes between items being produced over a given period, and distinguish between variations due to natural causes and assignable causes.

Natural causes (common causes or constant causes) are the result of distribution of outcomes over a long run, and can be expressed through probabilities. Manufacturing processes behave like systems of natural causes; if left to produce parts continually without change, variations would remain, and could not be altered without changing the process itself.

Assignable causes are events that disturb a process without an immediate known cause, and with an outcome that seems unnatural. A change of material, excessive tool wear, a new operator or accidents may be the catalyst for assignable causes.

SPC aims for the separation of natural causes from assignable causes, and elimination of the assignable causes of variation. The only reliable method of achieving this separation is through the use of control charts, which provide a graphic comparison of a measured characteristic against computed control limits. They plot variation over time, and help to distinguish between the two causes of variation through the use of control limits (Fig. 7.1).

In statistics, the terms ‘population’ and ‘sample’ are used quite often. ‘Population’ refers to the entire collection of units of interest. More precisely, population refers to all the cases or situations to which statistical conclusions, estimates or inferences can be applied. It may be logically impossible or impractical to study all members of the population, and thus, one has to select a smaller portion, known as a sample, to represent the population. A sample is a subset of the units or individuals from the population. Samples are usually pulled in rational groups called subgroups. Groups of samples that are pulled in a manner that show little variation between parts within the group, such as consecutive parts taken on a manufacturing line, are considered rational subgroups. The average value of the subgroup members ($\bar{x}$) will be referred to as the mean.

It is computed by:

$$\bar{x} = \frac{(x_1 + x_2 + x_3 + \dots + x_n)}{n} = \sum \frac{x_i}{n} \tag{7.1}$$

where n is the size of the subgroup.

Once data of several subgroups has been collected, the overall average can be computed. It will be referred to as ($\bar{\bar{x}}$) or the grand average.

$$\bar{x} = \frac{(\bar{x}_1 + \bar{x}_2 + \bar{x}_3 + \dots + \bar{x}_n)}{n} \tag{7.2}$$

where n is the number of subgroups.

It is very difficult and time-consuming to measure every part manufactured, so the use of a *subgroup* and statistical analysis will give an idea of what all the parts in the population look like. The statistical concept that is used to draw conclusions about the population is the measure of the central tendency.

Many processes are set up to aim at a target dimension. The parts that come off the process vary, of course, but they are close to the nominal, and very few fall outside of the high and low specifications. Parts made in this way exhibit what is called a central tendency. The most useful measure of a central tendency is the mean or average. The diagram in Fig. 7.1 displays the frequency distribution. The average value should not necessarily be among the high frequency values, i.e., the average may not provide enough information about the consistency of the subgroup.

Two measures of dispersion are used in statistics: the range and the standard deviation.

The range (R) is a measure of the difference between the highest value and the lowest value of the observation. It gives the overall spread of the data, and is computed by:

$$R = \mathrm{x}_{\max} - \mathrm{x}_{\min} \tag{7.3}$$

The Standard Deviation (σ) of a sample describes how the points are dispersed around the sample mean ($\bar{x}$). The defining formula for the standard deviation of a population of data is:

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{(n-1)}} \tag{7.4}$$

Table 7.1 Constants for statistical equations

Sample size	d_2	A_2	D_3	D_4
2	1.128	1.880	0	3.267
3	1.693	1.023	0	2.574
4	2.059	0.729	0	2.282
5	2.326	0.577	0	2.114
6	2.536	0.483	0	2.004
7	2.704	0.419	0.076	1.924
8	2.847	0.373	0.136	1.864
9	2.970	0.337	0.184	1.816
10	3.078	0.308	0.223	1.777

Note: when the sample size n is large (>30), the denominator $(n-1)$ will be replaced by n.

To make the calculation easier, the following equation has been developed:

$$\sigma_x = \frac{\overline{R}}{d_2} \tag{7.5}$$

where d_2 is a constant taken from Table 7.1.

This equation uses the sample range (R), where the sample size (subgroup) is usually of three to five samples and gives a good estimate of the standard population deviation. However, the sample range is very sensitive to *sample size*. The range value for larger samples will generally be larger than those for small samples. The d_2 constant, depending on n, is designed to give consistent values of σ regardless of the sample size. The value of $\overline{R}$ is computed by:

$$\overline{R} = \frac{R_1 + R_2 + R_3 + \ldots.. + R_k}{k} \tag{7.6}$$

where k is the number of samples, (usually on 20 to 25 small samples).

3.4 Probability of Distribution

There are two basic types of distribution: discrete and continuous. In a discrete distribution, observations are limited to specific values. Typical discrete distribution is the binomial, Poisson and hyper-geometric. Observations that can take any value are a continuous distribution or normal distribution, which is the most useful in statistical quality control.

Some of the characteristics of the normal distribution curve are as follows:

1. It is represented by a symmetrical 'bell-shaped' curve, centered about the mean $\overline{x}$.
2. The two extremes of the curve are asymptomatic, i.e., as the observation values move away from the mean, the curve gets closer and closer to the horizontal axis but never reach it.

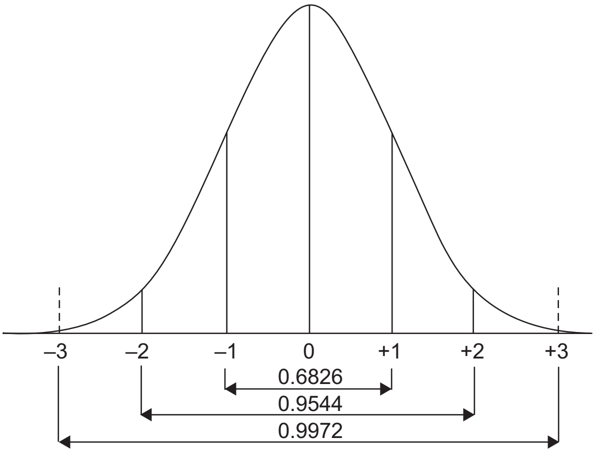


Fig. 7.2 The normal curve

3. The total area under the curve is equal to 1, and so, the area between any two points along the horizontal scale represents the probability or relative frequency of observed value between these two points (Fig. 7.2). Thus, it is sometimes referred to as the normal probability distribution.

A technique for finding the area between any two points uses values from the normal distribution probability in Table 7.2. Any normal distribution can be converted to standard normal distribution by changing the variable x to a variable z by the formula:

$$z = \frac{(x - \bar{x})}{\sigma} \tag{7.7}$$

Example: A process has a product mean $\bar{x} = 25.0$ and the standard deviation is $\sigma = 0.22$. Assume that the product specifications are 24.5 to Find the percentage of products that are outside of the specifications.

Solution: for the upper limit $z = (25.2 - 25.0)/0.22 = 0.909$ from Table 7.2, the area for $z = 0.91$ is 0.1814. Hence, there will be 18.14% product oversize.

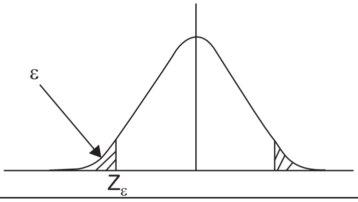
For the lower limit, $z = (24.5 - 25.0)/0.22 = -2.27$. From the above table, the area is 0.0116, i.e., 1.16% of the products will be undersize. Total nonconforming products will be $18.14 + 1.16 = 19.3$%.

3.5 *Prerequisites for SPC—Process Capability*

Process capability is the measure of a process's performance. Capability refers to how capable a process is of producing parts that are well within engineering specifications.

A capability study is done to find out if the process is capable of making the required parts and whether it performs its task as well as it might or if improvements are needed. It should be carried out according to select critical dimensions.

Table 7.2 The nominal distribution probability table



Z_ε	–0	1	2	3	4	5	6	7	8	9
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641
0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1036	0.1020	0.1003	0.0985
1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0147	0.0143
2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019
2.9	0.0019	0.0018	0.0018	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014
3.0	0.0013	0.0013	0.0013	0.0012	0.0012	0.0012	0.0011	0.0011	0.0010	0.0010

To employ and process capability, the process must be under control and have a normal distribution. If the process is not under control, normal capability indices are not valid, even if they indicate that the process is capable.

There are three statistical tools to use in order to determine that the process is under control and follows a normal distribution:

Control charts
Visual analysis of a histogram
Mathematical analysis tests

The control charts (which will be explained in the next section) are used to identify assignable causes. The capability study should be done only for random variations data.

A histogram is a graphic representation of a frequency distribution. The range of the variable is divided into a number of intervals (usually, for convenience, of equal size) and a calculation is made of the number of observations falling into each interval. It is essentially a bar graph of the results. In many cases, a statistical curve is fitted and displayed on top of the histogram.

It is possible to obtain useful information about the state of a population by looking at the shape of the histogram. Figure 7.3 shows typical shapes; they can be used as clues for analyzing a process. For example:

case (a): general type, normal distribution; the mean value in the middle of the range of data and the shape is symmetrical.
case (c): positive skew type; the process capability may be excellent, i.e. it uses only part of the tolerance. However, problems of excessive variation caused by shift and being out-of-control may appear. The cause may be attributed to the machine, the operator, or the gauges.

The $\pm 3\sigma$ of a normal distribution curve is regarded as a reasonable process capability and can be computed from Eq. 7.5. The capability of the process to meet engineering specifications is the comparison of the $\pm 3\sigma$ with the tolerance. Figure 7.4 shows the production tolerance versus $\pm 3\sigma$ of process capability. If the tolerances are within the $\pm 3\sigma$, it means that there will be rejected parts. The probability of the percentage of rejects, rework and scrap can be computed by the method shown in the example given in Sect. 3. If the tolerances are much wider than the process capability, no production problems of size are encountered, and inspection and SPC will most likely not be needed.

The most commonly used capability indices are C_P and C_{pk}. C_P, standing for Capability of Process, is the ratio of tolerance to 6σ. It is computed by:

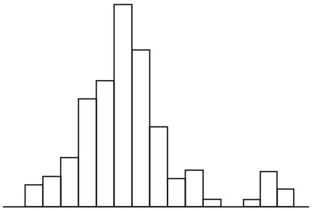
$$C_P = \mathit{tolerance}/3\sigma \tag{7.8}$$

As can be seen, the greater the C_P number, the better the process. $C_P = 1$ means that 99.73 % of the parts will be within engineering tolerances. However, any minute deviation from the mean will produce more rejected parts. Therefore, it is usual to aim for $C_P = 1.33$. Nowadays, a target of $\pm 6\sigma$ or $C_P = 2$ becomes a dominant figure.

(a) General type (b) Comb type

(c) Positive skew type (d) Left-hand precipice type

(e) Plateau type (f) Twin peak type



(g) Isolated peak type

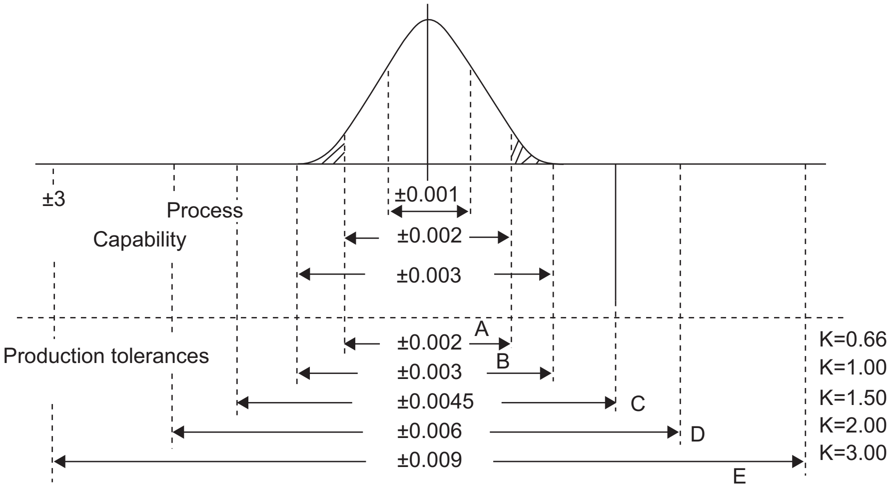
Fig. 7.3 Types of histograms

C_P is only a measure of the spread of the distribution; it is not a measure of centering. The distribution midpoint may not coincide with the nominal dimension, and thus, even when the C_P shows good capability, parts may be produced out of specification. Therefore, the C_{pk} index is introduced.

C_{pk} is a measure of both dispersion and centeredness. It computes the capability index once for the upper side and then for the lower side, and selects the lower of the two as the index. It is computed by:

$$\begin{aligned} A_1 &= (\text{ Upper Specification Limit } - \text{ Mean }) \ / \ 3\sigma, \\ A_2 &= (\text{ Mean } - \text{ Lower Specification Limit }) \ / \ 3\sigma, \\ C_{pk} &= \min (A_1 \text{ and } A_2). \end{aligned} \tag{7.9}$$

Sometimes, a C_R index is used as a substitute for C_P. It is simply the reciprocal of C_P.



Case	Remarks	Samples
A	High production risk; any shift in average will increase failure.	100% inspection is a must
B	No room for process, average shift, accurate setup	1:1 1:3 1:5 depending on part value
C	Standard requirement of system	1:5 1:10 1:15 depending on part value
D	Improve type C	1:15 1:20 1:30
E	Wide open tolerance, no production problems anticipated	Once a day or batch

Fig. 7.4 Production tolerances vs. process capability

3.6 Control Charts

Control charts are tools for statistical process control. Statistics and parameters by themselves are hard to interpret and visualize. The control chart, however, is a pictorial method which enables the operator to tell at a glance how well the process is controlling the quality of items being produced.

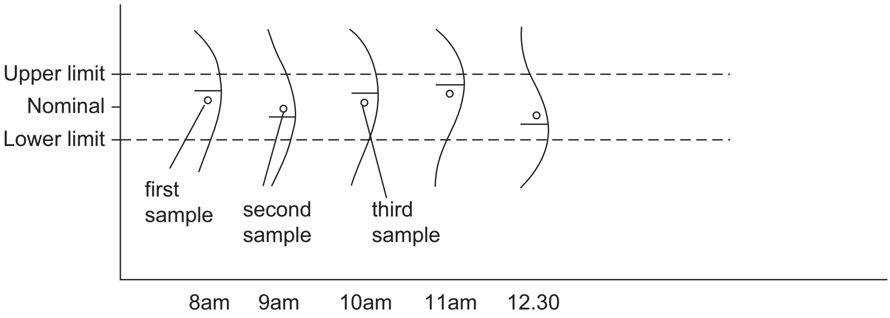


Fig. 7.5 Subgroup and samples

There are essentially two kinds of control charts: control charts for variable data (quantitative measurements) and those for attribute data (qualitative data or count). The variable control charts are more sensitive to changes, and therefore, are better for process control. The $\bar{x}$ and R chart is the most common form of control chart, and one of the most powerful for tracking and identifying causes and variations. In this book, only this control chart will be discussed.

Since the parts coming off a process are in large numbers, we need a way to establish and monitor the process without having to measure every part. This is done by taking samples (subgroups) of 2 to 10 parts (five being the most common amount) and plotting the measurements on a chart (Fig. 7.5). The sideway distribution curve (histogram) represents the mean and the range of each subgroup. The $\bar{x}$ and R chart (Fig. 7.6) is easier to make. Instead of calculating and graphing small histograms of data, separate graphs for the mean ($\bar{x}$) and the range (R) are used.

To interpret the chart at a glance, the centerline and control limits are drawn on the chart.

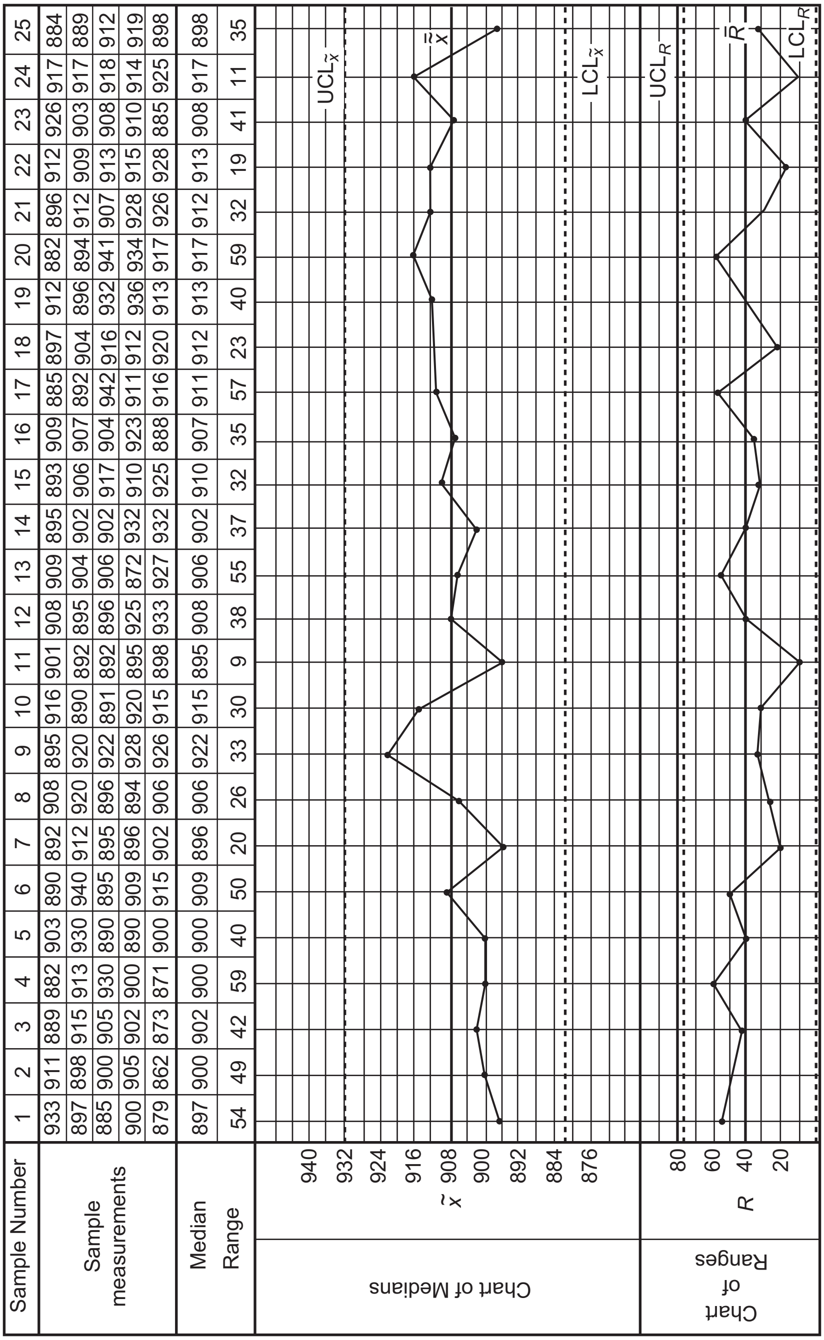
The centerline is marked as $\bar{\bar{x}}$. This is the average of the $\bar{x}$ values and is computed in Eq. 7.2.

The purpose of the control limits on the chart is to indicate if the process is under control, i.e., that 99.73 % of all the average of subgroups $\bar{x}$ will be within these limits. More accurately, "under control" customarily means that all $\bar{x}$ are within the estimated $\pm 3\sigma\bar{x}$ limits of the process.

According to statistical theorems, the sample mean from a normally distributed population is exactly distributed as a normal distribution, and, even if the distribution of a population is not normal, the sample mean is approximately a normal distribution. The approximation holds best for large samples (n), but is adequate for a value of n as low as 5. The formula for calculating the estimated sample deviation is:

$$s = \frac{\sigma}{\sqrt{n}} \tag{7.10}$$

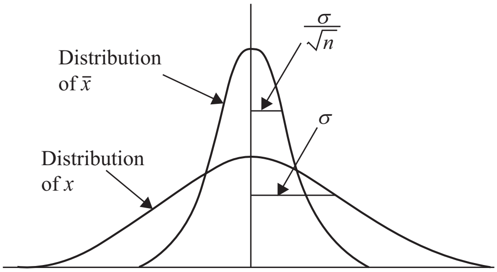
Just as the σ is a measure of variation in a sample, the s is a measure of variation that may be expected when obtaining one observation ($\bar{x}$) from the distribution mean. Figure 7.7 shows the relationship between σ and s.



Sample Number	Sample measurements					Median	Range
1	933	897	885	900	879	897	54
2	911	898	900	905	862	900	49
3	889	915	905	902	873	902	42
4	882	913	930	900	871	900	59
5	903	930	890	890	900	900	40
6	890	940	895	909	915	909	50
7	892	912	895	896	902	896	20
8	908	920	896	894	906	906	26
9	895	920	922	928	926	922	33
10	916	890	891	920	915	915	30
11	901	892	892	895	898	895	9
12	908	895	896	925	933	908	38
13	909	904	906	872	927	906	55
14	895	902	902	932	932	902	37
15	893	906	917	910	925	910	32
16	909	907	904	923	888	907	35
17	885	892	942	911	916	911	57
18	897	904	916	912	920	912	23
19	912	896	932	936	913	913	40
20	882	894	941	934	917	917	59
21	896	912	907	928	926	912	32
22	912	909	913	915	928	913	19
23	926	903	908	910	885	908	41
24	917	917	918	914	925	917	11
25	884	889	912	919	898	898	35

Fig. 7.6 The $\overline{x}$ and R chart

Fig. 7.7 Distribution of $\bar{x}$ and R



An easier method to compute the control limit is to use the following equations:

$$\bar{x} \text{ Upper Control Limit, } U_{\bar{x}} = \bar{\bar{x}} + A_2 \times \bar{R},$$

$$\bar{x} \text{ Lower Control Limit, } L_{\bar{x}} = \bar{\bar{x}} - A_2 \times \bar{R},$$

$$\text{Range Upper Control Limit, } U_R = D_4 \times \bar{R},$$

$$\text{Range Lower Control Limit, } L_R = D_3 \times \bar{R}. \tag{7.11}$$

Where the constants A_2, D_3, D_4 are given in Table 1, $\bar{\bar{x}}$ is computed by Eq. 7.2 and $\bar{R}$ is computed by Eq. 7.6.

The general rule is that at least 20 points on the control chart (20 subgroups) representing 100 measurements are needed before control limits can be calculated.

3.7 Control Chart Parameter Selection

The points on a control chart are the mean and the range of the sample subgroup. In this section, the subgroup size and frequency of taking measurements will be discussed.

A rational subgroup is one in which there is a very low probability of assignable causes creating variation measurements within the subgroup itself. If a subgroup has five measurements, then the opportunities for variation among those measurements must be made deliberately small. This usually means the subgroup should be taken from a batch of pieces made when the process operates under the same setting—one operator and no tooling or material changes.

Five consecutive pieces might be the easiest to collect. The logic behind rational subgrouping is that, if the variability between pieces within a subgroup is entirely due to common causes, then the differences in subgrouping averages and range will be due to assignable causes. The effect of assignable causes will not be buried within a subgroup and dampened by averaging. They will appear on the chart in the form of a point that exceeds the control limits or has an identifiable pattern.

If the time of day may contribute to variations between pieces, then one subgroup of five consecutive pieces from the process should be collected at selected times throughout the day. The time interval between subgroups reflects the expected time of variations in the process and the cost and ease of taking the measurements. In stable processes, every few hours might be satisfactory. In processes in which tools wear rapidly, or other changes in short periods of time exist, short intervals should be used.

If, in a multiple spindle machine, some of the spindles are less scattered than others, the subgroup should be five pieces from one spindle and five from the next rather than one piece away from each spindle averaged together.

An $\bar{x}$ and R chart is used to plot one set of causes. If several different machines contribute to a single lot of parts, a chart of samples taken from the lot will not reveal nearly as much as will separate charts from each machine. On the other hand, if one machine with the same setup produces different parts, one chart may be sufficient to control all the parts, as we control the process and not the parts. To do so, a chart of deviations from the nominal is used instead of charting the nominal itself.

In cases of small lots produced on the same machine with the same tooling, the technique of charting 'moving averages' or nominal or σ might be the answer.

3.8 Interpreting Control Chart Analysis

Analysis is accomplished through the use of control charts, mainly the R chart and the $\bar{x}$ chart. The most common feature of a process showing stability is the absence of any recognizable pattern. The points on the charts are randomly distributed between the control limits. A rare point outside the limits in a process that has shown stability over a long period of time can probably be ignored. The characteristics of a stable process are:

- Most points are near the center line
- Some points are spread out and approach the limits
- No point is beyond the control limits

The characteristics of a non-stable process are:

- points outside the control limits
- four out of five successive points outside $\pm\sigma$ limits
- points crowded near the center line
- two out of three successive points falling outside $\pm 2\sigma$ limits on the same half of the chart
- a trend of increasing or decreasing of seven points
- 12 out of 14 successive points on the same side of the center line
- a cycle or pattern that repeats itself
- patterns that may appear which are unnatural

Figure 7.8 shows several such cases.

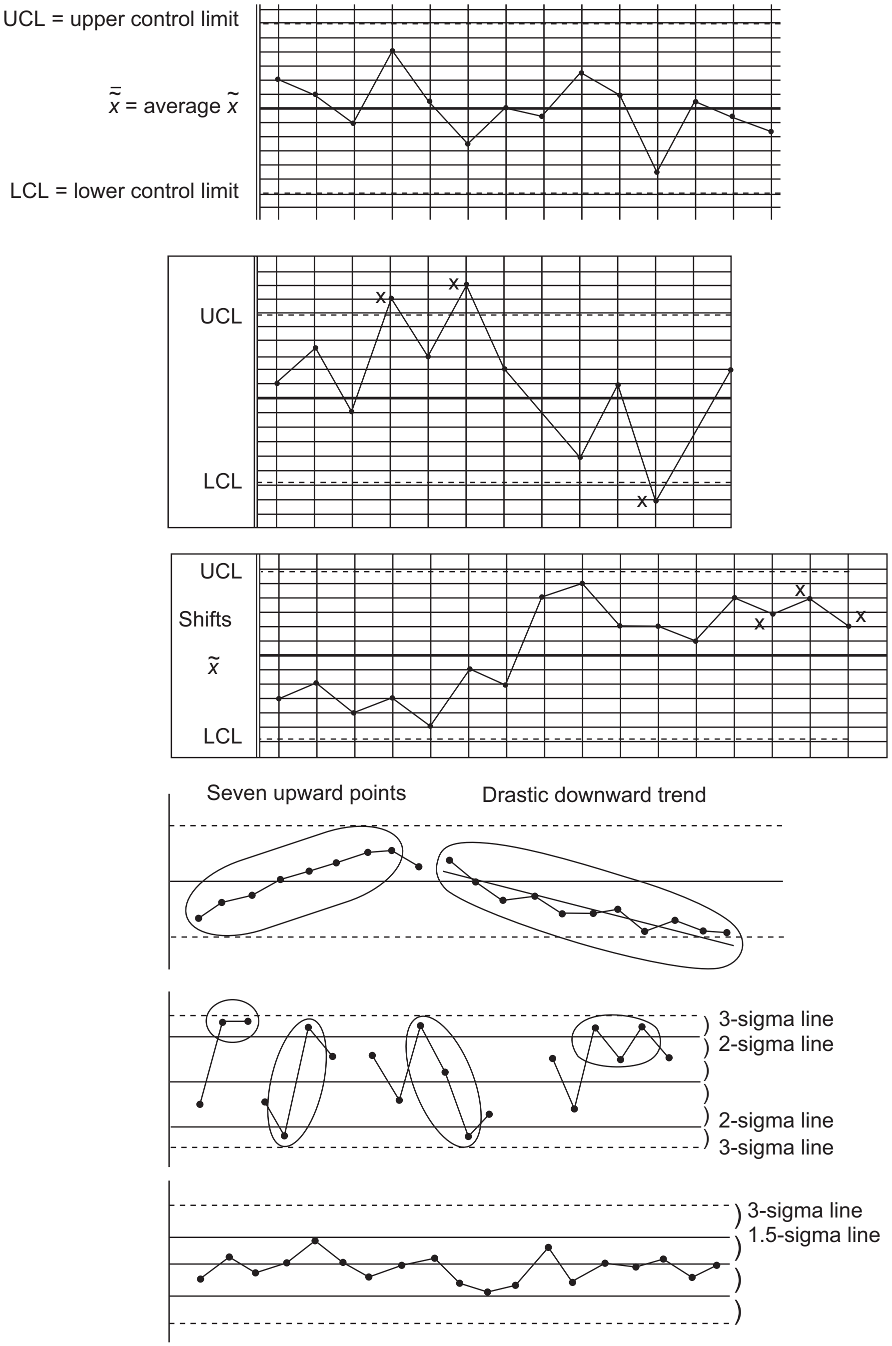


Fig 7.8 Control chart interpretation

It is recommended to review the R chart first, as it is more sensitive to changes. If defective parts start appearing in a process, they will affect the R chart. The variation will increase, so some points will be higher than normal. The lower the points in the R chart, the more uniform the process. Two machines producing the same part may produce different forms of the R chart. Any changes in the process, such as operator inexperience, poor material, tool wear, or lack of maintenance, will tend to shift points upwards.

When the R chart is unstable, the $\bar{x}$ chart can be very misleading. With a stable R chart, the variations on the $\bar{x}$ chart might be due to change of material, temperature change, new tool, machine set-up, gradual tool wear, etc.

SPC controls the process and not the parts. Therefore, any pattern on the charts that is not normal from a statistical point of view should set off an alarm, i.e., something has changed in the process. Action must be taken to correct it. There is a 50 % chance of having one point above the centerline and one point below it. There is also a chance that 68.25 % of the reading will be around the center line, and so on. Any deviation from such criteria should alert the user.

When a point is out of the control limits, the process should be stopped and immediate action should be taken to remove the cause before more incorrect pieces are produced.

When there is a trend, the pieces are still within control; however, in a short period of time, they will run out of control. Therefore, the process might keep on producing parts, but action should be taken to determine the cause and eliminate it.

When all points on the $\bar{x}$ chart are within $\pm\sigma$ and very low on the R chart, it means that all pieces have been produced within control. Statistically, however, the result is too good, and is, therefore, impossible! The process may continue to produce pieces, but action should be taken to learn the cause of this shift in the process. A sticking gauge might be the cause, or a new material or tool.

Action should be taken whenever the process does not behave according to statistical laws, even if it improves the process.

3.9 Cause and Effect Analysis—Troubleshooting

The role of statistics in SPC is to spot variations in the process and to alert the operator to take action when needed. However, it does not tell what action to take. The action is based on technology, and is handled by cause and effect study or troubleshooting technique.

The Pareto diagram is used to highlight the few most important causes and the results of improvements, and assists in determining the relative importance of cause. It can be the first useful document after data collection. Most of the defective items are usually due to a very small number of causes. Thus, if the causes of these few vital defects are identified, most losses can be eliminated by concentrating on these particular ones, leaving aside the other trivial defects for the time being. Figure 7.9 shows a Pareto diagram.

Type of Defect	Tally	Total
Crack	𝍸 𝍸	10
Scratch	𝍸 𝍸 𝍸 𝍸 .... 𝍸 //	42
Stain	𝍸 /	6
Strain	𝍸 𝍸 𝍸 𝍸 .... 𝍸 ////	104
Gap	////	4
Pinhole	𝍸 𝍸 𝍸 𝍸	20
Others	𝍸 𝍸 ////	14
Total		200

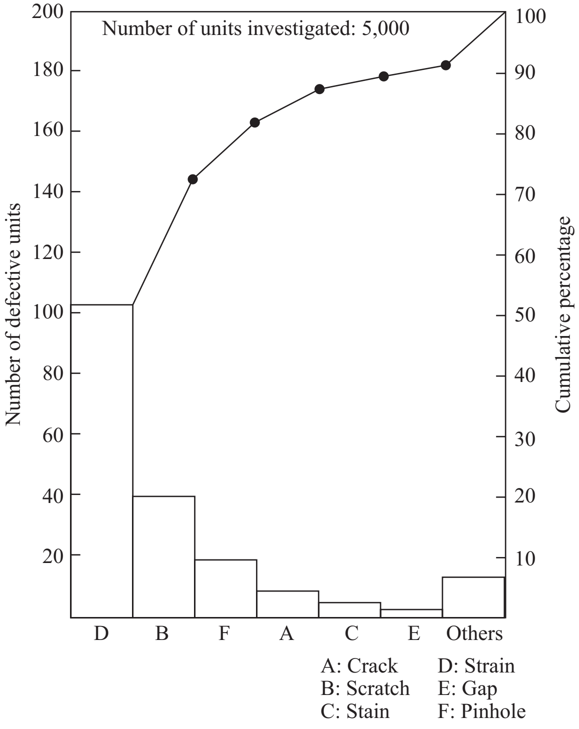


Fig. 7.9 Pareto diagram

Once the problem is defined, a cause and effect analysis should be carried out in order to determine the actions to be taken to remedy the problem. The more widely used approaches to industrial troubleshooting are:

- The ‘What Changed?’ approach
- Conventional approach
- Checklist
- Kepner Tregoe approach

Table 7.3. System event log book

Work station No.			Name:	
Date	Time/Shift	Changes: Oper/insp	Changes: Tools/Mat.l	Special notes
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

- Morphological approach
- Brainstorming
- Weighted-factor analysis
- Quality circle method (fishbone diagram)
- Relevance tree
- Statistical approach (experiment design)
- Simulation
- Expert systems

Variations in products will always be present. The causes may be due to design, process, operator, or assignable causes. The last two are easy to analyze and remedy. Usually, the ‘What Changed?’ approach will give good results. This is used for products that have been manufactured for quite some time with good results, but which have changed. If the effect is changed, then a cause must have occurred at the same time. A quick review of what has most recently changed often provides the clue to the underlying problem. Therefore, it is recommended to conduct a system event log book at each workstation, as shown in Table 7.3.

*Special notes should be taken in regard to any event, such as:

- electricity failure—tool breakage
- visitor interruption—new measuring instrument
- accidents—new set-up.

The conventional approach is the one most people use to solve problems. Hypotheses concerning the cause are made, and some potential solutions are developed based on common knowledge. Trials are carried out until the solution is found. This approach generally is not a good approach for new employees or for personnel who are not familiar with the specific operation.

The other approaches are basically aimed at directing the problem solver to think in a systematic way.

3.10 Management Control

Statistical quality control (SQC) uses specific rules of inspections, stating quantity of production, sample size, allowable defects, and how to treat them, in order to detect errors in manufacturing. Above all, the customers’ demand for quality requires inspection.

The statistics assists in preventing errors rather than detecting them after the fact. Yet, in regard to the internal decisions of the company, the manager might need to exercise some degree of freedom in interfering in the process in order to strengthen or loosen the control, in spite of the statistics.

3.11 Process Capability

It is up to management to decide the working capability desired. Process capability is the measure of a process performance. Capability refers to how capable a process is of producing parts that are well within engineering specifications, i.e. produce items with zero defect and rejects. Zero defects calls for working with ± 3, 6, or even 12 Sigma It can be done if the engineering design specifies generous tolerances, or if the resources are accurate (new) and costly.

In some cases, management may compromise and set a reasonable percentage of rejects, as may be computed by SPC, instead of purchasing more expensive resources.

Such decisions should be made by management.

3.12 SPC Parameters

Several decisions and parameters have to be set in establishing a SPC or SQC system. Most of them are of a technical matter, but affect the quality of the quality control system and its cost.

Such decisions include:

- Sample size, as a function of quantity
- Frequency measures
- A set range with upper and lower limits
- When to get immediate feedback
- Use of manual measuring tools or automatic computerized tools
- Use of operational instructions at the control chart, for dealing with out-of-control
- Whether the operator or inspector does the measuring
- Type of control chart
- Use of Pareto

Management should show some interest in decisions regarding the quality of the system, but mainly in those decisions that affect economics.

Part II
Engineering Support Management

Chapter 8
Inventory Management and Control

Abstract Inventory is an integral part of the manufacturing system. Inventory control is divided into two main parts: *inventory management* and *inventory accounting*. Inventory items may be divided into *dependent items* and *independent items*, and each needs to be treated differently, as described in this section.

Special attention is devoted to methods of inventory accuracy and size reduction and extra-order quantities.

This section discusses the possibility of extending the inventory system to serve as a management control system as well. Using the "two-way concept" can increase the reliability of the inventory system and serve as a *control tool*.

Manufacturing control can be by ***item level*** inventory, or by ***operation level*** production planning.

Many companies find it adequate to work at the item level, leaving the detailed scheduling to production planning and control.

1 Introduction

The main objective of inventory is:

To ensure that the supply of raw material and finished goods will remain continuous so that the production process is not halted and demands of customers are duly met.

The secondary objectives are:

- To minimize the carrying cost of inventory
- To keep investment in inventory at an optimum level
- To reduce losses due to theft, obsolescence, waste, etc.
- To make arrangement for sale of slow moving items
- To minimize inventory ordering costs
- To supply information to several disciplines of the enterprise

From an investment standpoint, inventory is commercially wasteful. However, from an operating point of view, of sales, marketing, production and purchasing, it is essential in order to: reduce the delivery time quoted for the end product; balance seasonal demand fluctuations; and take advantage of volume discounts in purchas-

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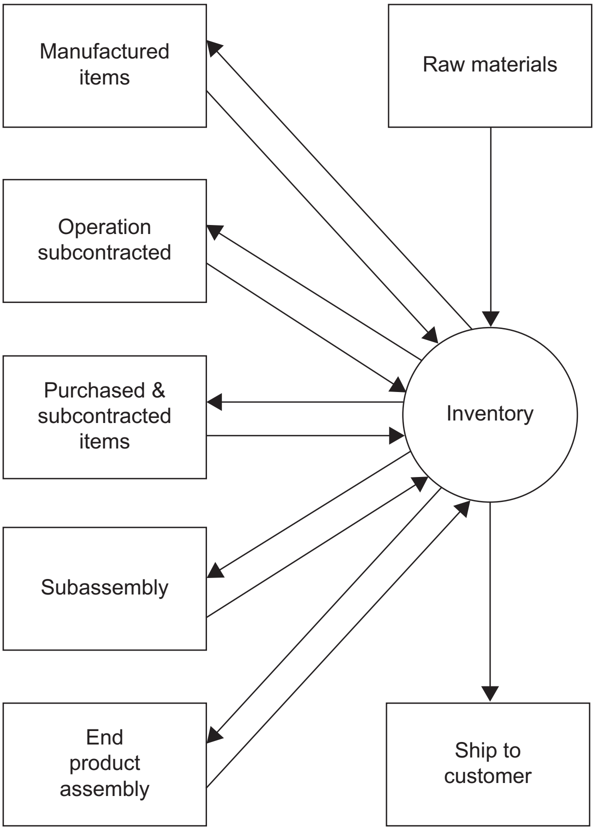

Fig. 8.1 Manufacturing activities flow

ing and manufacturing. Management is in a conflict of interest between the different disciplines of the organizational standpoints and has to find the optimum compromise in setting inventory management policy.

Inventory control is made up of two main functions: *inventory management* and *inventory accounting*.

The objective of inventory management is to keep capital investment in inventory to a minimum while maintaining a desirable service level; this is the planning and controlling aspect of inventory.

The objectives of inventory accounting are to keep track of inventory transactions and to supply information required by other disciplines.

Inventory is an integral part of the manufacturing system. The need for items and subassemblies is established to correspond with the exact date when assembly is scheduled to begin. These are *dependent items*; they depend on the production planning stage. The *independent items* are forecast and planned according to management policy.

Inventory control is central to the various manufacturing activities; in most industries, the activities begin and end in inventory. Figure 8.1 shows this flow of activities. The received raw material is first entered into the storeroom, and then issued to the manufacturing shops, after which the finished items are eventually

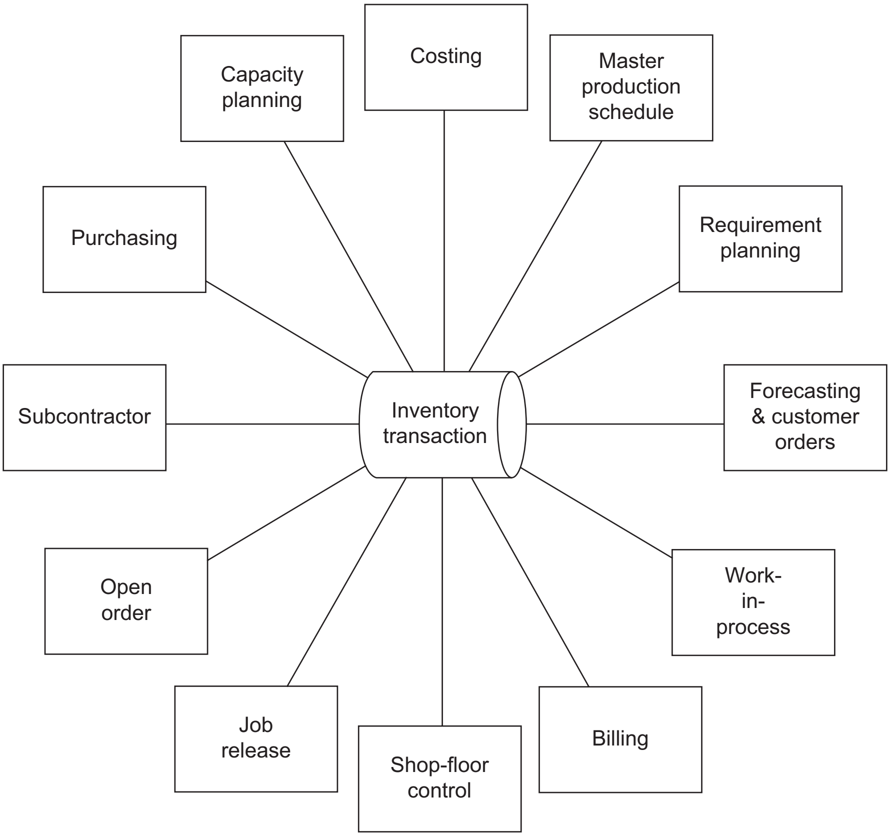

Fig. 8.2 Applications that require inventory data

entered into the stockroom; items are issued for assembly, and subassemblies and finished products are entered into the storeroom; purchased components are entered into the storeroom when received; finally, shipping to customers is carried out from inventory. This procedure places inventory at the juncture point of all activities, thereby making it a good source of information and control concerning the progress of manufacturing. Figure 8.2 shows the applications that require inventory data.

The objective of the inventory system is to supply information required by other systems; thus, the inventory system is a dependent system, relying on the applications desired and on the information required by the integrated system. The inventory system should be designed according to these specifications.

The following are examples of the above-mentioned applications and retrievable information that serve as the objectives of the inventory system:

- Supplying data about on-hand stock to the requirement planning system
- Supplying data to expediters on the availability of items required for assembly
- Supplying data for alternative materials
- Approval of suppliers' bills
- Supplying data on the value of stock to the balance sheet

- Supplying data on material cost to the accounting system
- Control over indirect material usage
- Supplying data to estimate cost of products
- Supplying data on order delivery dates
- Control over quality control of suppliers
- Supplying data to suppliers' rating system
- Supplying data for budget preparation
- Supplying data for evaluation of different price systems in inventory
- Control over dead stock and slow-moving items
- Control over physical count of stock

Inventory is a passive stage in the manufacturing cycle; it does not plan or initiate any activity, but merely serves the active stages. This fact can be used as a management control system for companies that do not wish to control manufacturing at the operation level and are satisfied with controlling it at the part level. This option will be discussed in Section 2.

Inventory transactions are not initiated by the storekeeper, but rather by one of the active stages of the manufacturing cycle. Therefore, each inventory transaction can be validated by comparing it to the planned activities. Figure 8.3 shows the inventory file as a nucleus with many reference files as satellites.

These reference files contain planned inventory activities. Each transaction is marked by a transaction code that indicates in which reference file the initiation of this transaction is recorded. Before updating the inventory file, a validation check will be made against the appropriate file. If the transaction is found to be valid, updating will take place; if not, the transaction will be marked as being in error. The numbers on the connecting lines in Fig. 8.3 indicate the transaction codes (see Appendix). For example, an inventory transaction with code 01 results from a purchasing order. The transaction indicates the item code number, the quantity, the supplier, the order number, and so on; furthermore, it must contain the key to the purchasing orders file. A validation check is made to ensure that the details of the transaction are correct. This is done by retrieving the appropriate record from the purchasing orders file. If all details match, the transaction updates the purchasing record with the quantity received, retrieves the unit price from the purchasing orders file, and records it, and then, the inventory file is updated.

The receipt from the production floor will be validated similarly by comparison with the records in the shop open order file. The receipt from other company stores will be compared with the issues from the same stores, while issues to customers will be validated against the customer orders file.

Issues to assembly will be validated against the shop assembly order file and against the bill of material file to check if the issued item is required for the said assembly and if the quantity issued corresponds with the items per assembly.

The principle of two-way data processing is applied; this saves reporting, and thereby increases the reliability of the reference files. Although the reference files are used for validation checks, at the same time, they can be updated if the transaction is found to be valid. The validation checks that the transaction was initiated at some phase, but at the same time, it also checks the presence of the item in stock and of the reported quantity. Negative on-hand balance, for instance, is unrealistic.

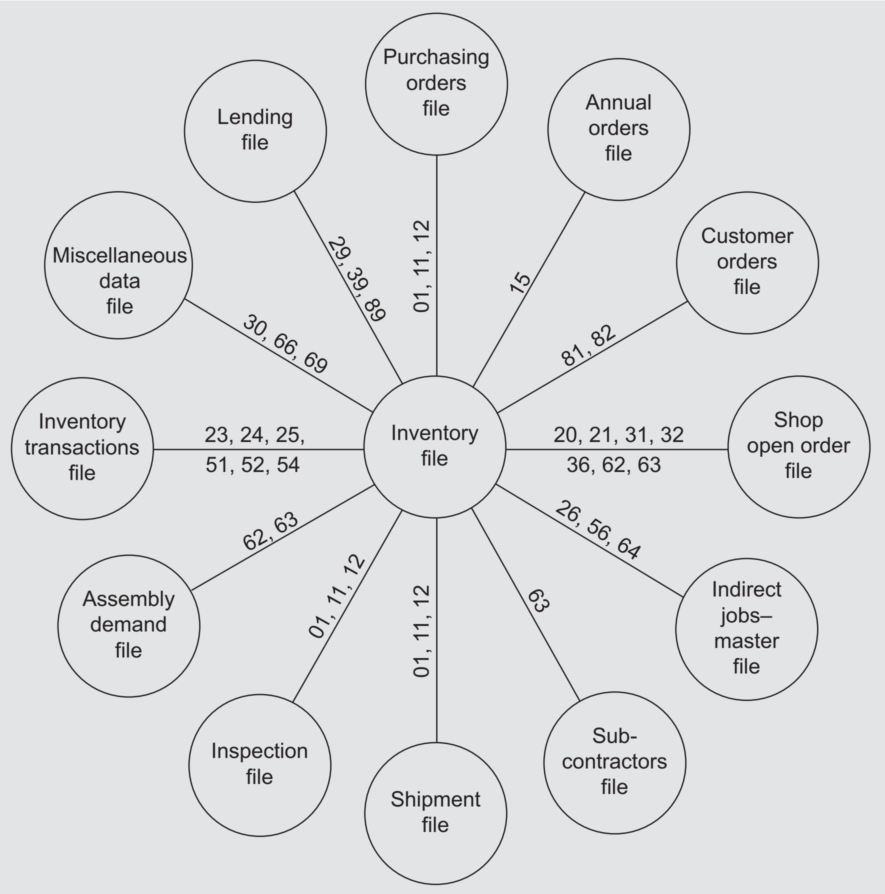

Fig. 8.3 Inventory files as a nucleus with satellites

This technique calls for retrieving all records involved from the appropriate files and bringing them into memory. It performs trial updating in the memory of all records while checking for validity. If found valid, the updated records are rewritten into their files. The use of the database technique is very helpful from the standpoint of programming.

Not all transactions can be so closely controlled. There are some unplanned activities for which no trace and backing can be found in any reference files (e.g., issues for overhead or miscellaneous use or receipts of items purchased and paid for in cash by plant personnel). The transaction code indicates this type of transaction and no validation against a reference file is carried out; however, some logical testing can be done. For example, the value of items received must be low and within company procedure. The issues can be verified according to item type and the department that made the request.

Other types of unplanned transactions include receipt of scrapped quantity, issue of quantity to replace scrapped items in assembly, and receipt of items due to production interruptions. These types of transactions are valid and should be controlled by the production phases, not by inventory. Inventory should serve production and not control its operation. Flexibility is, therefore, recommended in regard to quantities. Although the incidence of transaction errors is minimized through validation tests, inventory discrepancies still occur.

Some of the reasons for this are:

- Errors in count made in receiving or issuing
- Errors in recording unplanned transactions
- Failure to enter a transaction or entering the same transaction twice

To establish confidence in the system, these errors must be corrected. They can be revealed and corrected by physical inventory count. Inventory counts are a legal requirement in some places and company regulation in others.

Traditionally, many companies have shut down manufacturing facilities in order to freeze all stock movements and take a count. Although it seems a perfect tool, errors still occur frequently. Counting is done manually, and even trained personnel make counting errors. Research on this topic indicates that when one counts more than a few 100 units of a single item, it is very probable that mistakes are being made.

Because of the inaccuracy and cost of shutting down production activities, it is recommended that "cycle counting" be used. Cycle counting is a rotating physical count at random intervals. The interval differs for each item. Some of the factors that will determine when to count are:

- *Stock level*- Count when the stock level is low; with fewer pieces to count, the job is easier, faster, and more accurate
- *Number of transaction activities*- A dynamic item with many transactions is liable to be in error; any item should be counted, for example, after 10 transactions
- *Item value*- High-value items should be counted more frequently than low-value items; for example, high-value items should be counted every month, while low-value items can be counted only once a year
- *Physical zero balance*- "Count" any item with physical zero balance; storekeepers know when the physical balance is zero; they should record it on the appropriate transaction, and the balance will be compared to the recorded balance
- *History of discrepancies*- Items that were found to be in discrepancy in the past should be counted more frequently

These factors, and others, should be formalized into an algorithm and be part of the inventory updating program. Thus, the system (management) can decide when it is reasonable to count each item physically. The system can then prepare a list for counting.

Reporting physical count discrepancies is done as an inventory transaction with the appropriate "transaction code."

2 Inventory Control

Inventory accounting is a passive task; however, it has an incredible effect on the company's success. It is one of the major sources of data of production planning. Wrong data will cause missing items for assembly or extra items after assembly. It should be remembered that the average cost of purchased material and items is over 35 % of the processing cost.

2.1 Classification, Coding and Unit of Measure

Maintaining an accurate inventory is the most important function of inventory control. Inventory failures include inaccurate quantity information in the inventory system. A failure in inventory numbers causes problems with purchasing, manufacturing and shipments to customers. Therefore, management should appoint an inventory control analyst with the task of determining how the failure occurred and the steps that can be taken to prevent such failures in the future.

An inventory control analyst is a position that most companies use to monitor and control the most important part of their business. The cost of mistakes in inventory levels can affect the budget of large and small companies alike. When inventory numbers are not accurate, companies are not able to plan production, order materials or ship to customers. The analyst provides detailed information regarding inventory that helps various departments in the company accomplish their duties. This is accomplished with regular physical inventories scheduled throughout the year, cycle counting and transaction strategies to keep the numbers as accurate as possible. Using automatic transactions may reduce inventory errors.

2.1.1 Management Control

Management should treat the accuracy of the inventory record very seriously. It is suggested to appoint a control analyst, preferably but not necessarily from the management level, to be responsible for controlling and setting procedures for accuracy in inventory transactions.

2.2 Inventory Value—Pricing

The value of inventory plays a major role in a company's financial reports; however, its value is a function of the method of calculation. Different methods might result in different values.

There are several methods of pricing the selection of a method depending on **management decision policy**. The following are some methods.

First in first out method (FIFO) is based on the premise that the oldest material together with the price paid for it are issued first. As soon as the oldest lot is used up, the price of the material issue then reverts to that of the next oldest material. Under this method, since the material issued to the plant is charged to the current operation at the oldest price available, and also, since the material in stock is valued at that which most nearly approximates current market value, operating profits are exaggerated on rising prices. Company assets and capital tie-down are large.

The last in first out method (LIFO) is the reverse of the FIFO method. It assumes that the most recently received is issued first. Under this method, the balance sheet will show lower profits and lower capital tie-down on rising prices.

The cumulative—average method is based on recalculating the material price with each new receipt. This new price is calculated as follows:

*old price * quantity on hand + purchased price * received quantity*

Divided by the current on hand + received quantity.

The price and stock value represent the actual amount paid. On rising prices, the average will usually be lower than the current material price, resulting in increased profit, moderate assets, and moderate capital tie-down.

The last price (current price) method is based on adjusting the material price with each receipt. The value of on-hand stock is readjusted and debited or credited to an inventory-variation account. The issue of material is at the current price, and, therefore, does not affect operating profit; the assets are at current value. At the end of the year, the inventory variation account is cleared into a profit and loss account. On rising prices, the profit is clearly shown. The meaning of inventory value is not quite clear, since it does not represent the amount paid or the actual value.

The *standard cost method* is based on charging materials issued with a fixed price. The fixed price is established by estimate or taken from past purchases. Operating cost variations may be clearly analyzed, since no change in material cost occurs. Operating profit and asset value are determined by management. Since the price of receipts of new material varies from lot to lot, an inventory-variation account is used to absorb the variations; this account is finally cleared at the end of the year into a profit and loss account.

2.2.1 Management Control

Management should set procedures for inventory pricing and randomly check to make sure that the actual pricing computations are made according to the policy in practice.

2.3 Material Order Point

Inventory is a necessity in manufacturing. However, the level of inventory must be controlled. In many companies, management has little actual control over the level of this investment. Quite often, inventories tend to grow until some kind of crash program is initiated to reduce them. Investment in inventory is not usually planned; it simply happens. It is almost impossible to control inventory of dependent items (i.e., items that are not sold or ordered by customers as such, but are incorporated into products) without the use of a computer and a requirement planning program. Through this sort of planning, inventory is controlled as an integral part of the manufacturing cycle.

Before the computer became available to assist in such endeavors, one had to apply practical manual systems. In these systems, inventory control was carried out as a standalone application, in which such terms and concepts as order point, safety stock, and economical order quantity were very popular.

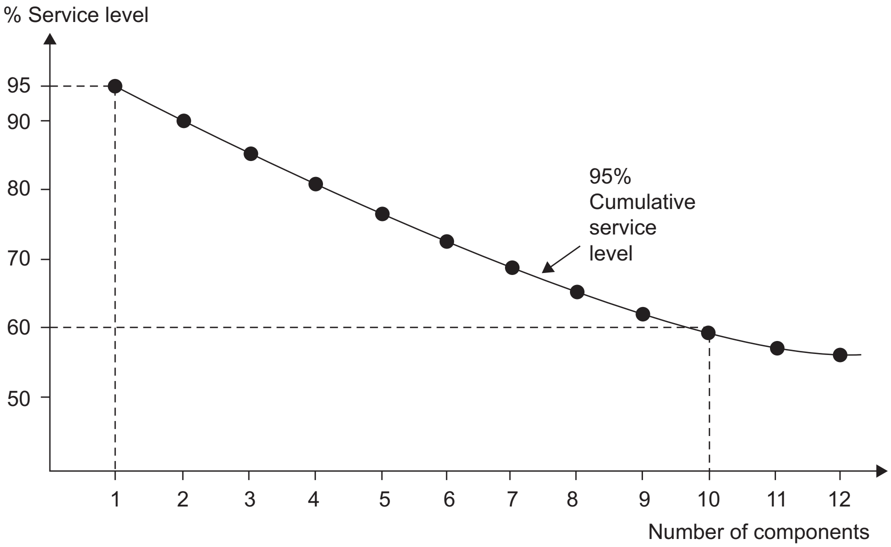

Fig. 8.4 Service level as function of the number of components in an assembly

In the manual systems, the inventory recording procedure, in most stockrooms, regardless of size, employed records of the perpetual inventory type. These usually show the movement of material in and out of stock, as well as the current balance of each item carried. Descriptive and identifying information, such as name, item number, and location in the stockroom, is entered on the record card; such inventory control information as order point and order size expressed in terms of both the minimum and maximum balance quantities is also included. It is very easy for the storekeeper who has updated these records to decide if the balance has reached the minimum value, in which case a new order should be placed to replenish used stock. Each item is treated separately using statistical, economic, and service level considerations, regardless of the production schedule.

When components are forecast independently, their inventories will not usually match assembly requirements well, and the cumulative service level will be significantly lower than the service levels of the parts taken individually.

This is caused by combining the individual forecast errors of a group of components needed for a given assembly.

If there is a 90 % chance of having one item in stock when it is needed, two related items needed simultaneously will have a combined chance of being in stock of 81 %. With 10 items, the odds of all of them being available are 35 %. Even with the service level set, the odds on 10 items would be no better than 60 % (see Fig. 8.4).

This kind of service would be unacceptable at the finished product level, but, in many companies, such a low service level does exist between components and assembly; expediting rush work and an increase in manufacturing costs compensate for this.

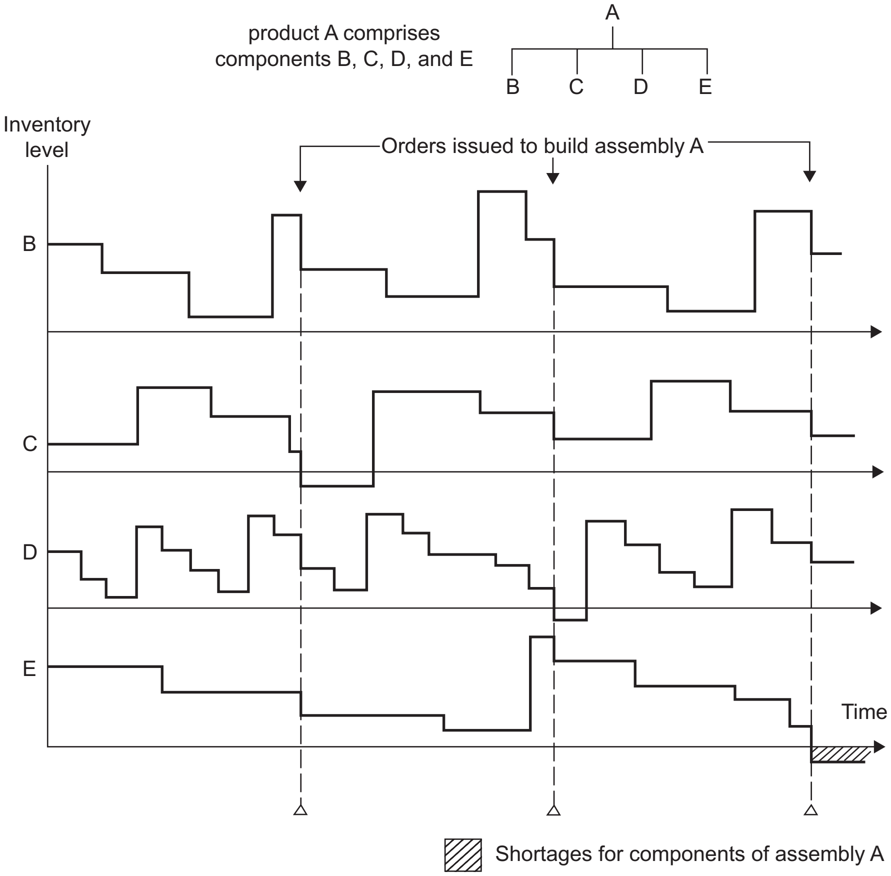

Fig. 8.5 Coordination of the components used in an assembly

Another way of visualizing the timing problem is shown in Fig. 8.5. Each time requisitions for components of assembly *A* are issued, a different component is out of stock. Requirement planning helps avoid this by using planning technique to coordinate component delivery for all required parts, with the intent of achieving 100 % availability of components.

Order point (statistical inventory control) techniques assume relatively uniform usage in small increments of the replenishment lot size. When this basic assumption of gradual inventory depletion is grossly unrealistic, the techniques of order point, safety stock, and economical order quantity will be invalid.

For components of assembled products, requirements typically are anything but uniform, and depletion anything but gradual. Inventory depletion tends to occur in discrete "lumps" because of lot sizing at higher levels. Components are often not available when actually needed because they have been ordered independently of the timing of end item requirements. Even with high safety stock, if two or more different assemblies require an "order point" component simultaneously, it may not be available in sufficient quantity because order point techniques assume that annual demand will average out (typically on a weekly basis).

The fact that some manufacturing companies still get most orders shipped on time even though they use order point systems and maintain safety stocks on components may seem to contradict the above observations. However, such companies do so by carrying unnecessarily high inventories and doing a great deal of expediting. Expediters usually have some kind of "hot list" of assembly components for which there is a shortage and, regardless of the due dates that the inventory system has put on component orders, try to get the right items to the assembly floor.

However, expediters face a dilemma with this hot list. If they expedite only those components for which shortages already exist on the assembly floor, it is obviously a case of too little, too late. On the other hand, if expediters try to anticipate shortages and expedite components on this basis, they will have an extremely long hot list, and the foreman's logical question will be, "Which do you want first?" To do an effective job, expediters really need a series of hot lists; they must break down assembly floor requirements into time periods and indicate by period what the future requirements will be. This concept, extended through a sufficient number of time periods to cover the entire manufacturing lead time, is, in effect, the basis of the technique usually called a "requirement planning system".

Requirement planning systems represent the correct solution to the problems that have been discussed. Such systems embody a set of techniques designed expressly for companies with assembled products the parts and raw materials of which have a demand that is, by definition, dependent. This type of system is a set of procedures and decision rules designed to determine the requirements of inventory items with respect to both quantity and timing on all levels below the end product, and to generate order action such that these requirements are met.

Safety stock is required to absorb a higher than average rate of demand during inventory replenishment. Figure 8.6 shows how safety stock is utilized. Starting from point 1 on the chart, inventory is reduced gradually until it reaches a level called "order point," at which time an order is released. Inventory continues to be depleted until, at point 2, the order quantity is received. However, if inventory is depleted at a higher than average rate, some of the safety stock is utilized (point 3). It is at this point, just before the receipt of the replenishment order, that there is the greatest chance of stock-out.

Safety stock is normally not required when demand is solely dependent. This situation is illustrated in Fig. 8.7. Only when an assembly order is placed for finished product A is demand for component C generated. The demand for component C is very discontinuous. Maintaining a safety stock of, for example, 20 units when faced with a periodic, "lumpy" demand of 100 units does very little good. Assuming a lead time of one period to replenish, the on-hand quantity of component C is kept unnecessarily high until the next shop order for finished product A is generated.

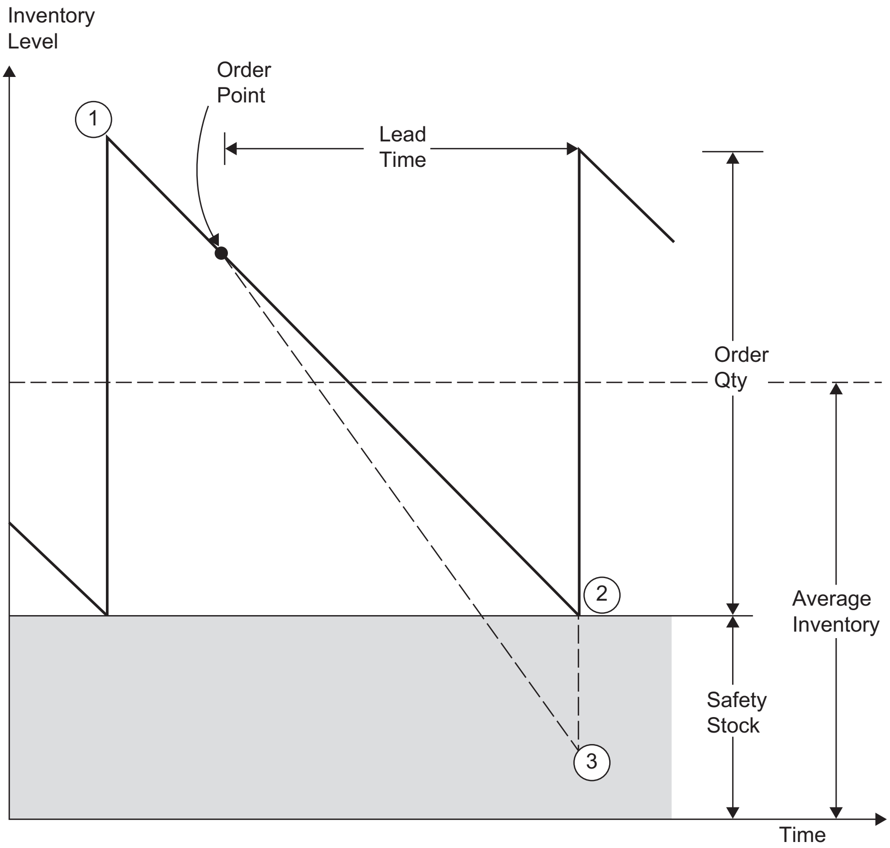

Fig. 8.6 Utilization of safety stock

The ideal situation is represented in the bottom graph of Fig. 8.7. The object is to schedule the production of component C such that it arrives just before being needed in assembling finished product A. In this case, the inventory of component C is carried for only a short length of time. This result is exactly what requirement planning is designed to accomplish: it times the delivery of lower level components so that inventory will be at a minimum. If the component is delivered on time, no safety stock is required and no stock-out will occur.

The size of the order has a significant impact on the average inventory level (Fig. 8.8). Through control of the order size policy, management can regulate the level of inventory. Control is exercised by changing either of the two cost elements that determine order size: inventory carrying cost and order cost.

The theory of economical lot sizing is illustrated in Fig. 8.9 over more units, and the unit cost. As the order quantity is increased, the average level of inventory rises, and the carrying cost, therefore, increases at a constant rate. On the other hand, as the order size increases, acquisition costs (e.g., set-up cost) can be spread over more

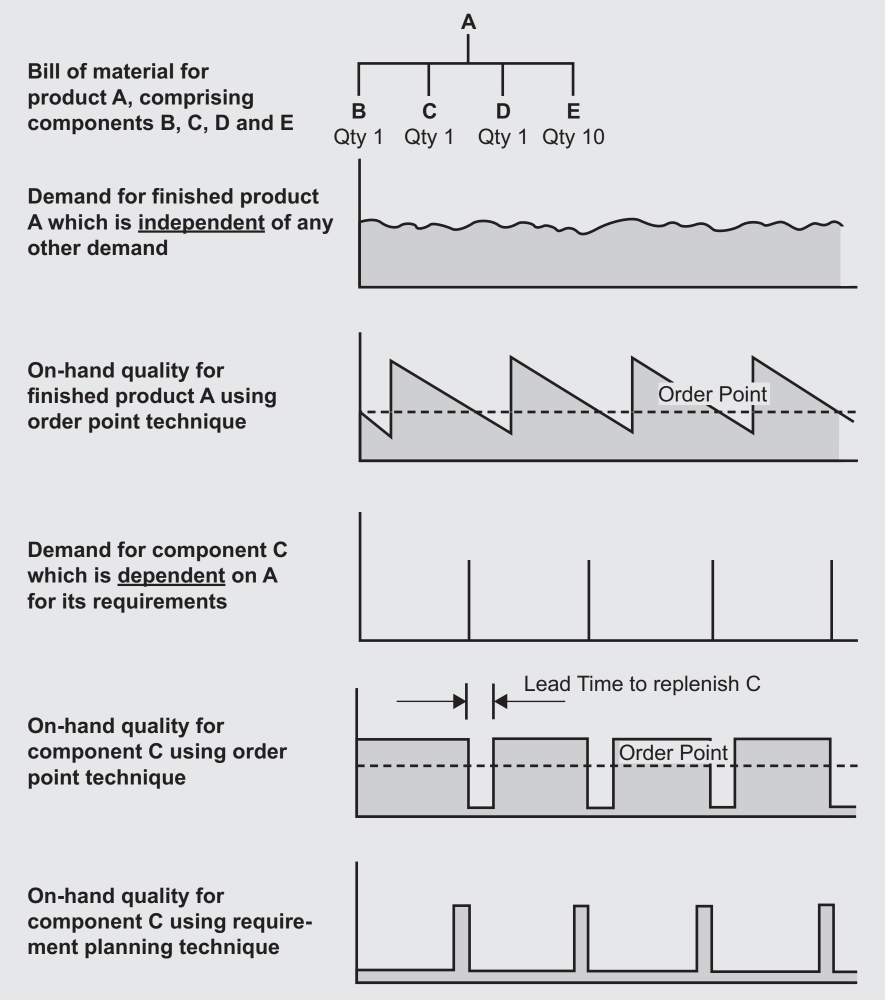

Fig. 8.7 Comparison of on-hand inventory with order point technique and requirement planning

units, and the unit cost, therefore, decreases. The total cost curve in Fig. 8.9 represents the sum of the carrying cost and order cost curve. The point of minimum cost indicates the most economical order quantity.

Many techniques are used to calculate the economic quantity (EOQ). The simplest form is: This equation is easy to use and works well for items subject to a fairly steady demand; therefore, it has found wide acceptance in manufacturing. It assumes that the annual usage is known and that inventory is gradual. In manufacturing, these assumptions are often not true, and thus, the equation ignores the timing of requirements. Therefore, the standard EOQ approach is not recommended for dependent items.

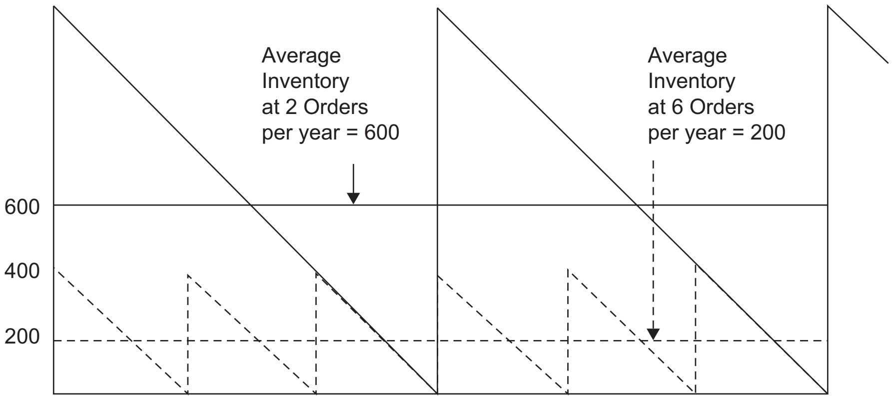

Fig. 8.8 The impact of order size on the average inventory level

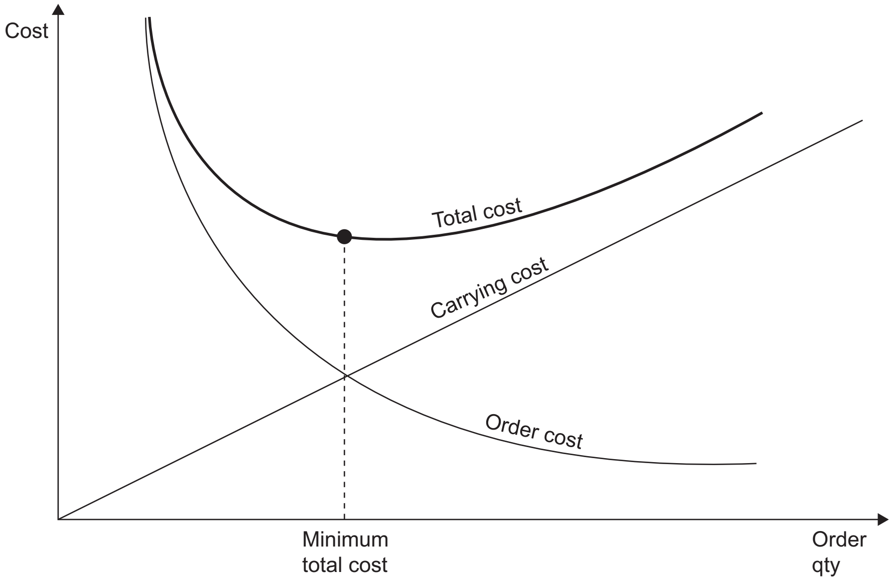

Fig. 8.9 The theory of economical lot sizing

2.3.1 Management Control

Material order quantity should be based on manufacturing orders or forecasting. It has nothing like a regular normal usage, as may be assumed for other materials.

Production planning and scheduling transform the orders into what materials are needed, at which quantity and at what date. These should be the basis for material (and purchasing) orders. Management may (and should) add for scrap, and so on.

2.4 Reduce Inventory Size

Inventory value might represent up to 50 % of the product processing value. A common agreement is that inventory size is not planned, it just grows regardless of efforts to control it. Therefore, special measures should be taken in order to keep growth to a minimum. Raw material inventory value is about 35 % of product processing. However, there are also working tools, spare parts, and various auxiliary items in inventory. The spare parts dominate, likely accounting for about 5–10 % of the total inventory value. This inventory, in many cases, becomes dead stock, as resources did not break or become obsolete. From the management point of view, it just means that the maintenance of the resources was excellent, and the resources were always available for production. It needs to be kept in mind that repair and maintenance personnel must be available, and it is a blessing if they end up being idle most of the time, because that means the processing resources are operating all the time.

A survey taken in one factory came up with the following figures of inventory items:

- There are 85 types of screwdriver
- There are 117 types of brush
- There are 79 sizes of HS drill, ranging from 1 to 10 mm

It does not make sense that they would actually need that many items for production. Although it is not a big deal, since the cost of a screwdriver or a cleaning brush is peanuts, each item still needs storage space, to be kept in the records, to have a catalog number assigned to it, etc. So, it is not the cost of the items that bothers, but the 'domino effect', i.e., once you have 79 sizes of HS drill from 1 to 10 mm, they will be followed by about 79 sizes of screws and bolts and probably rivets, several types of collets, reamers, and so on.

Many errors in inventory records will be due to recording brushes in the wrong catalog record. It will take great effort to trace and amend the records, which will probably end up costing more than the value of the items themselves.

2.4.1 Management Control

Management should consult with the appropriate discipline supervisor and set ratings as to the number of different items in each category. Such ratings should be marked on each auxiliary item record.

This by itself will not eliminate the growth of inventory size, but should be followed by periodic random checks to ensure that the rating of each item quantity is followed.

2.5 Reduce Inventory Size

Dead stock and slow moving items unnecessarily increase the volume and value of inventory, and thus, bias the balance sheet of the company (its inventory value).

The customary definition of dead stock is items in stock with no issue movement for a predetermined period (e.g., 2 years), and a slow-moving item is defined as one with issue movement of no more than, for example, 10 % of balance within a year.

Whereas these terms were suitable for the conventional system, with computerized production planning systems, the definitions should be changed. Modern systems plan future activities and do not count on historical data; thus, for example, a better definition of dead stock would be stock that is not planned for use for a predetermined period in the future. Requirement planning furnishes this information. In an extreme case, if an order was cancelled, dead stock might consist of items that have just arrived or that have not yet been received in inventory**.**

2.5.1 Management Control

***Management should make these decisions* and set *control* to follow.**

2.5.2 Open Stock

Inventory accounting is a passive stage. It does not initiate any activity, but just follows the customer's transactions. In many cases, the cost of issuing a purchase order is more than the value of the product. Therefore, it is proposed to regard such items as 'open stock', which means that one record is kept for all types, an *invoice* will be recorded, and immediate *issue* will be recorded for the entire quantity. The items will be stored in an open space, and anyone that needs them may take what they need and return it after use, all without issue or receipt of transaction slips. This procedure should be adapted to all low-cost items.

It seems that the biggest saving will be by eliminating waste in the activities of direct workers. They should work on the machines or at the work station, and not wander the shop floor to and from the stockroom, which takes time off production, as does standing in line at the stockroom window. Moreover, on the way to the stockroom, they might meet friends and stop to chat. All of this is a waste of processing time.

By reducing the number of stock items, the burden on the inventory recording system will be relieved, simplifying the data collection system.

2.5.3 Management Control

Management should set policy as to which distinct items will be regarded as "free stock" items, and set controls to follow.

Management control should ask for periodic reports on the value of the free stock.

2.6 Classification, Coding and Unit of Measure

From a data processing standpoint, each item in stock must possess a *unique name (barcode)*. This name should correspond to the data processing technique employed and, as far as possible, be short and numeric. It should also serve as the communicating language between all applications using inventory data. The same code should be used in the bill of material, routing, job release, purchasing, inventory files, and so on.

All applications need information on the quantities of materials, such as the definition of quantity per part, quantity on order, and quantity in inventory. The quantity is not self-explanatory, and one must always indicate the meaning of the Figure (unit, kilogram, meter, sheet, pair, etc.) describing the quantity.

It is not convenient to use the actual alphabetic name of the unit of measure, and it may also be a potential source of error. A code should be prepared for the use of the computerized system; the unit of measure assigned to an item usually corresponds to the shop-floor usage of that item, and the same unit of measure will probably also agree with the one designated in the bill of material.

However, for purchasing, a different unit of measure must sometimes be used, although often of the same family (e.g., kilogram in the shop and ton in purchasing, or meter and centimeter, respectively), and thus, easily converted to the other by calculation. On the other hand, sometimes the shop uses steel bars specified by length (according to the part length), but purchases it in kilograms or tons.

The manufacturing system, and especially requirement planning, must speak the same language; thus, for example, since on-hand and on-order quantities are added and subtracted, they must use the same unit of measure. If this difference cannot be avoided, a conversion coefficient for each item must be applied.

Without clear definition, confusion might cause errors in inventory files.

2.6.1 Management Control

Management must check if the inventory system has an appropriate solution to this problem.

2.7 Reduce Inventory Size

There are always rejected items in processing. Items might fall below tolerances, get scratches, tool breaks might leave marks on the item, etc. In a case in which extra raw material is not available, the rejected items will be missing in assembly. There will be rejects during assembly, and there must be extra stock to cover such rejects.

The question is, how much? The estimated percent of rejects is a statistical figure, which means that it was based on a decision of the adopted *confidence level*. The number of rejects is a statistical figure, which varies from one lot to another. Rejects may be caused in processing and/or during the assembly process. The decision of how much extra to order should be based on economic considerations, the risk being taken, the financial status of the company, and, probably, the cost of the item and its criticality in the assembly of the product, since it will increase inventory level.

The estimated number of rejects used in the product explosion is a function of the confidence level that management desires.

Reducing the confidence level from 0.5 to 0.3 % may allow the reduction of inventory by as much as 33 %. In a case in which management can be satisfied with a confidence level of 5 %, then the extra order may allow for the reduction of inventory by as much as 43 %.

2.7.1 Management Control

Management must not consider this decision to be a statistical problem, and thus, leave it to a discipline expert, but rather should set its own policy.

2.8 Left Over

The size by which stock is purchased is not equal to that issued for production. Cut pieces are left over in inventory. An anticipated reject factor is issued to increase the required quantity of items and subassemblies. The actual rejection rate is usually not as anticipated; leftovers will be accumulated from assembly. The reject items are not considered for use by any of the automated systems. If no assembly requires these items, they become dead stock

From a cost standpoint, even if most of the leftover items are rejects, they are still covered and have no reiterated value. If such items can be used, it is practically all savings.

2.9 Extra Order Quantity Size

The cost of raw material in any product is between 35 to 50 %. We regard this cost as a necessity, because without it there would not be a product. However, the value of raw material in stock is about 5–12 % higher than the value of raw material that goes into the products. These figures seem to be correct and reasonable. The reason is that the raw material cost was computed by the theoretical quantity and not by the actual number. The purchased quantity is not theoretical, but the actual number, in order to cover unexpected events.

The steps for computing the theoretical quantity of each item per order and the real number are presented by example of product A, as shown in Fig. 8.10.

The letters represents the items. The number within brackets represents the number of units per assembly. The number within the square brackets represents the estimated percentage of rejects in the process.

Product A is an assembly of one item C, 4 items D, and 2 subassemblies B (level 2).

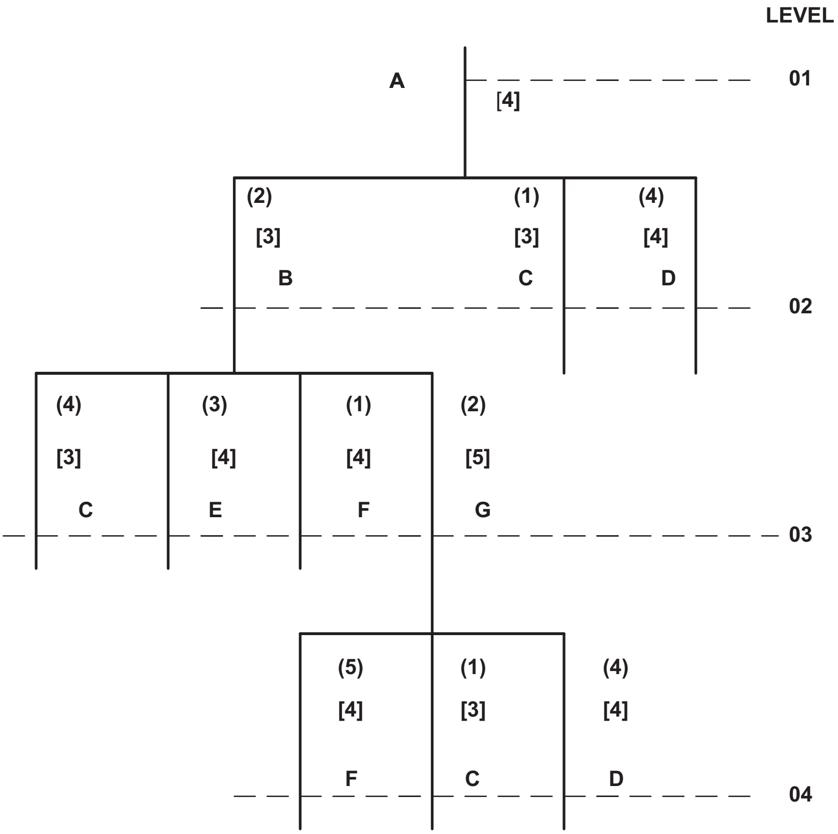

Fig. 8.10 Bill of material (BOM) explosion

Subassembly B is produced by joining 4 items C, 3 items E, 1 item F, and 2 subassemblies G (level 3).

Subassembly G is produced by joining 5 items F, 1 item C, and 4 items D (level 4).

The computations can be obtained from the following steps:

1. Break product A down to its elementary items. The results are shown in Table 8.1, columns 1 and 2. Notice that the number of units is per product and not per assembly.
2. Multiply the units per product (column 2) by order quantity, (assume 100). The results are shown in Table 8.1, column 3.
3. Add the estimated percentage of rejects to the order quantity, as computed in step 2 and presented in column 4.

   For example: To be able to supply 100 units of product A, the estimated reject percentage of 4 % is added, and thus, 104 products should be ordered for processing. 2 Subassemblies B are needed for assembly of 1 product A. Thus, for 104 units, 208 Bs are needed. The estimated reject percentage is 3 %, hence, $208*1.03=214$ B’s should be ordered for processing.

Table 8.1 Product A explosion

ITEM 1	Units/product 2	For 100 products 3	For 100 + rejects 4	Total no rejects 5	Total + rejects 6
A	1	100	104	100	104
C	1	100	108	1,300	1,453
D	4	400	433	2,000	2,097
B	2	200	214	200	214
C	(2*4) 8	800	882	–	–
E	(2*3) 6	600	668	600	668
F	(2*1) 2	200	220	2,200	2,560
G	(2*2) 4	400	450	400	450
F	(4*5)20	2,000	2,340	–	–
C	(4*1) 4	400	463	–	–
D	(4*4) 16	1,600	1,664	–	–

4. A quantity of item C is needed for assembly of 1 item B. Therefore, theoretically, 800 units are needed. Considering item B rejects, 214*4 = 856 items C are needed, and adding the 3 % estimated reject percentage results in 856*1.03 = 882 (881.68). The results are shown in column 4.
5. In order to compare the theoretical quantity to the actual required quantity, columns 5 and 6 are added.

   Examination of columns 5 and 6 shows clearly that the hash total of the actual required quantity is higher by over 11 % of the theoretical total.

Increase of the purchased quantity is a must, because of the inevitability of rejected items in processing. In a case in which extra raw material is not available, the rejected items will be missing in assembly.

A drastic example might demonstrate such a case. Suppose that the rejects of items C are as anticipated, i.e. 1,453 − 1,300 = 153 items. That means that, without extra inventory, there are only 1,300 − 153 = 1,147 items C.

Processing subassembly G uses the required 400 units. That leaves 1,147 − 400 = 747 items C in stock.

Processing subassembly B requires 800 units C, but only 747 are available, and 4 units are needed for each single B, i.e., 747/4 = 187, meaning that only 187 items B can be produced. And no item C remains for the final assembly of the order, i.e., item A.

The result of not purchasing the extra raw material for item C (153 units) will result in not being able to supply even a single unit of the order (item A).

Additionally, there will be leftovers of:

- 26 subassemblies G
- 13 items F
- 39 items E
- 187 subassemblies B
- 400 items D

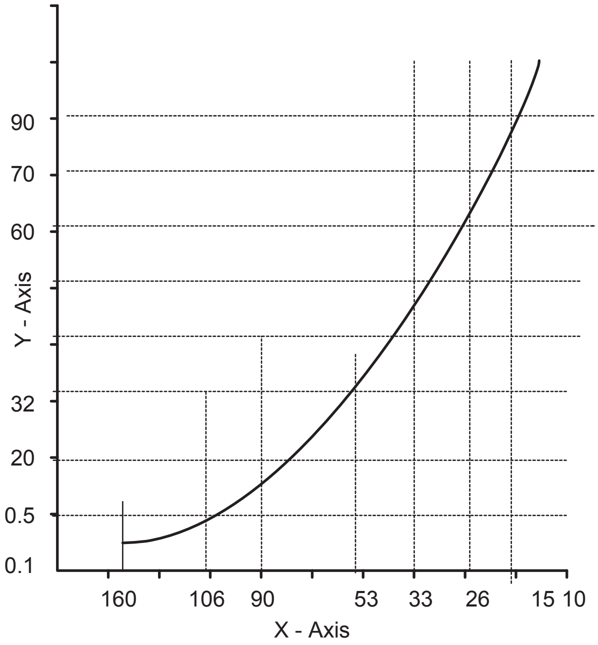

Fig. 8.11 Percentage of rejects as a function of extra inventory

That means that the purchasing of extra material saves money and is not a waste. The question is, how much? To answer this question, a histogram of past rejected items is made for each item. The histogram for item C will probably have a curve, as shown in Fig. 8.11.

The X-Axis represents the quantity of the extra inventory.

The Y-Axis represents the estimated percentage of rejects.

For example, with reference to item C:

When the extra quantity was 160 items in only 0.3 % of the cases, items were missing for assembly.

When the extra quantity was 106 items in only 0.5 % of the cases, items were missing for assembly.

When the extra quantity was 90 items in only 1.3 % of the cases, items were missing for assembly.

When the extra quantity was 50 items in 30 % of the cases, items were missing for assembly.

When the extra quantity was 10 items in 90 % of the cases, items were missing for assembly.

Therefore, the estimated number of rejects used in the product explosion is a function of the ***confidence level that management desires.***

As noted above, reducing the confidence level from 0.3 to 0.5 % may allow the reduction of inventory by as much as 33 % (in this case, from 160 to 106 items).

If management can be satisfied with a confidence level of 5 %, then the extra order should be for 90 items, which means a reduction of inventory by as much as 43 % (from 160 to 90 items).

Number of rejects is a statistical figure, which vary from one lot to another. Rejects may be caused in processing and/or during the assembly process. The decision of how much extra to order should be based on economic considerations, the risk taking, the financial status of the company and probably the cost of the item and its critically in the assembly of the product.

The proposed logic treats one order. However, if the same item (C) is used in more than one product, should the extra quantity be added for each item separately?

It seems to me that, from a statistical point of view, it is improbable that the number of actual rejects will be the same in both orders. It is more probable that, if the process is under control, the leftovers from one order might be enough for use in the other order. In such cases, the extra quantity should be further reduced.

It is a complicated statistical problem; the practitioner's rule of thumb is to order the full quantity for one product, 50 % of the quantity for the second product, 25 % for the third product and nothing for any other products.

3 Inventory System as Management Control Tool

Inventory is central to manufacturing activities. This fact can be used to increase the reliability of the inventory system and use it as a *control tool*.

The proposed inventory system is demonstrated in Fig. 8.3. The reference files contain most of the information required for management control. The information is on an item level, and not on an operation level. The operation level is considered in the production planning system, shop open orders and open assembly shop orders. The inventory system does not know at what operation or stage of assembly the open orders are. However, it contains the information that an order has been issued, the components taken for assembly, and the raw material issued or not issued for manufacture. It also provides information as to whether the assembly or processing has been finished.

Production planning and control will contain the missing information as to the stage (what operation) the order is currently in and when it is scheduled to be completed.

Many companies find it adequate to work at the item level, leaving the detailed scheduling to production planning and control. This section discusses the possibility of extending the inventory system to serve as a management control system as well.

The customer orders file contains the details of the orders. Shipment to the customer is an inventory issue transaction. This transaction will be checked against the customer orders file, and the latter will be updated if the transaction is valid. This file can then be used for reporting of both quantitative and financial open customer orders.

The inventory file is also updated quantitatively and with respect to price. The price value in the inventory file is the actual cost, while the customer orders file contains the selling price. These two files will be used to ***prepare a profit and loss report.***

The purchasing orders file contains the details of the orders. Receiving from a supplier is an inventory receipt transaction; this transaction will be checked against the purchasing orders file, and the latter will be updated if the transaction is valid. Thus, the purchasing orders file can be used to ***prepare financial commitment reports.***

The date when the goods were supplied is recorded on the receipt transaction, the promised date is in the purchasing record, and the quantity, number of rejects, and discrepancy between documented and actual quantity is in the shipment and inspection files. This information can be used to prepare the ***suppliers' rating value.***

Upon updating inventory balance, the unit price is retrieved from the purchasing orders file, the actual price of items in inventory thereby being preserved. Receipt transactions of small orders were paid from the petty cash fund, and will, therefore, carry the unit price on the transaction. This will be used as the actual price of the item in inventory.

A report of all transactions that did not follow company procedures with respect to value and type of items will be prepared and submitted to management.

The unit price of receipts from the shop floor is somewhat of a problem. To solve it, it is advisable to extend the shop open order file to contain cost information. The finance portion of the record contains the accumulation cost on the part level. Accumulated cost of material and items is updated by inventory transaction. The issue transaction carries the shop order record key, that is, the purpose of the issue-product-part batch. The transaction is checked against the shop open order file. If found valid, the issue quantity updates the inventory balance and the assembly demand file and the cost value of the issue is added to the accumulated material and items issue value field of the shop open order file. This accumulation is in actual value, since the inventory pricing system is actual cost.

Subcontracted operations, including price information, are registered in the subcontractors file, and these items will be designated in inventory by a work status code. The price is transferred from the subcontractors file to the inventory file and, when issued to production, to the accumulated subcontractors cost field of the shop open order record.

The design for reliability and the concept of two-way data processing hold true for the job recording system. Each job-card is checked against the shop open order file. If found valid, the information on the job-card is added to the shop open order file record. The hours reported are added to the accumulated working time. The department and cost center number is indicated on the job-card and checked against a table. If found valid, the hourly rate of that work center is known. This hourly rate multiplied by the hours worked gives the actual cost of the work reported on the job-card. This value is added to the accumulated working cost of the shop open order file record.

The sum of the three accumulated fields (labor, material, subcontracting) results in the actual cost of the above shop order.

When the job is finished, the item, subassembly, or finished product is sent to store. Upon receipt, the transaction is checked against the shop open order file. If the transaction is found valid, the quantity updates the "delivered to inventory" field of the shop open order file. The sum of the actual cost is divided by the quantity received, and the actual unit price is computed. The inventory file record is updated by quantity and the inventory unit price.

By this method, the unit price of inventory items is always the actual cost. It starts with individual items, and, as manufacturing progresses, grows gradually to encompass subassemblies, assemblies, and the finished product. It covers all expenses for material, labor, and subcontracted jobs. The actual cost of a product is not computed by the bill of material, since it is theoretical and suitable only for computing the standard cost or estimated cost.

The actual cost is not concerned with standard time per part, standard material, or items per assembly. The accumulated cost is retrieved from the shop floor by the job recording system and inventory transactions.

When rejects occur, and extra material or items are issued, their cost is accumulated and divided by the actual quantity of good acceptable items received and inspected by inventory. If extra material and items have been issued, they are returned to stock and the accumulated cost value credited. This is one of the reasons why the assembly demand file regards the quantity data as information alone and does not restrict or constrain a transaction for which the quantity issue is greater than demand. The accumulated fields are not concerned with standards, but rather with actual occurrence.

A problem arises when partial quantities are delivered to inventory. The question is then what portion of the accumulated cost should be transferred to inventory value and what portion should remain in the accumulated fields.

The solution depends on the method used for pricing, since one method will require more accuracy than another. The cumulative-average method, for example, allows rough division of cost, since, at the end of the batch, the average will be balanced out anyway. In such cases, the standard cost multiplied by a coefficient may suffice.

For more accurate results, the data included in the shop open order file, such as number of operations required, number of operations performed, quantity ordered, and quantity reported in the last operation, can be worked into an algorithm to compute the estimated cost of the delivered quantity. It should be borne in mind that no special reporting system is required.

The information will be updated by the job recording system, which is required anyway for salary, incentive, and other purposes. All of the computations and data transfer are done with no human effort, if the system is correctly designed.

In preparing a monthly or annual balance sheet, knowledge of the value of work-in-process is essential, but determining it always constitutes a problem. Some companies take a physical count of the work near each machine. This provides data on quantity, which must be converted to cost. This is usually done by multiplying the quantity near each machine by its standard cost. Other companies assume that, on the average, all open shop orders are 50 % complete. The value of work-in-process is thus 50 % of the standard cost.

The extension of the inventory system can be used to furnish the required data at any given moment. The actual value of work-in-process is in the system files and is continuously updated. The sum of the accumulated cost fields of all records in the shop open order file is the actual value of work-in-process.

Appendix

Table A8.1 Sample of transaction code

Issues			Date		Accumulation			
			Receipt	Issue	Receipts		Issues	
			(5)	(6)	+(1)	−(2)	+(3)	−(4)
	I.	*Issues*						
51		From central to plant storerooms		0		2		
52		From plant to other storerooms		0		2		
54		From plant to another storeroom within plant						
56		Tools from storeroom to departraent						
	II.	*Production*						
62		Materials for production in plant		6		3		
63		Materials for production by subcontractors		6		3		
64		Materials for overhead expenses		6		3		
66		Wasted tools		6		3		
68		Sundries to outside plants		6		3		
69		Fixtures to plant departments		6		3		
	III.	*Returns*						
71		Sending back of lent materials	0	0		2		
72		Sending back of unsuitable materials	0	0		2		
	IV.	*Sales lendings*						
81		Sales inland						
82		Sales abroad						
89		Lending materials to others						
	V.	*Decrease in balance*						

Table A8.1 (continued)

Issues		Date		Accumulation			
		Receipt	Issue	Receipts		Issues	
		(5)	(6)	+(1)	−(2)	+(3)	−(4)
91	As a result of stock physical counting						
94	As a result of discrepancy in shipment						
95	As a result of catalog numher changes						

Accumulation codes: 1 = + receipts, 2 = − receipts, 3 = + issues, and 4 = − issues Date codes: 5 = update receipt date, 6 = update issue date, 0 = no update, 7 = update receipt date in local store, and 8 = update issue date in locai store

Chapter 9
Resource Planning

Abstract Resource planning is a management decision, not an engineering decision. Management relies on economic models and techniques in making its decisions. Different concerns will adapt different economic models. However, regardless of the economic model employed, the decisions are restricted to the engineering data fed into it.

This chapter presents the roadmap method, the purpose of which is to supply sound engineering data to the decision-makers. The roadmap concept allows management to work with a computer that will supply engineering data in any desired form, eliminating the need to call the engineer each time information or data is needed.

The second part of this paper reviews several resource manufacturing methods.

1 Introduction

An organization in operation is continually undergoing modification, such as changes in equipment, in processes, and in the arrangement of the equipment. In the selection of new equipment, considerable judgment must be exercised to assure sound decisions. Such decisions establish a plant's level of performance, and thus, the ability to compete on the market. The equipment must have the capacity and other technical operating characteristics to enable it to perform the required work. It must also be economically justifiable on the basis of the savings in the various applicable elements of cost.

The need to make decisions concerning the purchase of new equipment may follow production needs or company policy, as detailed in the following:

Production needs might be:

- Adding manufacturing power—When the master production plan shows a continuous overload, management has to decide between expansion and turning down orders; if it decides to expand, new equipment must be purchased.
- Disposal of unsuitable, inefficient equipment—When a machine is continuously underloaded or passed over for selection as the first alternative for any product, management has to decide whether to dispose of it.
- New products—New products might require machine capabilities unavailable in the existing equipment.

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- Technological changes—New design technologies and new materials might call for new types of equipment; such new manufacturing technologies can include precision casting or molding instead of machining, or bonding instead of welding; the technology is added to the engineering files, and new equipment is needed.
- A new generation of machines is introduced—Management has to keep track of technological developments; the new generation of machines should be evaluated from a technical and commercial standpoint.
- Replacement of old equipment—The life of a machine is estimated at 10–20 years; this means that 5–10 % of equipment has to be replaced every year.

Company policy might be that management relies on economic models and techniques (e.g., total value, etc.) in making its decisions. Each company develops its own definite plan for machine replacement policy. Typical policies include:

- Set a definitive amount to be spent each year, such as the amount charged to the depreciation on the present equipment, or a fixed proportion of the net income earned the equipment selection plan is based upon choosing between many alternatives. The choice that results in the greatest gain from the expenditure of the available money will be selected.
- Any machine or equipment that can pay for itself through savings in two or so years will be purchased, whenever such determination is accepted as factual.
- Older and less adequate machinery will be replaced each year on the basis of available funds for such purposes.
- Purchase new machinery only when an increase in productive capacity is desired; some use equipment selection and replacement formulas as a guide to judgment due to many difficulties in forecasting the cost factors to be considered in these formulas, their use must be tempered with experience and judgment; when so used, these formulas become valuable tools in the solution to these problems.

Management relies on economic models and techniques in forming the ***engineering data,*** i.e., product bill of material and routing.

Manufacturing routing describes how items are processed and assemblies produced. Management decisions are based on the basic assumptions that routing is a constraint, while the routing quality depends heavily on the process planner's experience and talent.

The introduction of new machines might have a tremendous effect on manufacturing. New machines usually possess more capabilities than the old ones. However, to make sound engineering decisions and recommendations as to what machines to purchase, all company routings should be examined. Such a task is impractical; it is a huge job, and seldom justifiable for use in general practice.

The engineer is a process planning expert, but not an expert in economics. Their decisions are based upon engineering criteria of optimization, which do not always coincide with those of management. The engineer proposes the "best" resource for the job from their point of view and leaves the purchasing negotiation to others. However, the "best" resource for the job must be a combination of performance and cost. Using the present method, the "best" resource might not be considered at all.

A method for improving decisions by introducing engineering into the economic model is introduced. The basic assumptions of the proposed approach are that ***rout-***

ing is a variable. Engineering's task will be to specify the basic process, called TP—Theoretical Process, which is in their field of expertise. Based upon the TP process, a computer program will construct a roadmap. The roadmap establishes a network of many possible routings while deferring the decision of which one to take to a later stage. The roadmap represents the process planner's knowledge, but adds a new degree of freedom, and allows for economic decisions to be made at the right time and by the qualified professionals. By employing the roadmap concept, sound engineering data can be supplied to the economic models, and real economic decisions can be made.

2 Engineering Support of Management

Engineering support of management decisions and use of the roadmap in resource planning will be described in the following sections.

It would take quite a lot time, cost and effort to evaluate all the alternate resources, and the effort would most likely not be economical. Therefore, the process planner proposes a limited number of alternatives (if any at all) and lets the economist decide which one of them to select. Hence, the "best" alternative might not even be considered, and a biased decision might be reached.

The roadmap represents all possible processing methods. It includes almost infinite process plans without pointing to the "best" process. This is done because the term "best" is an ambiguous one and depends on the criteria employed in optimization. For the process planner, it might mean the process that will result in maximum production, while for the economist it might mean minimum cost of the component, and for management it might mean a compromise between cost and time or maximum profit. Therefore, the decision is left to the user, while the roadmap supplies the data for a meaningful decision.

Resource planning using the roadmap method is composed of several steps, detailed in the following section.

2.1 Step 1: Request for Quotation—RFQ

When the need to purchase a new machine arises, a list of alternate machines is assembled, usually based on catalogs, vendor information, specifications of old machines, or random choices. The process planner has to generate a process plan for each one of the machines, and transfer his recommendations to management for an economic decision. Process planning is quite a laborious task, and it will be quite expensive to evaluate many alternate machines. Each machine has its own specifications that might affect the process planning decisions. Once the process planner makes a decision, it becomes a constraint on all subsequent decisions.

For example, a selected machine imposes constraints on: the cutting power, the torque at the spindle, the maximum depth of cut, the maximum cutting speed and the available speeds and feeds, the machining dimensions, the number of tools that can be used, the accuracy, and the handling times. Similarly, a selected tool imposes constraints on the maximum cutting speed, depth of cut, feed rate and tool life. It is accepted that these constraints are artificial; they are in effect only because of the sequence of decisions made. Another sequence of decisions might result in a different set of constraints, and, therefore, in a different process plan.

To overcome the problem of ***artificial constraints***, the roadmap concept was constructed. Through this concept, a process is generated using only the actual constraints, such as the force that will break the part, the feed rate that will not produce the required surface finish, etc. Employing the concept means that the process planner generates a process plan in the usual way, but using an imaginary machine and tools, generating the Theoretical Process (TP).

The TP process is theoretical from the specific point of view of the shop, but it is practical from a technological standpoint. It does not violate any physical or technological rule. In this sense, the TP indicates the characteristics and features that are most desirable to have in the machine. The term “imaginary machine” might be ambiguous and frightening. It is a machine with unlimited power, with infinite speed, etc. However, one does not have to be alarmed. The “imaginary machine” is the machine that possesses the requirement specifications to perform the TP process plan.

Several operations are required to produce a part. There are roughing operations that require heavy forces, limited accuracy and moderate processing time, while finishing operations require light forces but significant accuracy and usually extensive processing time. The process considers many real constraints, such as part specifications, part shape and strength, fixture, etc. Therefore, most operations will require commercially available machines, with only a few operations requiring special machines. Each operation specifies the power, moment, forces, speed, revolutions per minute, feed rate, size of part, accuracy required by the operation, etc. These data actually point to the “best” characteristics that a machine should possess in order to perform the particular operation in the most economical way.

Therefore, the needs of the individual TP operations will be used as specifications.

2.2 Step 2: Constructing a Roadmap

The TP process operations and priority codes are entered into a roadmap. Following a quick review, the quotations received in response to the RFQ are entered at the heading of the roadmap, i.e., the candidate machines for the selected process plan.

At this stage, the characteristics of each individual resource are known by the quotation received, and the theoretical operation for each individual machine on the roadmap can take place. Only the technical capabilities of the machine are considered (such as: power, speed, moment, etc.). The entry Ti, j or Ci, j in the roadmap is the practical time (T) or cost (C) for performing each operation (i) on a resource (j). Table 9.1 demonstrates this stage of the roadmap.

The following is an example of the adjustments procedure for metal cutting machines:

Table 9.1 Constructing the roadmap—first step

Operation	TP	Priority	Resource RFQ #1	Resource RFQ #2	Resource RFQ #3	Resource RFQ #4	Resource RFQ #5	Resource RFQ #6
010	1.20	0						
020	1.00	010						
030	0.50	020			Ti, j		Ci, j	
040	1.00	020		99999	99999			
050	0.30	040						
060	0.70	040						
070	0.70	050						
Total	5.40							

- *Machine accuracy*. Some machines might be worn out, and thus, their accuracy capabilities are not compatible with the operation requirements. Thus, the machine is not capable of performing an operation. The machining time will be set to high values (999), but the machine remains in the roadmap, because this machine might be best suited to perform another operation. See operation 040 on resource RFQ #2 and resource RFQ #3 in Table 9.1. Moreover, its hourly rate will probably be low, and therefore might make it the best machine by minimum cost criteria.
- *Spindle bore constrains in the lathe*. If the spindle bore diameter of a machine is less than the part diameter, the part cannot be inserted through it. This might mean that the free length in chucking is not controlled by the chucking location of the TP, but rather by the machine. In such cases, the allowable bending forces should be adjusted to the new conditions, and the cutting conditions have to be recomputed. This will affect the machining time.
- *Machine maximum depth of cut*. Each individual machine has its maximum depth of cut value. Chatter might appear above this value. If the operation depth of cut is greater than the maximum value, it must be reduced. The reduction can be made by changing the cut distribution or by splitting the operation into several steps. In either case, the machining time is affected and must be adjusted accordingly.
- *Machine available speeds and feeds*. The TP speeds and feeds were determined by technological constraints, and it was not checked as to whether the required values were available. If the required values are not available on a particular machine, they have to be adjusted. If the required speed is above the machine's maximum speed, the maximum machine speed is selected. It is permissible to decrease the speed, but not to increase it. If the required speed is below the lower cutting limit, the machine is not capable of performing this operation. The machining time will be set to high values (999), and will remain in the roadmap, because it might be best suited to another operation.
- *Machine torque constrains*. Some machines are defined by power and maximum allowable torque on the spindle. On such machines, the operation torque should be examined. If it is higher than allowed, it must be reduced. A first attempt should be made by reducing the feed rate. If this does not work, reduce the depth of cut. The machine time is affected by this constraint and should be adjusted accordingly.

Table 9.2 The roadmap

Operation	TP	Priority	Resource RFQ #1	Resource RFQ #2	Resource RFQ #3	Resource RFQ #4	Resource RFQ #5	Resource RFQ #6
010	1.20	0	5.37	1.56	1.22	5.95	2.15	5.51
020	1.00	010	5.37	1.56	1.22	5.95	2.15	5.51
030	0.50	020	3.76	0.98	0.67	3.53	1.29	3.17
040	1.00	020	8.32	99999	99999	8.54	1.63	6.56
050	0.30	040	1.35	3.48	0.32	2.60	0.42	2.43
060	0.70	040	6.50	99999	99999	7.08	1.40	5.73
070	0.70	050	1.68	0.68	0.44	3.67	0.60	3.41
Total	5.40		32.35			37.31	9.64	32.32

- Note: The constraint (allowable) forces due to part shape, chucking, and accuracy were taken into account in the TP stage, and are the maximum allowed.
- Power adjustment. Power is a linear function of cutting speed and cutting forces. If the power required by the operation is greater than the machine power, the operation power has to be reduced, and thereby, the machining time increased. Initially, an attempt is made by reducing the cutting speed; if it cannot be adjusted, then the cutting forces have to be reduced.
- *Handling time*. Different machines might have different auxiliary features. There are manual machines, computerized machines, hydraulic jigs and fixtures, CNC or DNC machines, etc. The auxiliary features will have an effect on the auxiliary operations time, such as: chuck the part, change speed, change tool, measure the part, etc. Such times are given in the quotation. The Ti, j time of each operation is increased by the time given in the handling table for the operation type on the specific machine. This additional time will differentiate operation time (Ti, j) of machines with similar technical data but built by a different supplier or machine type. It is used to check if CNC or FMS machines are preferred.
- *Time and cost conversion*. The optimization criterion can be either maximum production or minimum cost. Maximum production means minimum machining time. Thus, both criteria call for a path resulting in a minimum value. In order to use one solution method, the content of the roadmap is altered from time to cost. Time is an engineering value and is determined by the operation data. Cost is the multiplication of time by the hourly rate. The hourly rate is a policy decision for an economist or management. The cost of the facility is given in the quotation received. The number of hours that the machine will be used, if needed, may be retrieved from the roadmap solution. The solution indicates the sequence of operations and machines required to reach the minimum processing time. Furthermore, it supplies data according to the capacity needed for production of the specified quantity. These data can be used by the economist in making the decision.

At this stage, the roadmap has real values for any Ti, j or Ci, j, as shown in Table 9.2.

2.3 Step 3: Solving the Roadmap

By using the roadmap format, the solution is transformed from a technological problem to a mathematical one. The problem may be defined as follows: Given a list of operations to be performed and a list of available machines, a decision is required as to which operation to perform on each machine, and what the sequence of operations and operation details should be, using the optimization criterion of either minimum machining time or minimum machining cost.

Extra time or cost should be added to cover extra set-up, and transferal of parts between machines; additional complications in capacity planning and job recording; and additional inspection, and so on, in case of machine change. The savings gained by changing machines must be greater than the additional expenses. The savings, however, must not be in one particular operation. The extra expenses will be refereed as transfer time or cost, and it is a function of the quantity to be produced. It is, therefore, possible that different process plans will result in different quantities. The larger the batch quantity, the lower the transfer time, thus, the higher the profitability of selecting the best machine for each specific operation. Naturally, in each case, the sequence of operations might be different.

The arrows in Table 9.2 indicate the best machine for each operation. Assuming that the total extra expenses for starting an operation on a new machine is 30 min, and the batch quantity is 100 pieces, the transfer penalty per part is 0.3 min.

Therefore, the first three operations should be performed on resource RFQ #3, with a time of 3.11 min. Operation 040 cannot be performed on resource RFQ #3, therefore, the best machine is resource RFQ #5, with a time of 1.63 min.

The accumulating cost is: $3.11+1.63+0.3$ (transfer)$=5.04$ min. Resource RFQ #3 gives the best machining time for operation 050 (0.32 min).

However, the transfer penalty for moving from resource RFQ #5 to resource RFQ #3 has to be added. The machining cost of performing operation 050 on resource RFQ #5 is 0.42 min. Thus, for a potential savings of $(0.42-0.32)=0.1$ min, a penalty of 0.3 min has to be added.

Therefore, it is better to work inefficiently and perform operation 050 on resource RFQ #5.

Operation 060 is best done on resource RFQ #5. Similar consideration is given to operation 070. Therefore, the selected process will be: operations 010–030 on resource RFQ #3 and operations 040–070 on resource RFQ #5, for a total machining time of ***7.46 min***.

Moving operation 070 so that it is performed after operation 050 (it is allowable according to the priority constraint) does not modify the decision. The saving in machining time is only 0.26 min, which is smaller than the penalty value.

For a batch quantity of 1000 PCs, the transfer penalty will be 0.03 min, and it will be profitable to select the operations as indicated by the arrows in Table 9.2 or to improve the machining cost by modifying the sequence of operations to be: operation 010–030 on resource RFQ #3, operations 040 and 060 on resource RFQ #5, and operations 050 and 070 on resource RFQ #3, for a total machining cost of ***6.96 min***.

For a batch quantity of 10 PCs, the transfer penalty will be 3 min, and thus, it is preferable to perform all operations on resource RFQ #5. The total machining cost will be ***9.64 min***.

Alternative generation. In many cases, a minor increase of processing time might result in a major decrease in machine investment. (Law of 80–20). The above roadmap and solution method can be used to examine alternative processes and alternative machines. An alternate process is generated by ignoring (pulling out of the roadmap) a machine during solution.

Economists may generate as many alternatives as they desire. It is possible to introduce such alternatives into a spread sheet, and to compute the optimum investment according to the individual company policy. Some alternatives as a function of quantity have been demonstrated.

2.4 Resource Planning

The economic model may vary from one plant to another. However, the basic data that goes into the model are similar. The required general data might include: machine cost, finance cost, installation cost, maintenance cost, energy consumption cost, labor cost, life cycle, etc. These data are available from the quotation supplied by the machine manufacturer and the accumulated experience of the plant's economics. The required technical data includes the machining time per part, the cost of machining a part, anticipated percentage of rejects, machine utilization per part, product and product mix. These data can be furnished by the roadmap.

The following example demonstrates the power of employing the roadmap as a resource planner. Table 9.2 shows the roadmap with the six proposed machines for the job. In Sect. 2.3, a solution for the best process was demonstrated. However, in this application, the target is to evaluate the cost/performance of these six alternative machines.

The role of the roadmap is to supply objective data to management, who will then make the decision. To accomplish this task, the computer program was programmed to generate many alternative processes, using different machines, criteria of optimization, lot sizes, and penalties. The purpose of generating alternatives is to prepare data that reflects machining time and cost, as a function of the investment in purchasing a new machine.

For purpose of illustration, the following assumptions were made:

- Machine relative purchasing cost is as follows:

RFQ #1	RFQ #2	RFQ #3	RFQ #4	RFQ #5	RFQ #6
1.0	0.2	1.5	1.3	0.7	0.3

- Machine hourly rate is in proportion to its purchasing cost
- The penalty for machine transfer is 0.5

Table 9.3 Alternative resources for producing an item

Alternative		Start	Penalty	Resources	Total time	Total cost	Relative investment	Coefficient of investment (%)
1	T	#5		#5	9.64	6.75	0.7	233
2	T	#6		#6	32.32	9.70	0.3	*100*
3	T	#3	0.5	#3; #5	*7.66**	8.00	2.2	733
4	T	#2	0.5	#2; #3; #5	8.50	7.45	2.7	900
5	T	#5	0.5	#5; #3	9.09	8.18	2.2	733
6	T	#6	0.5	#6; #3; #5	12.45	8.32	2.5	833
7	C	#2	0.5	#2; #5	8.65	*5.39**	1.2	400
8	C	#5	0.5	#5; #2	9.74	6.61	1.2	400
9	C	#6	0.5	#6; #2; #5	13.10	6.76	1.5	500
10	C	#3	0.5	#3; #2; #5	8.81	6.93	2.7	900

* designates the minimum time or cost

The results of the roadmap solution program are shown in Table 9.3. The table shows 10 alternatives for producing the part as indicated by the roadmap shown in Table 9.2.

In the alternative column, an indication is given as to the criteria of optimization used, where “T” means maximum production (minimum time) and “C” means minimum cost.

The “start” column indicates which machine will perform the first operation. The start machine may affect process selection, time and cost, as can be seen in alternatives #7 and #8.

Alternative #7 calls for performing operations 010-020-030 on resource RFQ #2 (4.1 min.), and then continuing on resource RFQ #5 with operations 040–070 (4.05 min.). Thus, machining time is $8.15+0.5=8.65$ min and the cost is $4.1\times 0.5+4.05\times 0.7+0.5=$ **\$ 5.39**.

Alternative #8 starts with operation 010 on resource RFQ #5 (2.15 min.), operations 020–030 on resource RFQ #2 ($1.56+0.98=2.54$ min.), and operations 040–070 on resource RFQ #5 ($1.63+0.42+1.4+0.6=4.05$ min.). Total time on resource RFQ $\#5=2.15+2.54+4.05+2\times 0.5=9.74$ min, while the cost will be $2.54\times 0.5+(2.15+4.05)\times 0.7+2\times 1=$ **\$ 6.61**.

The “Resources” column lists the resource RFQ that takes part in machining the part, while “total time” and “total cost” indicates the totals.

The “Relative investment” gives the relative cost of the resource RFQ that has to be purchased. If more than one resource RFQ is used in the alternative, then the sum of the relative cost is given. For example, the first alternative requires only resource RFQ #5, the relative cost of which is 0.7. Alternative number 4 requires the use of resource RFQ #2, #3, and #5, therefore, its relative cost is the sum of these three machines $0.5+1.5+0.7=2.7$.

The “coefficient of investment” column is the cost relative to the minimum cost of investment.

The smallest relative machine cost is that of resource RFQ #6, which is 0.3, and is regarded as the 100 % investment. All other alternatives’ “coefficients of investment” are computed relative to this minimum value. Hence, alternative #2 will be

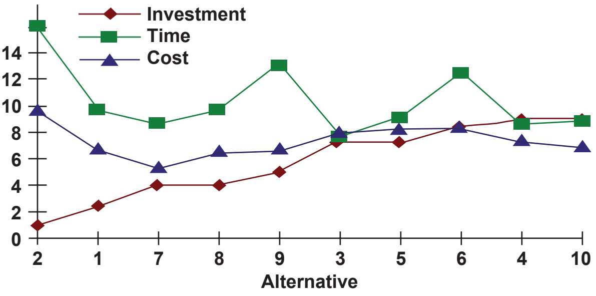


Fig. 9.1 Relationship of investment to processing time and cost

100 %, the minimum required investment, while the investment for alternative #4 (or #10) is (2.7 / 0.3) × 100 = 900 %, meaning nine times that of the minimum investment.

The effect of the amount of investment on machining time and cost is shown in Fig. 9.1, sorted by investment cost.

Examining the data in Table 9.3 and Fig. 9.1 indicates that the "best" machines for the maximum production criterion of optimization (alternative 3) are not the same as for minimum cost criterion. Furthermore, increase in investment by no means assures a better optimum (alternative 7).

Comparing the minimum time alternative (#3) to the minimum cost alternative (#7) indicates that an increase in machining time by **13 %** (from 7.66 min to 8.65 min) will reduce machining cost by **67 %** (from $ 8.00 to $ 5.39) and the investment may be reduced by **55 %** (from 733 to 400 %)**.**

The figure indicates that the optimum process plan, maximum production and minimum cost are not the best processes from an investment point of view. Each individual company may set its own rules to evaluate and make decisions as to which resources to purchase.

One method might be to compute an investment rating value. The proposed simplified rating is based on the time for the return on investment (ROI). The relative investment divided by the cost of producing a part gives the number of parts (for selling price based on cost plus) that must be produced by this alternative. Multiplying this quantity by the machining time results in the time that it takes to produce the number of parts in order to break even.

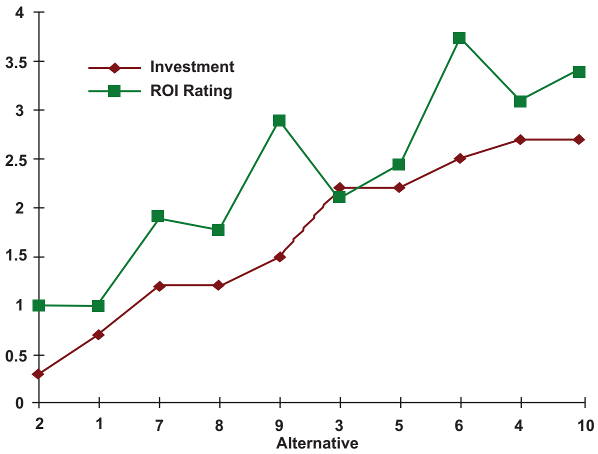
ROI rating = (Relative Investment/part machining cost) × Part processing time

The ROI rating was computed using the data as shown in Table 9.2, and the results are shown in Fig. 9.2.

Alternate	2	1	7	8	9	3	5	6	4	10
Investment	0.3	0.7	1.2	1.2	1.5	2.2	2.2	2.5	2.7	2.7
Ratio	1.0	1.0	1.92	1.77	2.9	2.1	2.44	3.74	3.08	3.43

Figs. 9.1 and 9.2 clearly indicate that there is not a direct correlation between the investment and the return on investment, or between the investment and the opti-

Fig. 9.2 Relationship between investment and ROI rating, fixtures and tooling required to produce a family of parts



mum process plans. Alternative 2 is the lowest relative investment and the process that gives the worst machining time, four times longer than the optimum machining time (32.32 / 7.66 = 4.22); however, it results in one of the two best investments from an ROI point of view.

A similar ROI is received by using alternative 2 (machine 5), which is 233 % of the relative investment, with a machining time of only 30 % and a machining cost of 143 % of the first alternative. It is ***up to management to decide*** which process alternative they prefer.

Naturally, the total required quantity has to be taken into consideration. For a very low quantity, resource RFQ #6 (alternative 2) will probably be preferable. For a higher quantity, resource RFQ #5 (alternative 1) should be preferable. However, if single machine RFQ #5 cannot handle the load, then two machines are needed.

In this case, it is better to purchase one machine #5 and one machine #2, thus reducing the investment from (0.7 × 2 =) 1.4 to 1.2. The best combination may be decided by examining the data in Table 9.3 and Figs. 9.1 and 9.2.

The utilization time of each machine can be crucial in making a decision. This information is also immediately available from the solution of the roadmap. Naturally, this figure is a function of the quantity required. The roadmap solution handles the unit time and cost. The quantity affects the transfer time value (penalty), but not the direct machining time. However, the total utilization time per period can be computed. In the example above, the time for each machine is as follows:

Minimum time alternative (3)	Machine 3 for 3.11 min
	Machine 5 for 4.05 min
Minimum cost alternative (7)	Machine 2 for 4.10 min
	Machine 5 for 4.05 min

It can be seen that the load on these two machines in the case of minimum time is not balanced, while, in the case of the minimum cost, the load is almost balanced. The roadmap can be used in an attempt to transfer operations from one machine to another in order to balance the load.

It is unlikely that any single part will supply the complete load to any machine, and the load will be balanced between several machines. Increasing the load and load balancing may be done by considering other parts. Therefore, considering many parts in one run is preferred. The many parts might be all parts of one new product, or parts already in production.

As stated, different plants will use different economic models. Therefore, we regard the proposed method as a data generator and not as a recommended mode. The method by which the table presents the data may vary from one plant to another. Additional data, if required, may also be retrieved from the roadmap format method.

2.4.1 Management and Engineering

Management relies on economic models and techniques (i.e., total value analysis. ROI, etc.) in making its resource planning decisions. Different concerns will adapt different economic models. However, regardless of the economic model employed, the decisions are restricted to the engineering data fed into it. Engineering is no doubt doing the best they can. However, engineering's considerations and optimization criteria are not always similar to those of management.

The presented method introduces engineering technology into the economic model. It employs the roadmap concept. The roadmap concept can generate, in a few seconds, alternatives, and supply the data needed to reach economic decisions. The alternatives may be of different formats, such as minimum cost, maximum production, maximum profit, indicating machine utilization and investment ratio for each alternative. It may be used for a single part or many parts. It may consider resources for a new product, or evaluating and generating alternatives for all the parts produced in the plant.

The decision of which machine to purchase must consider many parameters. The roadmap is not intended to make an economic decision; its sole purpose is to supply sound engineering data to the decision-makers. A simple example presents the following options: ***if an increase in machining time by 13 % will reduce machining cost by 67 %, and probably also reduce the investment by 55 %,*** should it be selected?

This is a decision for finance or management, not engineering. Management has to consider many more parameters, such as total load, load balancing, fitness of the machine to many products, machine standardization, cash flow, interest, marketing, etc.

The roadmap concept allows management or finance to work with a computer that will supply the engineering data in any desired form, instead of having to call the engineer each time information or data is needed. Experience has shown that the computer model can furnish any alternative or data within a few seconds.

3 Evolution of Resources and Manufacturing Methods

The above recommendation and evaluation methods were restricted to universal machines. The term “machine” can be expanded to cover any manufacturing technique, including Group Technology GT, work cells NC machines, machining center, and automatic factory.

3.1 Group Technology—Work Cell

Group Technology (GT) is one of the oldest manufacturing methods and philosophies, dominating the field of job-shop manufacturing before the era of computers.

There are many definitions of group technology, and they are continuously changing as the scope of GT changes, and as it have become apparent that some planned activities cannot be accomplished by GT. On the other hand, it has been realized that this technology can serve as a solution to additional activities.

One of the first explanations of GT was as such: *“The main goal of GT is to produce a single or small quantity of items using mass production techniques”.* Some claim that GT is responsible for a 270 % rise in labor productivity and 240 % rise in shop output.

A later definition of GT states: *Group Technology is the technique of identifying and bringing together related or similar parts in a production process in order to utilize the inherent economy of flow production method.*

A more general definition proposes using GT concepts in other fields:

Group Technology is the realization that many problems are similar, and that by grouping together similar problems, a single solution can be found to a set of problems, thus saving time and effort.

GT is a method of alleviating problems associated with short run low batch size in job shop work. In the job shop, because of the variety of jobs encountered and the short number of parts in each run, set—up time may be the most significant part of production time. While conventional methods such as computer integrated manufacturing (CIM) or integrated manufacturing system (IMS) tries to increase productivity by using capacity planning to attack the direct machining time, GT is concerned with the lead time. One way to achieve this is by organizing the plant layout according to ***work cell*** rather than functions.

A work cell is a unit that includes all of the machines required to produce a family of parts. Raw material enters a cell, and a finished part emerges. The reported success in reducing lead time through this method is very impressive.

The shop usually uses a functional layout of equipment with no interrelation between groups of different functions. Each part takes a confused, unpredictable path through the shop in order to reach all the necessary equipment involved in its processing. Every time a job is moved from one (operation) workstation to the next, there is a delay. Production control becomes extremely complicated, and it is almost impossible to get realistic, up-to-date information on the production status of any particular job.

With a GT work cell, the saving will be in transfer time between operations and reduced set-up times. The work cell method calls for a machine layout according to a component flow analysis, in which a component will enter a work cell and be terminated there. Hence, one work cell might include all machines, fixtures and tooling required to produce a family of parts.

A ***family of parts*** is composed of parts the routing of which requires similar machines and tooling. The batch size for a family of parts will be the sum of all parts of the family, thus increasing the number of parts per set-up and reducing ***set-up time*** considerably.

A group of the machines in the work cell are placed near each other, thus drastically reducing the scope of production scheduling and control problems, and improving material handling and group morale of the workers. Tooling and fixtures are designed by using group concepts common to the part family. To use tooling and fixtures to the full, the operations must be arranged so that the maximum number of parts in the family can be processed in one set-up, which means that jigs accepting all the members of the family have to be designed.

For example, the design of a master jig with additional adapters is one way of dealing with changes in size and number of locations of features. As a result of these advantages of GT, the cost reduction in tool design, tooling and equipment, production control, etc., becomes very significant.

Thus, the goals and applications of GT are expanded beyond the original requirement of work cell manufacturing technique, and the broad meaning of GT now covers all areas of the manufacturing process. The following is a list of such applications.

Design—In creating a new part design, there is the design time, detail drafting time, prototyping, testing, documentation, and certainly drawing maintenance. When the new part design hits manufacturing, many things happen. There is advance manufacturing engineering from a central location and possibly at a remote plant location. There is tool design. Tools have to be either made or bought. Time study is involved. Production control has to schedule the part, cost accounting is involved, data processing, purchasing, quality control, N/C programming are all affected—we could go on and on. It is expensive to support new parts. With the GT technique, some of these expenditures can be avoided.

The GT concept involves carefully examining the active parts of the company, creating a family of products and parts, and making them company standards. When a new part is required, before rushing to design, retrieve and compare the available parts to decide if they can be used. Experiments show that at least 5% of new required parts can be avoided by using standard parts.

Process planning—Savings in process planning result from using the same process for a family of parts. Examining the actual process plans in a shop usually reveals that, for similar parts belonging to the same family, many different processes are on company files. This can be explained by the fact that several process planners were involved in the development; the processes were developed at different times, and many other personal reasons.

GT proposes examining the different process plans and evaluating them in order to find the "best" process. This process will be the master process plan. It is suitable for a virtual part of the family. The specific part will retrieve the master process plan and update it to suit the specifics of the specific part. By applying the master process plan to the available part, immediate improvements and benefits will be achieved. When a new processing technique becomes available, the master process plan will be updated.

Material management and purchasing—The use of groups of materials has led to greater purchasing efficiency, lower stock levels, and savings in procurement.

GT, using a family of parts, may reduce the number of orders through blanket orders and through larger lot sizes. Parts are bought on a family-of-parts basis. Blanks may be purchased to suit a family of parts and not any specific part. It might increase processing time, but reduces purchasing and inventory expenses, and probably lowers the cost of blanks.

Production control—Production planning and control becomes simple, with the only necessary decisions being to which work cell to direct the job and setting a due date. Work cell personnel are responsible for internal scheduling and quality.

Cost estimating—First, determine to which family of parts the new parts belong. Retrieve the cost of the master part, perhaps add a factor, and arrive at the estimated cost. Experience shows that a very accurate cost is determined.

3.1.1 Practical Applications

For practical applications of GT, it is essential to create part families. A part family is defined as a collection of related parts that are similar, if not nearly identical. They are related by geometric shapes and/or size and require similar machining operations. Alternatively, they may be dissimilar in shape, but related by having all or some common machining operations. Parts are said to be similar in respect to production techniques when the type, sequence and number of operations are similar. This similarity is, therefore, related to the basic shape of the parts or to a number of the shape elements that are contained within the part shape. The type of operation is determined by the methods of machining, the method of holding the part, and the tooling required.

The general manufacturing philosophy of GT is accepted, although it was practiced under different names, or without any label whatever, even before receiving formal recognition.

In order to practice GT as a systematic scientific technology, tools for identification of the groups must be prepared.

Industrial classification is a technique for arranging the individual parts comprising any aspect of a business in a logical and systematic hierarchy whereby like things are brought together by virtue of their similarities, and then separated by their essential differences.

Forming a good classification system is quite a problem, Classification systems can be categorized as design-oriented, production-oriented or resource-oriented. Each one calls for different characteristics. Design-oriented requires that a retrieval request draw a limited number of drawings. Otherwise, the engineer will prefer to design the required part instead of comparing many drawings with the hope that one of the old drawings might fit its purpose. On the other hand, production-oriented requires retrieving as many parts as possible.

3.1.2 Management Control

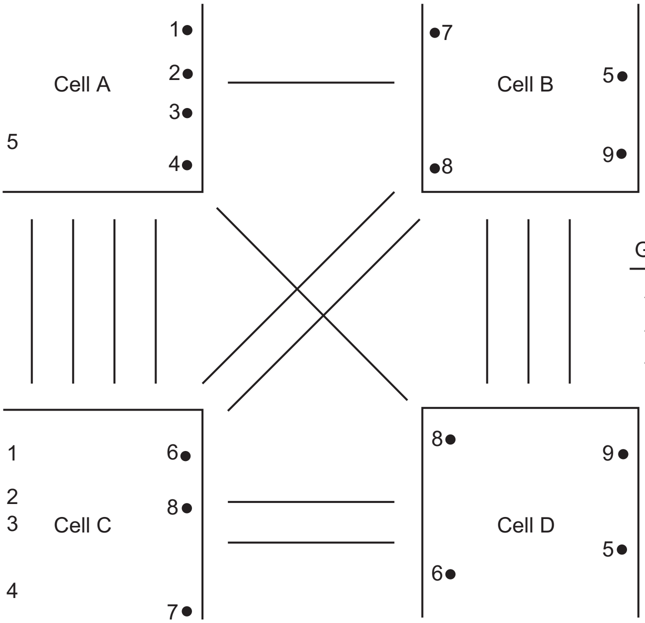
The success of a GT system depends on the ability to form a family of parts. The problem of generating families required transforming the problem of GT into a problem of forming a suitable classification system. The developments of such a system were a main topic of research for many years, but then slowly faded away, as did GT with it. In several very small plants, where families of parts could be formed manually, GT survived.

3.2 NC, CNC, DNC

The introduction of personal computers enabled the building of numerical control machines. Process planning instructions were prepared by external computer and transferred by punched tape to the NC machine. The method for generating processes for this group of machines is no different from that of any other machine. The actual machining (metal removal) is unchanged. The difference lies in the handling times. Starting/stopping the machine, engagement of the feed, adjustment of tools, and so on, are performed automatically and much faster than on universal machines.

Numerical Control (NC) is the automation of machine tools that are operated by practically programmed commands encoded on a storage medium, as opposed to controlled manually via hand wheels or levers, or mechanically automated via cams alone. The development of servo-mechanisms and sensors enables us to improve the NC machines by replacing the punched tapes with computer numerical control. The existing tools were modified with motors that moved the controls to follow points fed into the system on punched tape. These early servo-mechanisms were rapidly augmented with analog and digital computers, creating the modern Computer Numerical Control (CNC) machine tools that have revolutionized the machining processes.

Direct Numerical Control (DNC) systems are a further development of the numerical control machine. Software was added, enabling the machine to develop a process plan automatically and translate it to the op-codes of the machine. Thus, it might generate a process plan from a computer-aided design file and set it in a format that the machine controller understands. Upon the "start" command, the machine will process the item.



Groupings	Cuts
AB CD	10
AC BD	6 **
AD BC	10

Fig. 9.3 Example of four work cell on shop floor

These groups of machines are a success story, and revolutionized the metal-cutting industry. It accomplishes the GT desire of reducing set-up time on the shop floor, and transfers it to the office.

One of the drawbacks of this kind of machine is that it makes decisions on its own, without manual introversion or approval of the user. This leads to selecting a machine first and not the optimum process.

This drawback might become an advantage if management would have its process planner review the proposed process and transform it into a roadmap.

3.3 Machining Center

A further development in metal-cutting machines is the machining center. Such machine improvement is achieved by adding a tool storage and automatic tool changer exchange unit. Using these two features further reduces the set-up time of the machine.

The inconvenience of such a machine might be its cost, thus forcing the user to use an elephant to kill a fly. Management should not be tempted by its magnificent feature, but rather check its economic usefulness (Fig. 9.3).

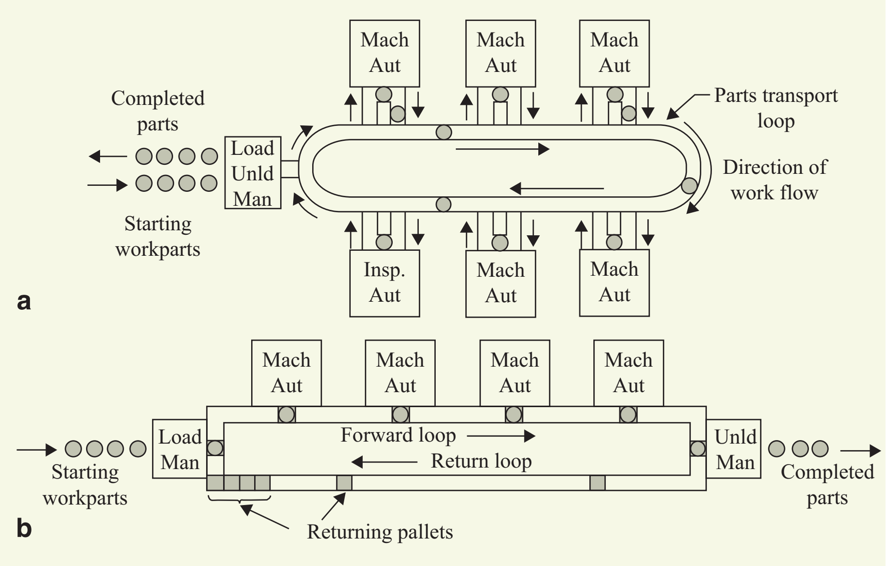


Fig. 9.4 **a** FMS loop layout. **b** Rectangular layout system

3.4 *Flexible Manufacturing System*

A flexible manufacturing system is a ***machining center*** with added transfer mechanism and buffers to move items from one machine to the other, unloading the processed item, loading a new item, and inserting the routing commands to process. There are several methods of FMS transfer mechanism. Two are shown in Fig. 9.4. One is constructed as a loop layout and one as a rectangular layout. Others use industrial robots, or AGV—automated guided vehicle.

3.4.1 Management Control

FMS's promises are a dream comes true: a unit for which you merely schedule the jobs to be processed for a period, lay the material in one end of the unit, and then sit back and relax. After relaxing, the items are ready to be removed to stock.

The main drawback to this system is that the number of items that can be loaded on the transfer mechanism is limited by the length of the line and the number of resources that the line should contain. Therefore, the length of time that FMS may work unattended is limited.

A more serious problem is the scheduling of the items to be loaded on the line and the number of resources. This means that items may follow the sequence of resources along the line.

For example: There are six resources located in the following sequence: *R1 R2 R3 R5 R7 R9*. And there are six items *P2 P4 P6 P8 P10 P12* loaded onto each resource. Suppose that the sequence of operations of item *P2 is R3 R2 R9 R5*. That means that when Operation1 on resource *R3* is done, it has to move to *R2*, and, to get there, it has to rotate a full turn of the transfer line.

Such scheduling problems diminish the enthusiasm for FMS.

To overcome the scheduling problem, different methods were proposed, such as using buffers near each resource and robots to move the items independently. Another idea was to use AGV to move items between storage and resources. Such an idea solves the scheduling problem, but creates traffic scheduling of the AGV.

Management should carefully consider whether the time for them to use FMS has arrived.

3.5 Automatic Factory

The idea of the automatic factory consists of a series of (or one) FMS unit, controlled transfer lines or industrial robots. Process and load optimization are carried out by the central computer. Direct control over any device in the plant is possible through a computer hierarchy network. The network links the main central processor to the individual microprocessor controlling a single device. The automatic factory utilizes the benefits of all the facilities previously mentioned. It has the same reduced operation handling time as the DNC machine (handling time table), the same interoperation transfer time as in the machining center (transfer time table), the same chucking and gripping as in the production line (handling time table), and the same increased flexibility as in the work cell. Thus, by assigning the appropriate values in the relevant table, the system can be used in decision-making concerning the automatic factory.

3.6 Production Line (Transfer Line)

This type of manufacturing is characterized by having several types of machines laid out along a transfer line. Raw material, or the initial body, is entered at the feed station, and a finished product emerges at the end of the line. All in-between operations are carried out automatically. The automation is achieved through mechanical means and controlled by switching the circuit's technology. Thus, unless set-up work is done, the production line is capable of producing only *one preplanned* sequence of operations. The actual machining operations are carried out as on any other machine. The roadmap regards the production line as one machine, having an appropriate column in the handling time table.

Recommendation or evaluation of this technique can be carried out for only one product, that is, the product mix used for evaluation is restricted to one product or limited to a selected group of products. The evaluation technique is as previously described. In addition, line balancing capabilities can be introduced.

Chapter 10
Master Production Planning

Abstract The master production schedule is a management tool which coordinates functions between manufacturing, marketing, finance, and management. Furthermore, it is a management tool with a “look ahead” feature—a feature that is needed in order to plan the future of a company, prepare the budget, plan cash flow, manpower, and resource requirements, and forecast company profits.

Engineering can provide a set of profiles that may assist management in organizing a reasonable master production plan.

This chapter presents two methods of creating profiles: one with conventional tools and one with flexible tools.

1 Introduction

The master production schedule transforms the manufacturing objectives of quantity and due date for the final product, which are assigned by the non-engineering functions of the organization, into an engineering production plan.

As a coordinating function between the assorted aspects of the company, a master production schedule is the basis for further detailed production planning, such as requirement and capacity planning. Its main objective is to plan a realistic production program that ensures even utilization of plant resources, people and machines. This will be the driving input for detailed planning, and will ensure, as much as possible, against overload and underload of resources at all periods of time. If formulated properly, the master production schedule can serve as a tool for marketing personnel in promising delivery dates.

The master production schedule is the phase where due dates are established for the production phases. Thus, it controls the relative priorities of all open shop orders. If the master production schedule is unrealistic in terms of capacity, many shop orders will be rush orders with high priority, and the entire capacity planning system will not function properly. To maintain valid shop priorities, the master production schedule must not exceed the gross productive capacity in any one period.

Planning the master production schedule is a difficult task, since it normally covers a wide range of products and represents a variety of conflicting considerations, such as demand, cost, selling price, available capital for investments, and company marketing strategy.

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It is not purely engineering work. The engineers supply information and can simulate different strategies, but the final decision lies with management. In some companies, the sales department is responsible for preparing the master production schedule. In any case, production engineering must be involved in order to ensure a realistic program.

It is erroneous to talk about long-range capacity planning, since no capacity plan can last more than a few days; the conditions in the shop are simply too dynamic for that. The new orders and changes in existing orders that occur continuously have an impact on the capacity requirement. However, it is important to have a long-range master production plan, the main objective of which is to supply management with a "look ahead" tool—a tool that is needed in order to plan the future of the company. It provides simulation of capacity requirements for different marketing forecasts, purchasing of new equipment, and profit forecasts. In addition, it indicates the necessary requirement planning with respect to shop-floor space, warehouse space, transport facilities, and manpower.

No one actually believes that the master production schedule will be accomplished as predicted. However, it is a good starting point for planning; it does not really matter if product A or B will be manufactured sometime in the future. The master production schedule represents a framework for the prediction of overall plant performance based on the planning for individual items. Preparing a master production schedule is not a one-time job, but rather a continuous process.

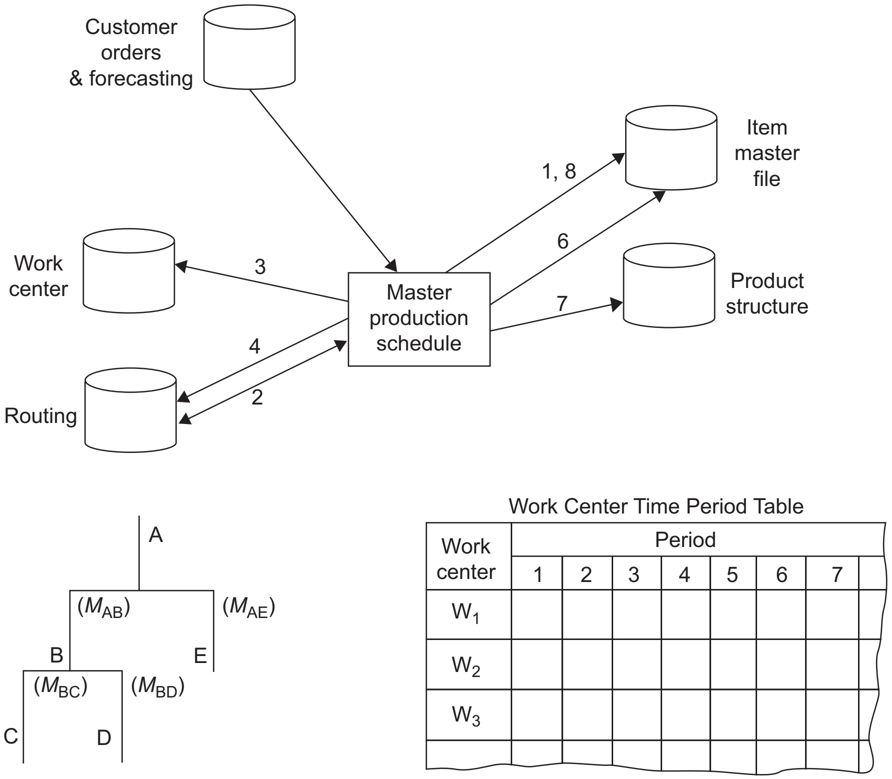
The early periods are known with reasonable accuracy, while the distant future periods are rough estimates. As time passes, the estimates become confirmed customer orders, and the future is extended further. Every once in a while, a new master production schedule is prepared, and **it** does not have to agree with the previous schedule.

The importance of master production scheduling is becoming more and more recognized. It is now acknowledged as recognized that it is the key to the success or failure -of the detailed production planning. However, all of the mathematicians and economists that are developing economic models for production, such as sequencing, economic lot size, safety stock, and reorder point, just assume that there is a master production schedule. It is external to their area of interest, and how good the master production scheduling actually is does not matter to them; they are willing to build a whole theory on sand. It is a complicated problem, so let us leave it alone.

The small amount of literature available on this subject merely states its importance and that it should be done; numerous articles have been published on inventory management, scheduling, and forecasting, but, to the best of my knowledge, not a single one has been devoted to the topic of master production scheduling.

The modern manufacturing systems are no different as regards the preceding discussion. It is a source of information that can display the capacity requirements for different combinations of product demand, lot size, and due date. It is recognized that it is impractical to try out all the possible combinations possible. Thus, human judgment is necessary to predict the most likely combinations, and only those that will be simulated by the system.

Basically, from the capacity point of view, the master production schedule represents long-range (infinite) capacity planning. Suppose that the company plans to produce certain products in certain quantities with different due dates. The impact of the plan in terms of production capacity is needed. (Refer to Sect. 2.1 of Chap. 5)



Work Center Time Period Table

Work center	Period						
	1	2	3	4	5	6	7
W_1							
W_2							
W_3							

Fig. 10.1 Master production planning computations

The files of the master production schedule contain the product structure for each product and the routing for each item. The routing file tells in which work centers processing takes place and the sequence of operations; it also provides such lead time information as set-up time and standard machine time. By means of this information, we can break down each product in the order file, or the alternative plan under test, to its components and accumulate the workload at each work center by time periods. Figure 10.1 shows one rough way of doing this.

Product A can be produced in quantity Q_A at time T_{DA} as follows:

1. We can now take The product A record is retrieved and its information made available. This record points to the first assembly operation in the routing file.
2. The first operation is retrieved; it includes such general information as set-up time and machining time. The total lot size processing is computed (t_{AL}). This record contains information on the work center (W_3) in which this operation is processed and points to its location in the work center file; it also contains a pointer to the second operation. This address is stored in memory.
3. The record of this work center (W_3) is retrieved. The record contains the time period table for the total planning period. Time t_{AL} (in which this work center is scheduled to perform this operation) is added to the table location of the starting period: $T_D - t_{AL}$

4. The address of the second operation is kept in memory. Its record is retrieved, and computations similar to those in step 2 are performed. Operation time t_{A2} is computed, it is stored in order to update the work center time period table, and it is added to counter T_A, which gives the assembly lead time.
5. Steps 3 and 4 are repeated until a code in memory indicates that there are no more operations for product A.
6. Controls return to the item master file and use its pointer to the product structure file.
7. The product structure record is retrieved in the same way as in the product breakdown. This record indicates that the first item in product A is item B in a quantity of M AB per assembly. This record points to item B in the item master file.
8. The item B record is retrieved. Its due date is the product A due date minus the assembly lead time: $T_{DB} = T_{DA} - T_A$; the quantity is $Q_B = Q_A \times M_{AB}$. This record points to the first operation of subassembly B.
9. Steps 2–8 are repeated until all items of product A have been broken down.
10. The next product in the order file is read and steps 1 to 9 are repeated.
11. Steps 1–10 are repeated until all products in the order file have been processed.

We can now take cross-sections along the different axes in order to obtain useful information. Figure 10.2 presents some of the important cross-sections. Part *a* is an overall capacity profile of the shop, which shows the profile of normal available capacity (or planned capacity) and total capacity required per time period.

This profile is for general knowledge only. If the required capacity is greater than that available, it indicates that the sales forecast exceeds plant capabilities. On the other hand, if the required capacity is equal to or less than the available capacity, it indicates that the plant, as a unit, is underloaded, However, in both cases there might be some work centers that are overloaded and some that are underloaded. To examine this, a work center load profile per time period, such as the one given in Part *b,* is developed for each work center in the shop. From these profiles, one can learn which work centers in the plant are overloaded and which are underloaded. One can also learn if the overload occurs at all time periods and to what extent, or if there is a mixture of overloaded and underloaded periods, and what the average load is.

These profiles provide the information necessary for such decisions as whether to purchase new facilities for highly overloaded work centers; whether to work extra shifts or overtime in moderately overloaded work centers; and whether to balance the load by working overtime or extra shifts at certain time periods, changing due dates, changing lot size, subcontracting, or increasing the inventory buffer. Poorly loaded work centers can be eliminated by transferring their operations to other work centers.

Information on the capacity requirements at a given time period at different work centers can be obtained from a profile of the type given in Part c. This information is useful for balancing the load throughout the plant, not just in a single department.

If a decision is made to balance the load by changing product orders or lot size, information concerning the effect of each order on the load profile is needed. This information can be obtained from a profile of the type given in Part *d.*

It should be remembered that forecasting is not a precise tool, and thus, has its tolerances in the standard deviations. A trial fit of the master production schedule can be made by using the average, lower, or upper limit of the quantity of each product.

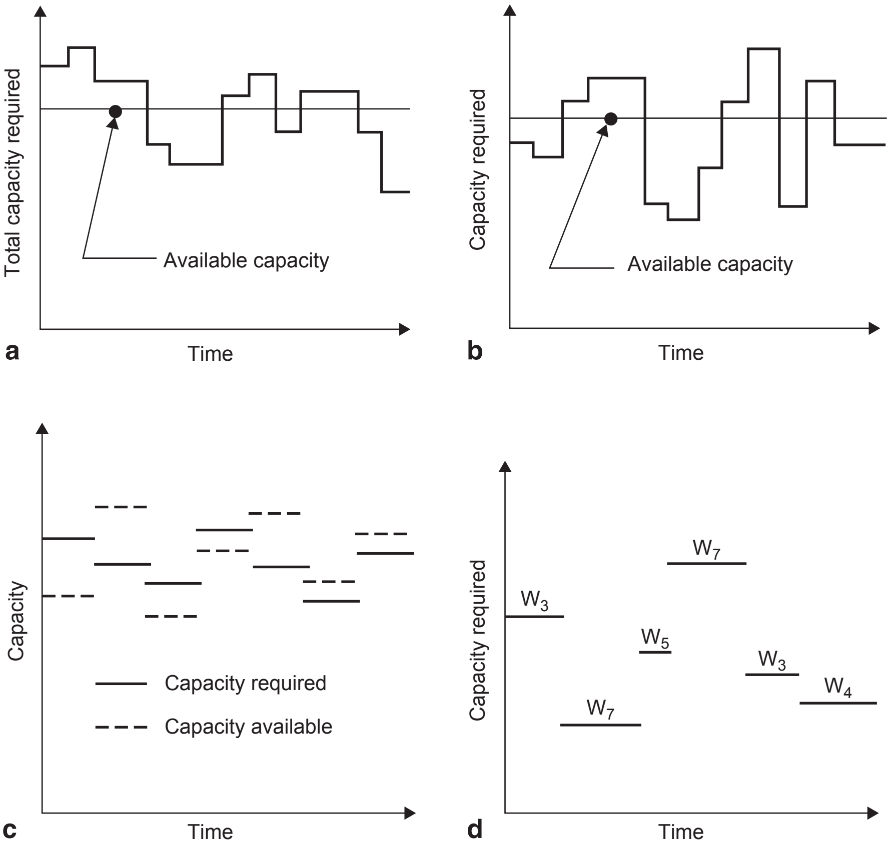


Fig. 10.2 Cross-section information of the master production planning

There is a general agreement that lot sizing should be made at the master production schedule level. The master production schedule considers the final product as a whole, not its components; the detailed planning is left to the requirement planning and capacity planning phases. The existing models for lot sizing are usually single stage, taking into consideration the set-up cost, but ignoring the capacity of the work center. Using these models, benefits gained due to economic lot sizing at one level of the product tree may be more than offset by the impact this has on other levels. Furthermore, these lot sizes are meddling with the master production schedule, since the previously balanced work center load is upset. These problems would not arise if the master production schedule took lot sizing into account.

Unfortunately, this is a complicated problem, and, to the best of my knowledge, at present, there is no feasible mathematical model.

As one may conclude from the above discussion, preparing a good, realistic master production schedule is recognized as a must. However, no one actually knows how to do it scientifically, and thus, it is usually done by intuition.

Actually, the same scheduling is repeated three times (but for different purposes): master production scheduling, requirement planning, and capacity planning.

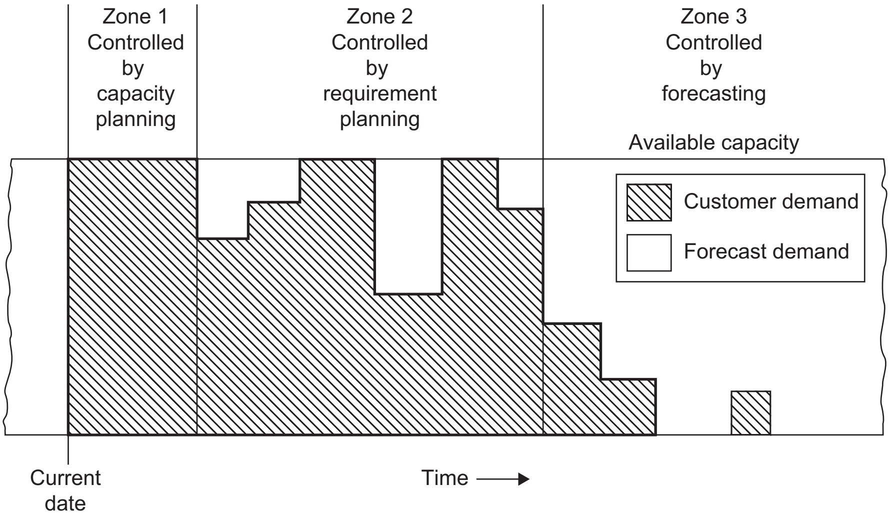


Fig. 10.3 The zones of master production planning

In each one of these systems, the product is broken down to its components and scheduled by the lead time.

The three systems function in series and, in practice, represent a loop problem. For example, master production scheduling ignores inventory and available open orders; consequently, there might be artificial loading in its planning.

On the other hand, requirement planning considers inventory and open orders, but ignores capacity; this can create an artificial overload at some work centers and unnecessary rush orders.

One practical way to plan the master production schedule is to look at it as a continuous process in which only changes occur. These changes would include additional orders, cancellation of orders, and revisions of due dates and quantities. The master production schedule is composed of three time zones, as shown in Fig. 10.3.

The first zone is the "frozen zone." This zone covers job shop open orders or orders containing an item on which work has been started; moreover, it usually covers the product lead time period.

In this stage, the order is under the control of the capacity planning and dispatching (order release) phases. Changes in the master production schedule cannot be made during this period. The capacity load profile is obtained from capacity planning and is supposed to be accurate.

The second zone covers the confirmed customer orders that have been processed by requirement planning and entered into capacity planning. However, this zone is out of time range for job shop open orders.

The third zone covers the forecast orders and management filler orders, which represent estimates that enable plans to be made for the future.

In a job-shop (or anyplace where many items, each with a different lead time, are produced), the zones overlap each other; in this case, instead of referring to them as zones, it would probably be better to refer to them as types of orders.

Items constantly advance through these three zones in time. Hence, the delivered orders become historical data, while items that were outside the production range enter as job-shop open orders. New customer orders are accepted, and each order received is checked against the master production schedule. If it was covered by a forecast or management filler order, the order type is changed and no further action is necessary. When the order does not exist in any form, a capacity trial fitting is made.

Initially, it will be attempted to supply the extra capacity required by removing some of the filler orders. If this is not sufficient, some of the forecast orders will be removed. When an order does not fit the schedule, a decision must be made either to change the schedule, postpone the delivery date, or split the ordered quantity into several delivery dates.

The master production schedule system will, on request, simulate any course of action and supply data for a manual decision. If the order is accepted, the system updates the master production schedule with a reliable delivery date.

The master production schedule will be reviewed once in a while (monthly or quarterly). Initially, only confirmed orders will be used to display the capacity load profile; eventually, however, the forecast and filler orders will be used to balance the load along the range of the planning horizons.

2 Management Control and Finance Planning

The master production schedule is the driving force behind further detailed production planning. However, it is also a management tool for controlling and planning the future development of the company. In this section, some of the applications of the master production schedule will be discussed.

2.1 Facility Requirement Planning

In planning the master production schedule, different load profiles are generated, as was shown in Fig. 10.2. The planner must schedule within the constraint of available facilities. However, management will use these profiles for decisions on facility requirement planning.

Short-range or periodic overloads can be compensated for by subcontracting, working extra shifts, or working overtime. On the other hand, long-range or permanent overloads may make it necessary to buy additional machines (or even to build a new factory). The cross-sections and profiles discussed indicate where a production bottleneck lies and what product creates it. Management must decide if orders are to be turned down and production restricted to available facilities, or if it wants to expand in response to demand.

The master production schedule can supply information for the simulation of different policies with respect to capacity, profit, investment, and manpower.

It is estimated that the life of a machine is about 10 to 20 years. Hence, about 5–10 % of the facilities in a plant should be replaced every year. A machine load profile, whether indicating overloading or underloading, can assist management in deciding what type of new machine(s) should be purchased and what changes should be made in routing.

2.2 Manpower Requirement Planning

Manpower requirement planning is a conversion of facility requirement planning. Direct labor needs can be specified according to work center (more accurate planning may be done by specifying the skill classification necessary for each operation in the routing file and computing it in a similar way to work center load planning, however, we do not believe that such accuracy is needed at this stage). Thus, the work center load profile can be converted into a manpower profile.

The historical job recording data can be used to arrive at some useful modifiers: A ratio of direct labor to indirect labor can be computed for each department; the efficiency (i.e., the ratio of standard to actual time per each operation) and its average for each department can be computed; and it is possible to compute the ratio of absent time to working time for each department or even for the whole plant.

The work center load profile predicts the total amount of direct labor required for each work center; this total amount can be expressed in terms of the needs of individual departments. The modifiers introduced above can be used to obtain an equation for the required manpower per department:

$$\begin{aligned}\text{Required manpower} = {} & \frac{(\text{profile prediction})}{\text{efficiency}} \times (1 + \text{absentee ratio}) \\ & \times (1 + \text{indirect labor to direct labor ratio})\end{aligned}$$

When the manpower requirements of the individual departments are summed and the general management staff is added, the result is the total manpower requirement in the plant per period. These figures can assist the personnel department in planning recruiting and training activities; they may also be of assistance in preparing a budget.

Manpower planning at this stage is a rough approximation; for the most part, it represents a prediction of future needs. A more accurate plan, but only valid for a short period, is obtained by using the open order files. Thus, detailed requirement and capacity plans have been made, the demands are confirmed customer orders, and inventory and on-order items have been taken into account.

3 Cash Flow Planning

Cash is an important resource, and the predicted cash flow per period of time can assist management in its decisions on when to invest and what commitments to make.

The master production schedule estimates what products will be produced, the quantities, and the delivery dates. These deliveries can be converted into costs and (by the company credit policy) into cash receivable.

The manpower profile, which was discussed previously, can be converted into salaries and wages. This conversion can be made in the form of a rough estimate (one that we believe is accurate enough at this stage) by using an average salary and wage multiplied by the number of anticipated employees. A more accurate estimate, if so desired, would use departmental averages or skill averages. The final result of either estimate will be classified as cash payable.

Subcontractors are considered part of the work centers in the master production planning, but these work centers are not included in facility and manpower planning. Their load profile indicates the amount of work per time period to be subcontracted. One may define one work center as covering all subcontracted jobs, or define many work centers according to the accuracy desired, or according to other planning purposes, and they can be organized with respect to suppliers, hourly rates, type of process, or any other leading variable.

Accordingly, the load of these work centers can be converted into cost, and, upon consideration of the terms of payment policy, these costs can be offset and converted into cash payable.

Material (including purchased items) accounts for a substantial portion of the standard cost of a product—usually about 35 %, although for some products, it is likely to rise to 80 % or more.

The percentage of the total cost of any product or item that is contributed by the material cost can be computed using data from the bill of material file or the cost system. The average percentage contributed by the material cost over the complete product mix of the plant can be computed by using the balance sheet; it is a rough approximation, but one that is very easy at which to arrive. Assume that material purchasing is a continuous process that has no particular relationship to time, and that new orders are continuously released to the shop. Thus, a rough estimate of cash payable, which is accurate enough for the purpose of predicting cash flow, can be obtained from the following equation:

Cash payable per period for material
= total standard cost of master production schedule products
× average percentage contributed by material to total cost of product mix
/number of periods that the master production schedule covers

If greater accuracy is desired, each product can be treated individually. The amount of cash payable is then equal to the standard cost of the product multiplied by the percentage contributed by material to the total cost of the product multiplied by the quantity. This pay will fall in the period given by the delivery date minus the production lead time minus the safety lead time and term of payment.

Other expenses, such as heat, energy, rent, and office, can be treated as if divided equally along periods. The main purpose of the predicted cash flow is to serve as a tool for management in deciding when to invest and what commitments to make. Commitments already made by management will serve to modify the cash flow predicted by using the master production schedule.

3.1 Profit Forecasting

Profit forecasting is an important source of information for management. It is essential in planning the future of the plant, since decisions on investment in expansion, new facilities, and research and development are based on potential profit.

The master production schedule can be used to forecast profits. The actual future (forecast) cost can be obtained by conversion of the master production schedule from time to cost, if the sales prices are known and the difference between these two is the predicted profit. A profit margin per product is computed. The master production schedule lists all of the products that will be produced, the quantities, and the delivery dates. Multiplying the product profit margin by quantity gives the predicted profit. Even though it may not be completely accurate, it is a good enough approximation to serve its stated purpose.

The profit estimate is one of the parameters in evaluating different combinations of master production scheduling. Here, each product has its profit value, and the problem is to balance the work center loads under the constraints of the forecast orders and the goal of maximum profit. As the master production schedule is made, the profit forecast is known and can be used by management for decisions of various natures.

3.2 Budget and Management Control

The master production planning represents a statement of management objectives in the form of a production program that is the best mutually acceptable compromise between the conflicting requirements of the production and sales functions. The approved master production schedule is the yardstick by which management controls operations. If performance deviates from the plan, management must either take corrective action to overcome the deviation or reexamine other decisions and plans that are based on this schedule.

The master production plan includes many variables with different dimensions. For management control, it should be expressed in a common denominator—money. In other words, the production plan is expressed in monetary terms, that is, in the form of a budget.

The conversion of the master production plan to monetary value is best done by using standard costs. Standard costs are determined from carefully analyzing the two sets of cost elements of labor and material for a given level of efficiency.

Labor elements cover the whole sequence of operations and can be determined by means of a time study, if one is carried out.

Material elements can be determined on the basis of the engineering specifications set forth in the bill of material and anticipated rejects.

A production budget based on standard costs measures efficiency in relatively absolute terms. This shows management how much improvement in performance is still possible and in which areas it could most profitably direct its activities.

Hence, the production budget should be a dynamic one. Whenever a new master production plan is prepared, a new production budget must also be prepared. The budget is a zero-base budget; it is built on the basis of actual elements, not on the basis of the past budget.

The production budget should be realistic and a working tool. At this stage, we have only estimates; although these estimates are accurate enough for general information, they are not accurate enough for working and controlling purposes. It is recommended that a budget be prepared at a later stage, after requirement planning and capacity planning have been done in detail. At that stage, the opening and closing stock of goods on hand, the net requirement, subcontracting, and shop orders are all known with good accuracy.

The budget should specify the amount of work that is planned to be done with a predicted amount of money. Controlling only the money is senseless. There is not much use in knowing, for example, that only 80% of the budget was used; it is very good if all the work has been completed, it is fair if 80% of the work has been completed, and it is disastrous if only 10% of the work has been completed. The figures must be reliable and accurate; otherwise, they cannot be used for controlling purposes.

There are elements in the budget that are not direct expenses, and are, thus, independent of production. These elements can be controlled on a fixed yearly basis and organized in three additional separate budgets:

1. An indirect expenses budget, which includes such elements as general supervision, material handling, maintenance, security, light, heat, electricity, office supplies, engineering, depreciation, and tooling.
2. An investment budget, which includes the approved investment in machinery, buildings, office equipment, laboratories, and so on.
3. A research and development budget, which includes the approved R&D projects of the company.

Budgets are prepared for the lowest controllable level of the company, such as the department. The budget for each successive higher level consolidates those of the level beneath it. This process continues right up to general management.

4 Improve Master Production

The control profiles, as described in the previous section, were generated based on conventional methods (i.e., engineering design, product structure, and the bill of materials), while process planning defined the routing. In this section, master product design and the roadmap method are used to improve the master production schedule.

The methods are: review the product design before constructing the load profiles, and add a new degree of freedom in dealing with load profile fluctuations.

If product design was done a long time before the present period, it is a good practice to review the design and incorporate technological improvements and new customer wishes and needs.

The load profile might indicate continuous overload and underload periods. Continuous overloads usually indicate a need to purchase new equipment. However, before making such a major and costly decision, it might be possible to make some design or process changes that will balance the load. The roadmap method can supply data to management in considering such a decision.

4.1 Product Review

Normally, the master production schedule regards product design as a fixed constraint. Product review is not usually done unless there is an urgent need to do so. An urgent need arises when sales decline or competition becomes fierce and prices must be reduced or options added as a matter of survival. Product review utilizes time and resources.

When everything is going smoothly, no funds or resources are allocated for product review, not because it is not needed, but because there is always something more important to do. With the master product design method, product review is easy; it does not take much in the way of time or resources.

Review is important as technological changes and improvements are introduced. New ways of assembling parts are introduced, new plastic materials replace metals items, and new standard components are developed. Such technological changes can alter product design. Customer needs and wishes also necessitate change. A new option, shape, or color in a competitor's product can do the same.

Product specification and product design done by the master product design method are kept in the product design file. The process is a product design dialogue. A dialogue asks the user to respond to a series of inquiries. Responses are checked against the technical data file, and the system responds with system messages.

After responding to, or ignoring, the system messages, the user makes a decision, and the decision is recorded in the product design file. The product review process uses a similar method, but in order to save time and make the review as automatic as possible, the product design file is regarded as the user. Recorded decisions made in the past are used as the present responses to the dialogue inquiries. If there were no changes in the technical data file, there will be no discrepancies between past decisions (product design) and the recommended design. Such a review can be carried out in a few minutes and with no operator present. If there were technological developments relevant to the product being reviewed, an exception report is generated. The report draws management's attention to recommended changes in the product.

Management decides whether to make the changes or add the options to the product. The roadmap method can be referred to in aid of this.

4.2 Profile Load Balancing

The load profile is constructed based on the product structure and the routing of each item in the product. Routing is conventionally fixed, as determined by the

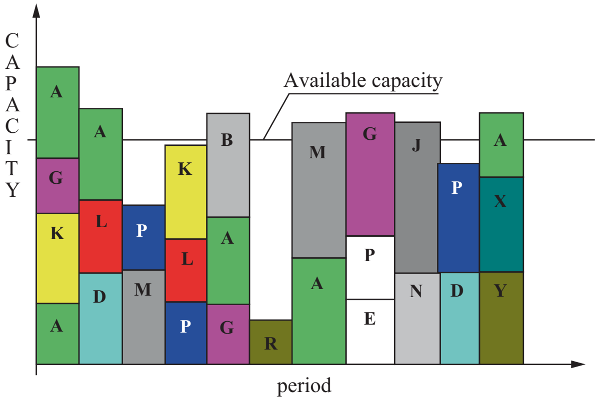


Fig. 10.4 Detailed load profile of machine X

engineering stages, and is regarded as a constraint. Any disruption or accumulation of a load at a specific resource can be resolved by adding capacity, subcontracting jobs, or other means detailed in the previous section. The master product design introduces an additional possible course of action, which is to change the product structure or product design to balance the load profile.

The load profile is constructed by loading each of the product's items and the number of orders, computing the required quantity, and multiplying the quantity by the processing time as indicated in the routing file. The load profile in Fig. 10.2 gives the overall load for each period. However, in computing the load, the load for each individual item is computed, and its processing time in each period is accumulated to give the total load on each of the resources that participate in the processing of that item. The individual item load for each period on each machine is known, and a detailed load profile, as shown in Fig. 10.4, can be constructed. The load profile is for a specific machine, and details the items that make up the load. The letters in the boxes represent the item numbers as specified in Fig. 10.4.

The main concept in master product design (and the roadmap method) is that manufacturing looks for overall optimization, not for optimization of an individual item or discipline. The product design was probably the optimum design from an engineering design standpoint.

Examining alternative designs usually indicates that there is not much difference between the optimum design and the next best alternative. In many cases, the optimum is more mathematical than practical in nature. This means that the optimization curve is flat near the minimum point. It moves incrementally to both sides of the optimum point on the curve, resulting in an insignificant change in value. Thus, instead of purchasing new machines in order to balance the load, it might be more economical to change the design. This solution does not work in all cases, but it is worth considering.

The load profile can furnish the information needed to consider such an option. For example, Fig. 10.4 indicates that item A appears in most of the overload periods. If item A can be replaced by item RA, the load profile changes to the one shown in Fig. 10.5.

Fig. 10.5 Profile when item A is replaced by item RA

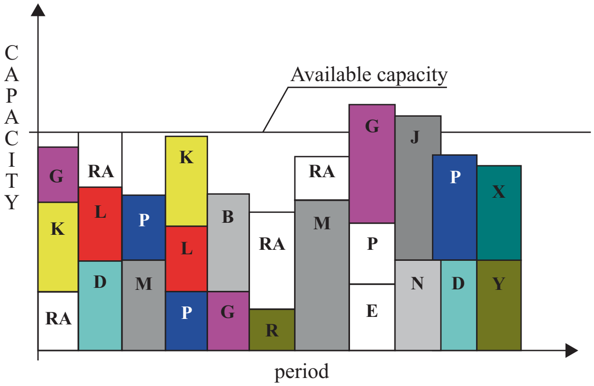
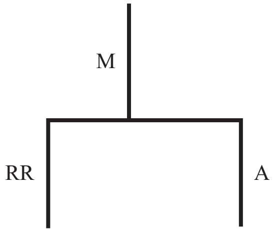


Fig. 10.6 Product structure of subassembly M



In the example, the cost of the product will probably increase by a few percent, but the need to purchase a new machine is eliminated. This is an economic decision, and it is up to management to make such a decision.

The same logic that was used to change design in order to reduce an overload period can be used to increase an underload period.

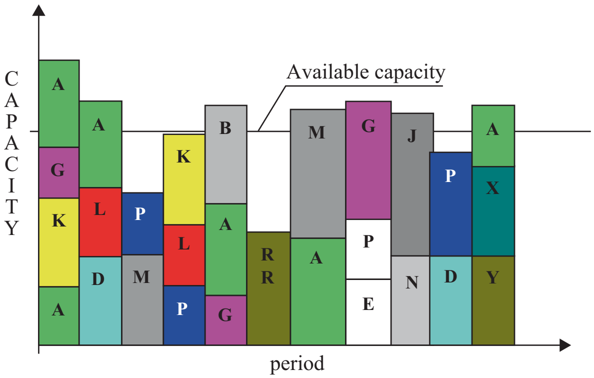
For example, in Fig. 10.4, the sixth period is loaded only with item R and it is very underloaded. Item R might be a very expensive item required for assembly or subassembly M, as shown in Fig. 10.6.

Other such changes can be used to improve the load profile of the master product schedule. The master product design and its auxiliary files guide the user in considering possible options.

It seems that, due to logistical problems, subassembly M can begin only when items R and A are available. Item R is processed in the sixth period and stored until item A is ready. If the design of item R can be changed to use an inferior and less costly material, the process time will be increased. However, such an increase does not affect the overall plan. By changing item R to item RR, product cost can be reduced while improving the load profile. The effect of this change is shown in Fig. 10.7.

Other such changes can be used to improve the load profile of the master product schedule. The master product design and its auxiliary files guide the user in considering possible options.

Fig. 10.7 Profile for item R replaced by item RR



4.3 *Profile Load Balancing—Roadmap Method*

In Sect. 3.2, several ways to improve the master product schedule were presented. This section presents the power of using the roadmap.

The roadmap method presents several possible routines and leaves the decision of which one to use up to the user at the time the decision is needed. The main question is which routine to use initially in preparing the master production schedule.

The two main obvious criteria of optimum process planning are minimum cost and maximum production (sometimes maximum profit is the criterion). There is quite a gap in time and cost between the two optimum process plans. For minimum cost, the processing time is high and the cost low; for maximum production, the processing time is low and the cost high. There are many more options between these two boundaries, and the process plan must be flexible so it can be modified to solve loading problems.

This function can be used to improve profile load balancing in the master production schedule. The load profile shown in Fig. 6.4 can be used to illustrate implementation of this method.

The first two periods are overloaded. Examination of the items that contribute to this overload indicates that item A appears in both periods. Moreover, examining the loads of other machines indicates that machine Y is underloaded during these two periods, as shown in Fig. 10.8.

The idea is to change the process for those items that are in the overload period. In the first period, items A, G, and K can be moved from machine X to machine Y, if it is economical to do so. The roadmap and the forced process planning feature are used to identify a process that uses machine Y instead of machine X. This alternate process will not be optimum, but the difference in cost or processing time may be insignificant, and the change will assist in solving the load profile problem. All three items that are loaded onto machine X during the first period are checked. The one that is the most economical and causes the least deviation from the optimum process is assessed first. The check determines whether transferring this item from machine X will reduce the load to the extent that it will be equal or below the available capacity.

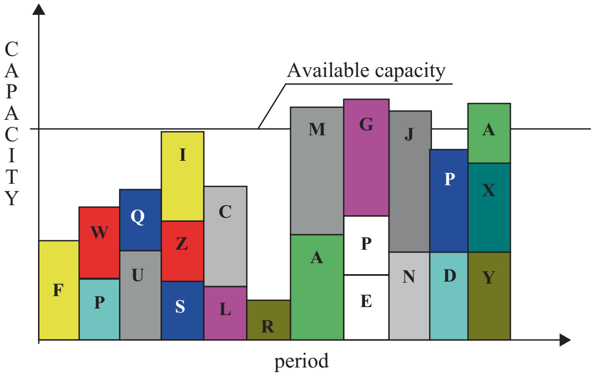


Fig. 10.8 Detailed load profile of machine Y

A numerical example illustrates this process. The load on machine X during the first period is as follows (as shown in Fig. 10.4):

item A = 50; item G = 20; item K = 50, and item A = 30.
The total load is 150, and the available load is 100.
The load on machine Y during the first period is
item F = 40, and the available load is 100.

Therefore, machine Y needs additional work in order to balance the load for the first period.

The economics and possibility of moving work from machine X to machine Y are checked. If item G can be processed on machine Y with the same efficiency as on machine X, the savings will not be enough. The load will be reduced by 20, leaving a total required load of 130.

Next, items K and A are checked. Item K can be processed on machine Y instead of machine X; however, its load will be increased from 50 to 52. Item A can be processed on machine Y instead of machine X, which increases the required load from 50 to 54.

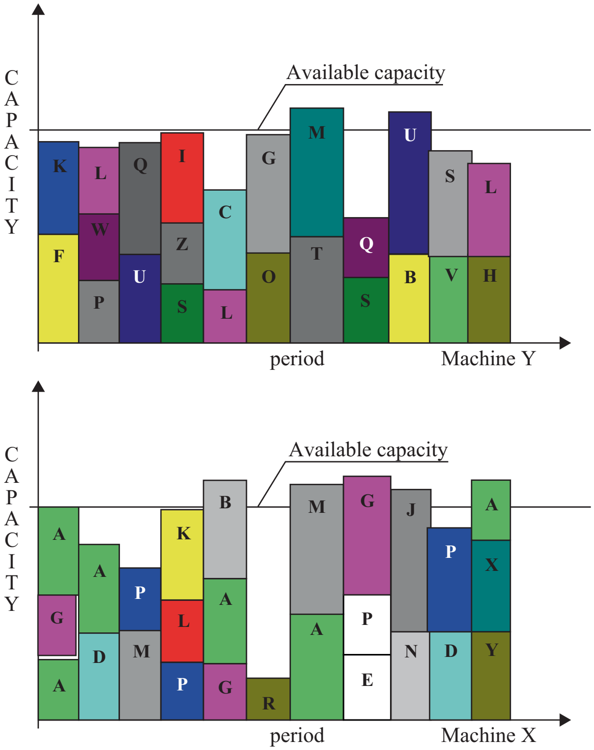
The least additional cost is incurred by transferring the processing of item K from machine X to machine Y. (In this example, the hourly rate for each machine is ignored. Actually, the check should consider changes in time as well as cost). The added time on machine Y does not create an overload situation, and the change is approved, as shown in Fig. 10.9.

The second period is also overloaded. The load on machine X during the second period is as follows:

item D = 40; item L = 30; and item A = 50.
The total load is 120, and the available load is 100.
The load on machine Y during the second period is as follows:
item P = 25 and item W = 20. The total load is 45, and the available load is 100.

Item D can use machine Y instead of machine X, which increases the required load from 40 to 58. Item L can use machine Y instead of machine X, which increases the required load from 30 to 34.

Fig. 10.9 Improved profiles of machine X and machine Y



Item A can use machine Y instead of machine X, which increases the required load from 50 to 54. The penalty for changing the processing of item D is too much, and thus, this option is ignored. Changing the processing of item L or item A may be a better alternative. The load will be better balanced if item L is changed. The total required load on machine X will be 90 and the required load on machine Y will be 79. The improved load profile is shown in Fig. 10.9.

Flexible processing can also be used to improve processing cost if it does not endanger the load profile balance. Figure 10.9 provides an example. During period 6, item R is processed on machine X and uses a load of only 20 out of an available load of 100. If no work can be transferred by the method previously described, and **if** item R is not needed immediately for assembly, the cutting conditions can be modified so as to reduce the tooling cost while increasing machining time.

For example, the cutting speed can be reduced and the processing time increased proportionately. The savings come in the form of increased tool life, which means fewer tools will be needed. The feed rate or depth of cut can be reduced for a similar effect. The roadmap method can be used to examine such process changes and recommend a course of action.

4.4 Management and Engineering

The master production schedule is a management tool with a “look ahead” feature—a feature that is needed in order to plan the future of a company. It provides simulation of capacity requirements for different marketing forecasts, purchasing of new equipment, and profit or loss forecast. It indicates the necessary requirement planning with respect to shop floor space, warehouse space, transport facilities, and manpower.

The master production schedule is used to prepare the budget, to plan cash flow, manpower, and resource requirements, and to forecast company profits. The budget is a management tool for controlling the activities of a company.

However, the present-day method of planning the master production schedule assumes fixed, unalterable routing, and thereby robs the manufacturing process of its inherent flexibility. Management decisions are, thus, biased, and, in many cases, unrealistic decisions are made.

This chapter demonstrates how master product design and the roadmap method assist in preparing and improving the master production schedule, and thereby all its derivatives. Adjusting product design and treating routing as a variable can avoid many scheduling problems and investments in unnecessary resources.

Chapter 11
Determining Delivery Date and Cost

Abstract Management makes decisions that set orders, cost and delivery dates.

Production planners do not question how the delivery date was determined, but regard them as a constraint. Due date is one of the determining factors in establishing the quality of the shop's performance. Impractical due dates can result in severe losses for a company, such as loss of reputation and extra cost in meeting the promised dates by working overtime, extra shifts, or on weekends and holidays.

Engineering, through its flexible methods, may supply management with accurate data on the cost-delivery date relationship.

This chapter presents a method of establishing a realistic due date, based on shop floor load. Furthermore, it correlates the due date and processing cost, and prepares, in a few seconds, table of several process planning alternatives, listing the due date and processing cost for each one.

1 Introduction

Traditional practice is that production management activities begin with customer orders as input. The order delivery date is part of the order information. The delivery date plays a major role in the production management stages. The Material Requirement Planning stage uses it for determining due dates for purchased and in house production orders. Capacity Planning uses material requirement planning due dates for in-house machine loading. Due date is one of the determining factors in establishing the quality of the shop performance. However, no one questions how the delivery date was determined. In many cases, sales promises unrealistic delivery dates, but production planning regards them as a constraint.

The roadmap system can be used by sales and/or management to establish realistic delivery dates. Because routing is regarded as a variable, the processing lead time is flexible. The flexibility affects the processing cost as well. Hence, there is a direct relationship between the processing lead time (the delivery date) and the processing cost. Information about this relationship can be very helpful to management when negotiating price and delivery dates with a customer.

Hence, there is a direct relationship between the processing lead time (the delivery date) and the processing cost.

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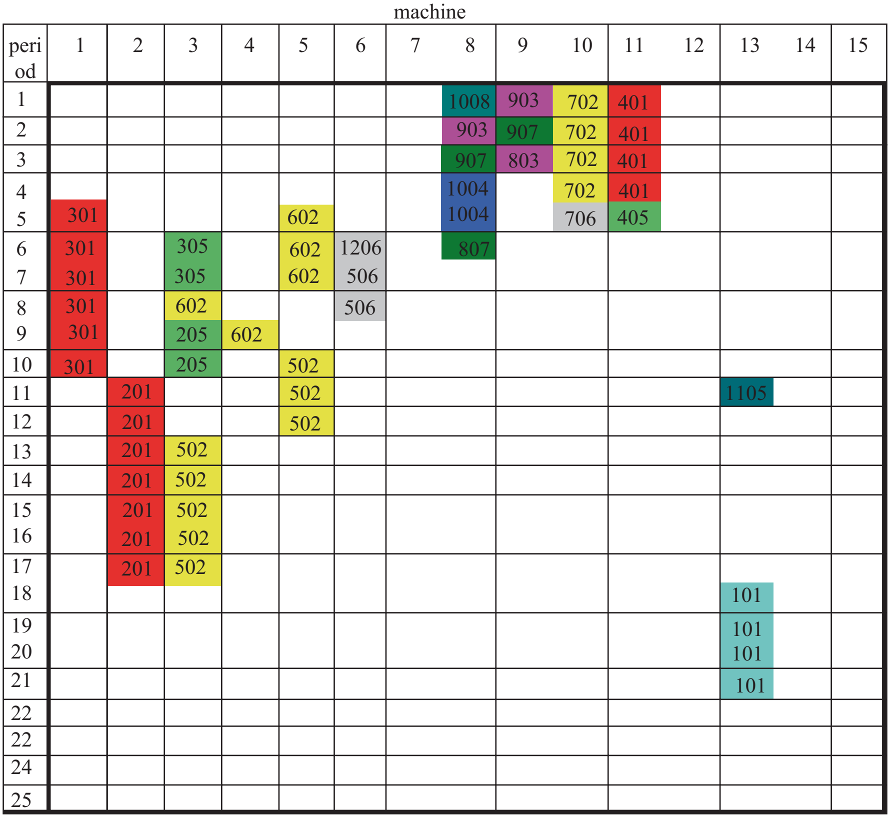


machine

period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1								1008	903	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004		702	401				
5	301				602			1004		706	405				
6	301		305		602	1206		807							
7	301		305		602	506									
8	301		602			506									
9	301		205	602											
10	301		205		502										
11		201			502								1105		
12		201			502										
13		201	502												
14		201	502												
15		201	502												
16		201	502												
17		201	502												
18													101		
19													101		
20													101		
21													101		
22															
22															
24															
25															

Fig. 11.1 Last resource capacity plan

The information regarding this relationship might be very helpful to management while negotiating the selling conditions of price and delivery date with a customer.

The proposed module for establishing a realistic delivery date module is as follows: the last resource capacity plan (Fig. 11.1) will be referred to as the present "load profile". The load profile is a result of a finite capacity resource loading process. The load profile shows the existing jobs planned on all available resources and idle times.

In any plan, there might be some resource idle time. When a new order arrives, its bill of material is used to compute the gross requirement of all items involved. Then, a search in inventory is made, the net requirement of each item is computed, and the working product structure is built. The roadmap is called to generate a process plan to construct a time-based product structure. The time-based product structure is used to set the priorities of resource loading.

Loading of the items of the new order, as computed by the working time-based product structure, will be determined by a similar method as the resource loading method. However, as it is a new order, it is planned superimposed on the present load profile. This means that the present load planned will remain unaltered, and only the idle periods of each resource or at the end of the loading periods will be considered for loading the new order.

However, as the new order is loaded only at idle times or at the end of the loading period, the due date might be far ahead. The roadmap method may generate alternative processes by using different resources. As an alternate process cannot be as efficient as the best process, the cost of producing the order will increase. On the other hand, the idle time of the alternate resources might be at an earlier period, and thus, the due date may turn out to be earlier.

The roadmap method has several features that might be handy in this case. One is the “Resource blocking option”, in which the roadmap is asked to ignore certain resources in the loading table.

The other is “Forced process planning option”, in which the resources to be used are dictated externally. These features are used to generate alternatives.

The alternative cost-delivery date will be generated in three steps:

1. Loading the new order and all its items as one unit with alternate process plans.
2. Generating alternatives while allowing working overtime or extra shifts.
3. Splitting the order into several orders.

These methods will be demonstrated in this section.

The roadmap system can also be used when the customer insists on having the order ready by a certain delivery date but may compromise on the quantity. Sales personnel do not need to consult a process planner, as they may generate alternatives themselves through an appropriate computer program.

2 Generating Alternatives for Cost-Delivery Date: New Order

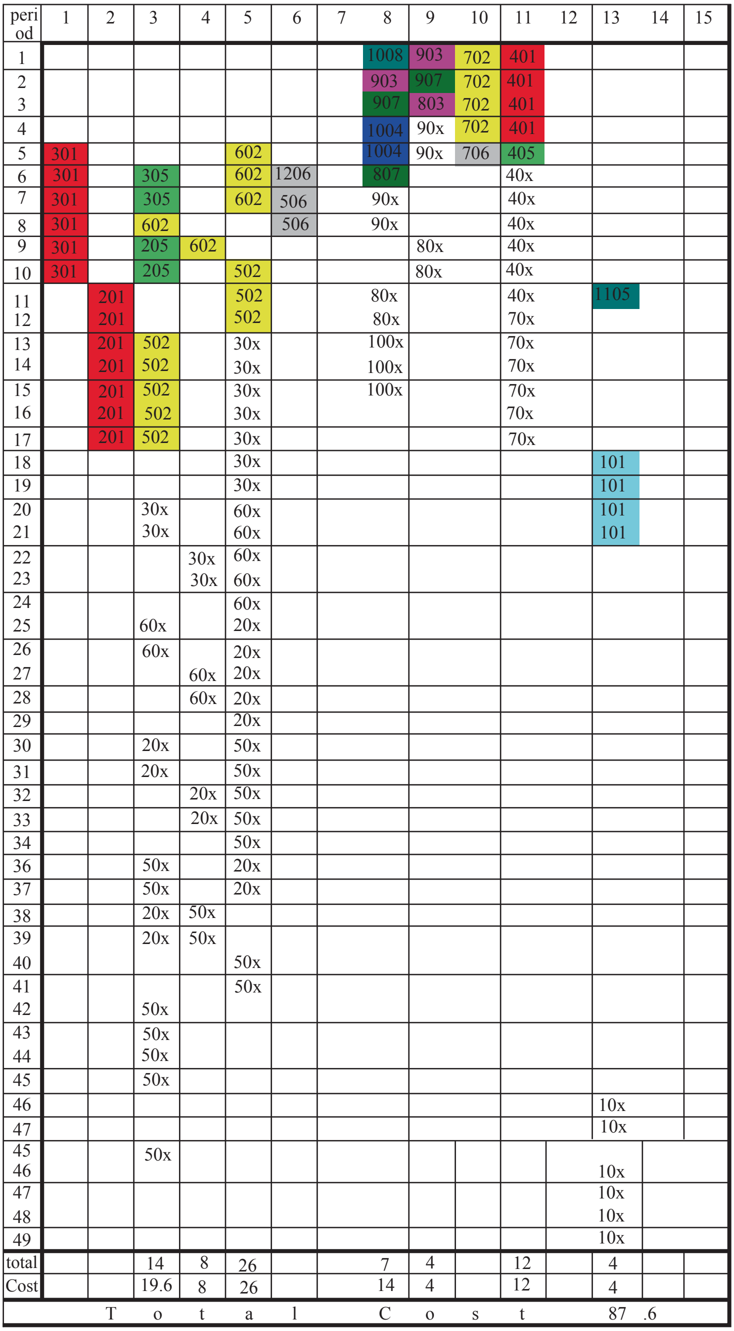
In this stage, many alternatives are generated and a table of cost delivery dates is built. The alternatives are generated following the working product structure and the priority set by the earliest start date of the low-level items, similar to capacity loading. The machine loading is superimposed on the last working load profile constructed. The method is best demonstrated by continuing the example used in the Appendix.

Example: A company receives a new order for 100 units of a pneumatic spring return cylinder. The customer would like to set an acceptable delivery date and cost for the order. Assume that not a single item is in stock and all the required items must be produced. The last load profile is as shown in the Appendix, Fig. 11.1, while the new load order appears in Figs. 11.2, 11.3, 11.4, 11.5, 11.6, 11.7 and 11.8; the new order will be denoted by an “x” as the last character, with the first digit indicating the item number.

2.1 Cost-Delivery Date with Minimum Cost Process Plan

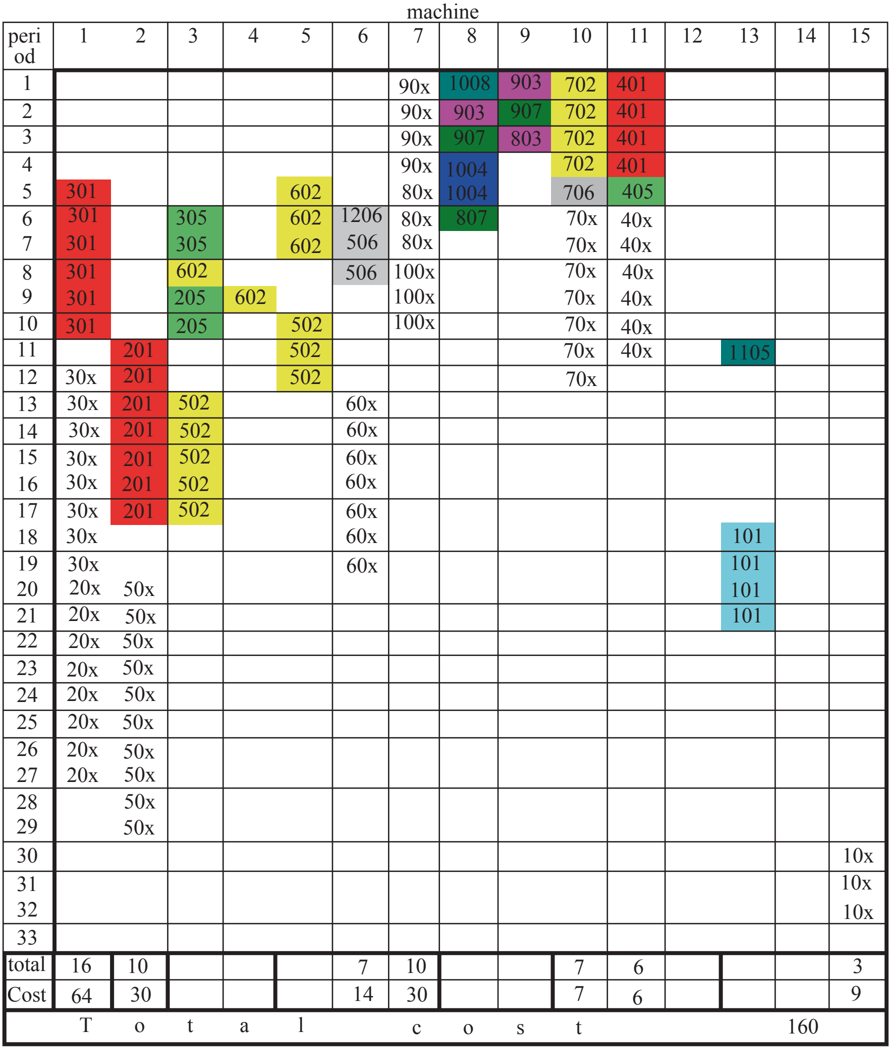
The first alternative is minimum cost order; this is examined by loading a minimum cost process plan. The cost value is computed by multiplying the number of periods that each resource is occupied by its relative cost, as follows:

Machine 1 2 3 4 5 6 7 8 9 1 0 1 1 1 2 1 3 1 4 1 5
Relative cost 4 3 1 . 4 1 1 2 3 2 1 1 1 1 1 1 . 5 3



period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1								1008	903	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004	90x	702	401				
5	301				602			1004	90x	706	405				
6	301		305		602	1206		807			40x				
7	301		305		602	506		90x			40x				
8	301		602			506		90x			40x				
9	301		205	602					80x		40x				
10	301		205		502				80x		40x				
11		201			502			80x			40x		1105		
12		201			502			80x			70x				
13		201	502		30x			100x			70x				
14		201	502		30x			100x			70x				
15		201	502		30x			100x			70x				
16		201	502		30x						70x				
17		201	502		30x						70x				
18					30x								101		
19					30x								101		
20			30x		60x								101		
21			30x		60x								101		
22				30x	60x										
23				30x	60x										
24					60x										
25			60x		20x										
26			60x		20x										
27				60x	20x										
28				60x	20x										
29					20x										
30			20x		50x										
31			20x		50x										
32				20x	50x										
33				20x	50x										
34					50x										
36			50x		20x										
37			50x		20x										
38			20x	50x											
39			20x	50x											
40					50x										
41					50x										
42			50x												
43			50x												
44			50x												
45			50x												
46													10x		
47													10x		
45			50x												
46													10x		
47													10x		
48													10x		
49													10x		
total			14	8	26			7	4		12		4		
Cost			19.6	8	26			14	4		12		4		
Total Cost													87.6		

Fig. 11.2 Loading profile for minimum cost routine



	machine														
period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							90x	1008	903	702	401				
2							90x	903	907	702	401				
3							90x	907	803	702	401				
4							90x	1004		702	401				
5	301				602		80x	1004		706	405				
6	301		305		602	1206	80x	807		70x	40x				
7	301		305		602	506	80x			70x	40x				
8	301		602			506	100x			70x	40x				
9	301		205	602			100x			70x	40x				
10	301		205		502		100x			70x	40x				
11		201			502					70x	40x		1105		
12	30x	201			502					70x					
13	30x	201	502			60x									
14	30x	201	502			60x									
15	30x	201	502			60x									
16	30x	201	502			60x									
17	30x	201	502			60x									
18	30x					60x							101		
19	30x					60x							101		
20	20x	50x											101		
21	20x	50x											101		
22	20x	50x													
23	20x	50x													
24	20x	50x													
25	20x	50x													
26	20x	50x													
27	20x	50x													
28		50x													
29		50x													
30															10x
31															10x
32															10x
33															
total	16	10				7	10			7	6				3
Cost	64	30				14	30			7	6				9
Total cost														160	

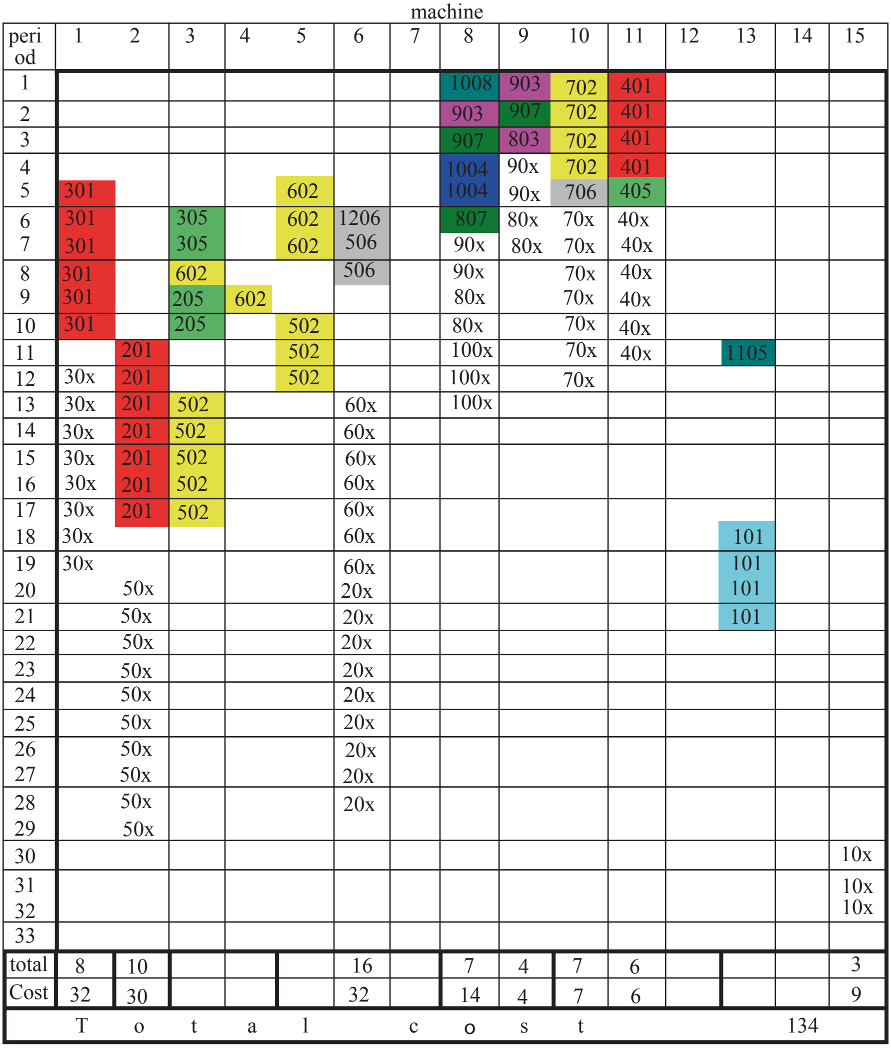
Fig. 11.3 Loading profile for maximum production routine

Item 4 is loaded first, with a quantity of 100 units; therefore, the penalty is 30/100 = 0.3. The roadmap is called to generate a process. The recommended process plan is to use machine 11 for 6.6 + 0.3 = 6.9 min × 100 units = 690 min + 120 min (one period) = 5.75 periods, rounded to 6 periods.

This operation can begin immediately; however, the earliest idle period for machine 11 is period 6, and it is idle for at least six periods; therefore, item 4 can be loaded onto machine 11 from period 6 to period 11, and is marked 40x in Fig. 11.2

Next, item 3 is treated. The quantity is 100 units. The roadmap is called and a plan is generated. It calls for:

Machine 5 for operations 1, 2, 4 total of 8.54 + 0.3 min × 100 units = 884/120 min per period =
= 7.37 periods rounded to > 7 periods



period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	machine														
1								1008	903	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004	90x	702	401				
5	301				602			1004	90x	706	405				
6	301		305		602	1206		807	80x	70x	40x				
7	301		305		602	506		90x	80x	70x	40x				
8	301		602			506		90x		70x	40x				
9	301		205	602				80x		70x	40x				
10	301		205		502			80x		70x	40x				
11		201			502			100x		70x	40x		1105		
12	30x	201			502			100x		70x					
13	30x	201	502			60x		100x							
14	30x	201	502			60x									
15	30x	201	502			60x									
16	30x	201	502			60x									
17	30x	201	502			60x									
18	30x					60x							101		
19	30x					60x							101		
20		50x				20x							101		
21		50x				20x							101		
22		50x				20x									
23		50x				20x									
24		50x				20x									
25		50x				20x									
26		50x				20x									
27		50x				20x									
28		50x				20x									
29		50x													
30															10x
31															10x
32															10x
33															
total	8	10				16		7	4	7	6				3
Cost	32	30				32		14	4	7	6				9
Total cost														134	

Fig. 11.4 Improved cost for maximum production loading

Machine 3 for operation 3 $1.82+0.3\ \text{min}\times100=212/120$
$=1.76>2$ periods

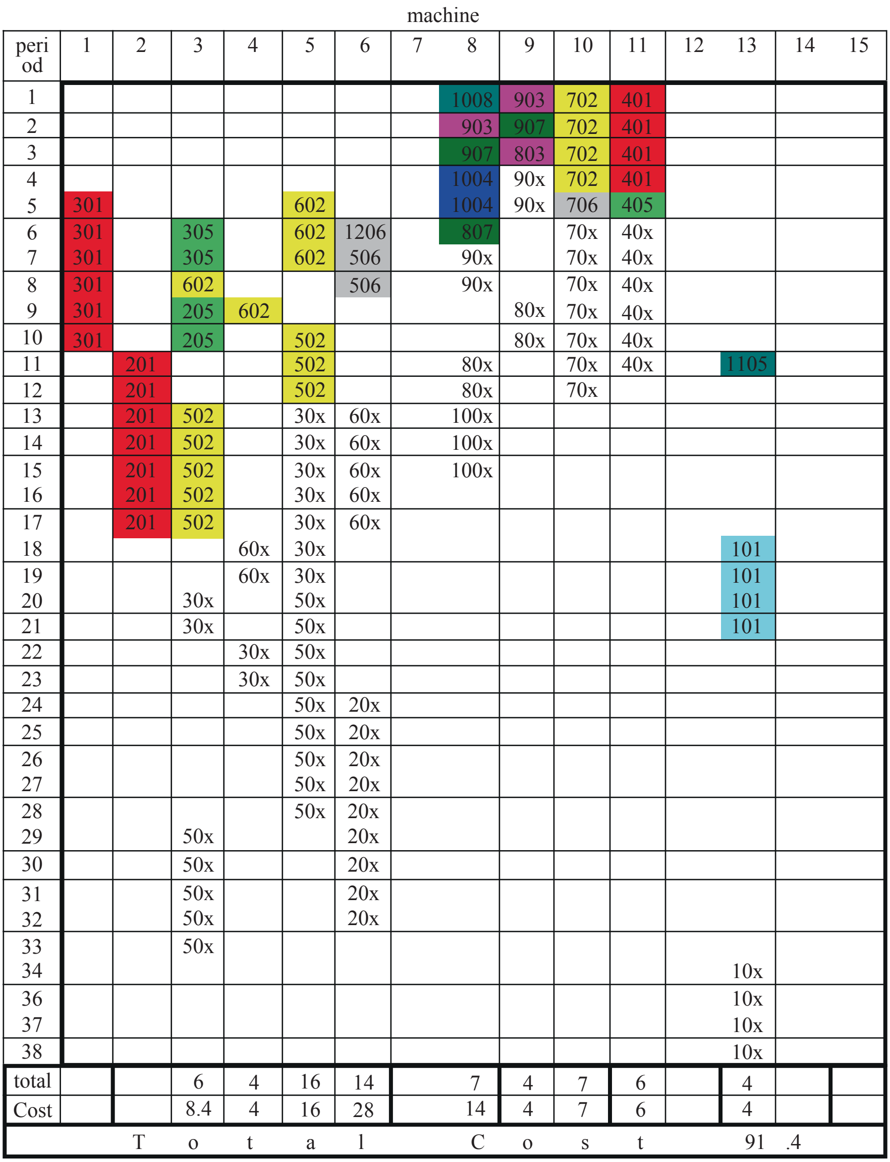
Machine 4 for operation 5 $2.62+0.3=2.92\times100=92/120=2.43>2$ periods
The loading starts with machine 5. The operation can begin after operation 4 is done (i.e., period 12). However, machine 5 is occupied in period 12 and is idle starting in period 13 for more than seven periods. Therefore, the first operation for item 3 is loaded onto machine 5 in periods 13–19 and marked 30x.

Item 3 on machines 3 and 4 begins after the previous operation. The roadmap finds idle machine time and the first operation is loaded and marked 30x.

machine

period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1								1008	903	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004	90x	702	401				
5	301				602			1004	90x	706	405				
6	301		305		602	1206		807		70x	40x				
7	301		305		602	506		90x		70x	40x				
8	301		602			506		90x		70x	40x				
9	301		205	602					80x	70x	40x				
10	301		205		502				80x	70x	40x				
11		201			502			80x		70x	40x		1105		
12		201			502			80x		70x					
13		201	502		30x	60x		100x							
14		201	502		30x	60x		100x							
15		201	502		30x	60x		100x							
16		201	502		30x	60x									
17		201	502		30x	60x									
18				60x	30x								101		
19				60x	30x								101		
20			30x		30x								101		
21			30x		50x								101		
22				30x	50x										
23				30x	50x										
24					50x										
25			50x		20x										
26			50x		20x										
27				50x	20x										
28				50x	20x										
29					20x										
30			20x		50x										
31			20x		50x										
32			50x	20x											
33			50x	20x											
34			50x		20x										
36			50x		20x										
37			20x												
38			20x												
39													10x		
40													10x		
41													10x		
42													10x		
total			12	8	21	5		7	4	7	6		4		
Cost			16.8	8	21	10		14	4	7	6		4		
		Total Cost											90.8		
Cost			16.8	8	21	10		14	4	7	6		4		
		Total Cost											90.8		

Fig. 11.5 Loading profile for improved minimum cost process plan



period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1								1008	903	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004	90x	702	401				
5	301				602			1004	90x	706	405				
6	301		305		602	1206		807		70x	40x				
7	301		305		602	506		90x		70x	40x				
8	301		602			506		90x		70x	40x				
9	301		205	602					80x	70x	40x				
10	301		205		502				80x	70x	40x				
11		201			502			80x		70x	40x		1105		
12		201			502			80x		70x					
13		201	502		30x	60x		100x							
14		201	502		30x	60x		100x							
15		201	502		30x	60x		100x							
16		201	502		30x	60x									
17		201	502		30x	60x									
18				60x	30x								101		
19				60x	30x								101		
20			30x		50x								101		
21			30x		50x								101		
22				30x	50x										
23				30x	50x										
24					50x	20x									
25					50x	20x									
26					50x	20x									
27					50x	20x									
28					50x	20x									
29			50x			20x									
30			50x			20x									
31			50x			20x									
32			50x			20x									
33			50x												
34													10x		
36													10x		
37													10x		
38													10x		
total			6	4	16	14		7	4	7	6		4		
Cost			8.4	4	16	28		14	4	7	6		4		
Total Cost													91 .4		

Fig. 11.6 Loading profile for minimum cost process plan

Next, item 2 is treated. The quantity is 100 units. The roadmap is called and a plan is generated. It calls for:

Machine 5 for operations 1,2 total of 6.07 min + 0.3 = 6.37 * 1001120 = 5.3 > 5 periods

Machine 3 for operation 3 2.05 + 0.3 = 2.35 c* 100/20 = 1.96 > 2 periods

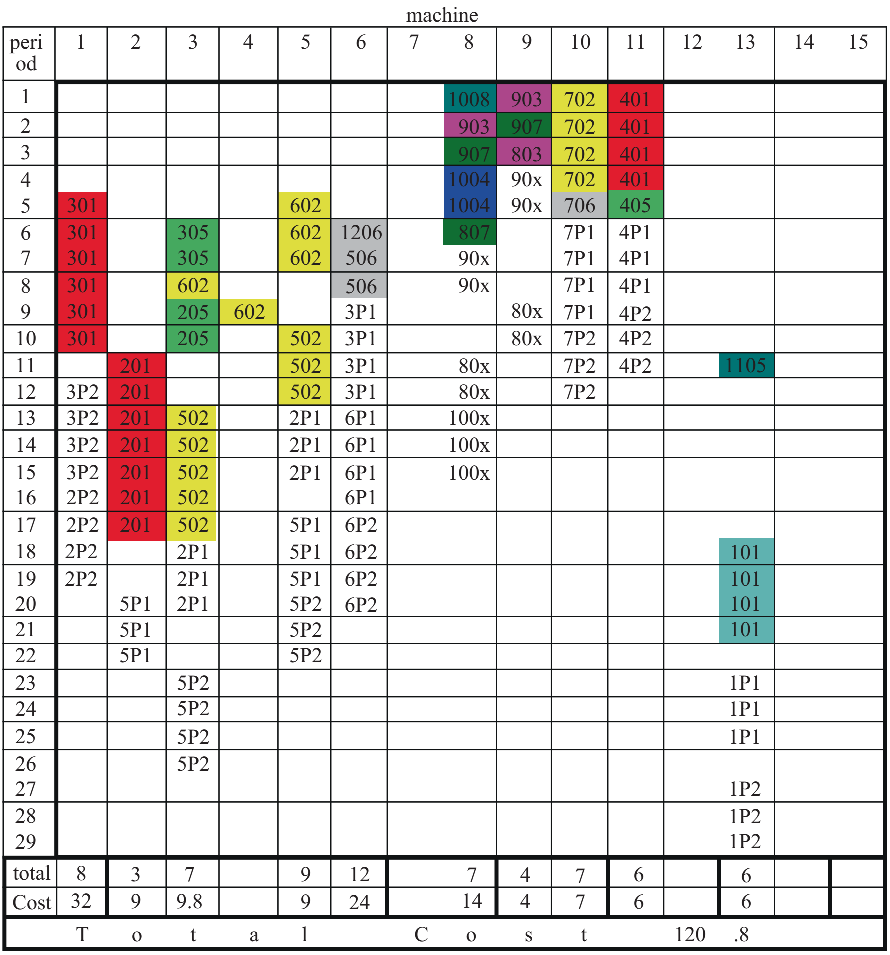
period	machine														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1								1008	903	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004	90x	702	401				
5	301				602			1004	90x	706	405				
6	301		305		602	1206		807			40x				
7	301		305		602	506		90x			40x				
8	301		602			506		90x			40x				
9	301		205	602					80x		40x				
10	301		205		502				80x		40x				
11		201			502			80x			40x		1105		
12		201			502			80x			70x				
13		201	502		30x			100x			70x				
14		201	502		30x			100x			70x				
15		201	502		30x			100x			70x				
16		201	502		30z						70x				
17		201	502		30z						70x				
18			30x		60x								101		
19			30x		60x								101		
20				30x	60x								101		
21				30x	60z								101		
22			60x		20x										
23			60x		20x										
24				60x	20x										
25				60x	20z										
26			20x		50z										
27			20x		50z										
28				20z	50x										
29			50z		20x										
30				50z	20x										
31			20z		50z										
32			50z												
33			50z												
34													10x		
36													10x		
37													10x		
38													10x		
total			6x + 4z	4x +2z	12x +7z			7	4		12		4		
Cost			21	8.5	27.75			14	4		12		4		
Total Cost													91.25		

Fig. 11.7 Loading profile for splitting the order into two orders

Machine 4 for operation 4 1.86+0.3=2.16 * 100/20 =1.80>2 periods

Machine 5 for operation 5 2.18+0.3=2.48 * 100/20 =2.07>2 periods

Machine 3 for operation 6 2.07+0.3=2.37 * 100/20 =1.98>2 periods



machine

period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1								1008	903	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004	90x	702	401				
5	301				602			1004	90x	706	405				
6	301		305		602	1206		807		7P1	4P1				
7	301		305		602	506		90x		7P1	4P1				
8	301		602			506		90x		7P1	4P1				
9	301		205	602		3P1			80x	7P1	4P2				
10	301		205		502	3P1			80x	7P2	4P2				
11		201			502	3P1		80x		7P2	4P2		1105		
12	3P2	201			502	3P1		80x		7P2					
13	3P2	201	502		2P1	6P1		100x							
14	3P2	201	502		2P1	6P1		100x							
15	3P2	201	502		2P1	6P1		100x							
16	2P2	201	502			6P1									
17	2P2	201	502		5P1	6P2									
18	2P2		2P1		5P1	6P2							101		
19	2P2		2P1		5P1	6P2							101		
20		5P1	2P1		5P2	6P2							101		
21		5P1			5P2								101		
22		5P1			5P2										
23			5P2										1P1		
24			5P2										1P1		
25			5P2										1P1		
26			5P2												
27													1P2		
28													1P2		
29													1P2		
total	8	3	7		9	12		7	4	7	6		6		
Cost	32	9	9.8		9	24		14	4	7	6		6		
Total Cost												120.8			

Fig. 11.8 Loading profile for splitting the order into two lots

The loading of item 2 can begin only after item 3 is done (i.e., period 24). All required machines are idle at the required periods and are loaded and marked 20x. The same loading procedure continues for all order items. Figure 11.2 shows the loading and the cost of the new order.

2.2 *Cost-Delivery Date with Maximum Routing*

Another alternative will aim at minimum lead time. This is examined by loading a maximum production process plan.

The roadmap is called to generate a process using the maximum production criterion of optimization. The following processes are generated:

Item 4 uses machine 11 for 6.6 min=(6.6+0.3) * 100/120=5.75 periods >6 periods 6 to 11

Item 3 uses machine 1 for 9.16 min=(9.16+0.3) * 1001120 =7.88 periods >8 periods 12 to 19

Item 2 uses machine 1 for 9.85 min=(9.85+0.3) * 1001120 =8.46 periods >8 periods 20 to 27

Item 7 uses machine 11 for 6.6 min=(6.6+0.3) * 1001120 =5.75 periods >6 periods 12–17

Item 6 uses machine 1 for 7.59 min=(7.59+0.3) * 1001120 =6.58 periods >7 periods 28 to 34

Item 5 uses machine 1 for 11.29 min=(11.29+0.3) * 1001120 =9.66 periods >10 periods 35 to 44

Item 9 uses machine 7 for 3.94 min=(2.9+0.3) * 1001120 =3.53 periods >4 periods 1 to 4

Item 8 uses machine 7 for 2.9 min=(2.9+0.3) * 1001120 =2.66 periods >3 periods 5 to 7

Item 10 uses machine 7 for 2.86 min=(2.86+0.3) * 1001120 =2.63 periods >3 periods 8 to 10

Item 1 uses machine 15 for 3.0 min=(3.0+0.3) * 1001120 =2.75 periods >3 periods 45 to 47

The order can be delivered in 48 periods and the processing cost will be 183 units.

2.3 Cost-Delivery Date: Improved Maximum Production Routine

The maximum production process plan correctly chooses machine 1 for all items; therefore, this machine is overloaded, and the lead time increases significantly.

The improvement method uses the blocking feature of the roadmap; that is, when an item must wait for a machine, that same machine is blocked (i.e., a process that does not use that machine is generated). For the maximum production process plan, item 6 must wait 10 periods until machine 1 has an idle period. Instead of waiting, machine 1 is blocked and the roadmap generates an alternative process with the maximum production process plan. The recommended process is to use machine 2 instead.

The order can be delivered in period 33 and the processing cost will be 160 units. The loading profile is shown in Fig. 11.3.

2.4 Cost Delivery Dates: Other Alternatives

The roadmap has generated several other alternative delivery-cost combinations.

Figure 11.4 presents a profile of improved cost for maximum production loading.

2.5 Cost-Delivery Date: Improved Cost with Minimum Cost Process Plan

The minimum cost process plan correctly chooses machines 3, 4, and 5 for all items; therefore, these machines are overloaded, and the lead time increases significantly. The improvement method uses the blocking feature of the roadmap; that is, when an item must wait for a machine, that machine will be blocked. In the case of a minimum cost process plan, item 7 must wait for 11 periods until machine 11 has an idle period (periods 1 to 11). Instead of waiting, machine 11 is blocked and the roadmap generates an alternate process plan. The recommended process is to use machine 10 for 7.8 min = (7.8 + 0.3) * 100/120 = 6.75 periods > 7 periods. Item 7 can be started at any period, and machine 10 is idle at period 6; therefore, item 7 is loaded and marked 70x on machine 10 for periods 6 to 12.

Item 6 can start after item 7 is done (i.e., period 7); it requires machine 5 for five periods, machine 3 for three periods, and machine 4 for two periods. However, machine 5 is idle only in period 20; therefore, machine 5 is blocked. The recommended process is to use machines 3 and 4. However, because machine 3 is occupied, it is also blocked, and the alternate process generated recommends using machine 6 for operations 1,2, and 3 for a total of 5.98 min, and then machine 4 for operation 4.

This change is made as shown in Fig. 11.5. The order can be delivered in period 43 with a processing cost of 90.8 units.

2.6 Cost–Delivery Data: Loading Profile for Improved Minimum Cost Process Plan

The use of machine 4 for item 5 increases the lead time. If machine 4 is blocked, the roadmap generates a process plan using only machines 5 and 3; it calls for using machine 5 to perform operations 1, 2, 4, and 5 for a total time of 10.45 min (10.45 + 0.3) * 100/120 = 8.96, rounded to 9 periods. Then, machine 3 performs operations 3, 6, and 7 for a total of 6.12 min (6.12 + 0.3) * 100/120 = 5.35 > 5 periods.

Machines 3, 4, and 5 are heavily loaded. To ease the load, they are blocked and the roadmap recommends using only machine 6 for 10.75 min, which is (10.75 + 0.3) * 100\120 = 9.2 > 9 periods. These modifications are shown in Fig. 11.6. Through these changes, the order can be delivered in period 39 with a processing cost of 91.4 units.

2.7 Generating Alternatives for Cost-Delivery Date: Working Overtime Shifts, and Splitting

The lead time can be reduced if, when necessary, a second shift is worked. However, the salary for working the second shift is higher than for the first shift. By working a second shift, the number of periods required to produce each operation can be reduced by half. However, this does not always reduce the order lead time. In some cases, the time will actually be reduced by half, but the process will have to wait during certain periods because a machine is occupied. In such a case, working a second shift is a waste.

Figure 11.7 shows the load profile for loading with the minimum cost process plan, as shown in Fig. 11.3. In this figure, "x", as the last character, indicates the new first-shift loading, and *"z"* indicates the second shift. The totals in the last row indicate the number of periods that the resource worked during one shift or two shifts. In other words, resource 3 was employed for six single-shift periods (6x) plus four double-shift periods (4z). The total cost of the new order that contributed to this resource is, therefore, 6+4+4=14 regular paid shifts +4 shifts with extra pay. Assume the second shift received an extra 25 % over its regular rate; therefore, the total cost is

$$14 \times 1.4 \times 4 \times 0.25 \times 1.4 = 21 \text{ relative cost.}$$

The total cost is the sum of the cost of all the periods. The result is that the order can be delivered in period 39 with a processing cost of 91.25 units.

Figure 11.8 shows the load profile for the case of splitting the order into two orders of 50 items each. In this figure, the symbol "P" indicates that the new order was split, and the last digit indicates first or second batch. The first digit is the item number.

The results show that the order can be delivered in period 30 with a cost of 120.8 units.

2.8 Management Control

Delivery date plays a major role in the production management stages. However, traditionally, it is set by management without a practical basis. It depends on sales promises and customer demands. In many cases, promised delivery dates are impractical and can result in severe losses for a company, such as loss of reputation and extra cost in meeting the promised dates by working overtime, extra shifts, or on weekends and holidays.

The roadmap method does not pretend to remedy the method of establishing delivery dates; it merely aims to supply management with accurate data on the cost-delivery date relationship. This information can be used by management in negotiations with the customer.

This chapter presented a method for computing the relationship between cost and delivery date for an order. It considers the available stock and the present load of the company. Several methods have been simulated, and a table of the results is as follows (Table 11.1):

Table 11.1 Summary of alternate cost-delivery date **sorted** by figures, cost, method. (First Alt. sort by cost, second by method)

Alt.	Section	Figure	Cost	Delivery period	Remarks
1	2.1	11.2	87.6	50	Minimum cost process plan
2	2.2	–	183.0	48	Maximum production process plan
3	2.2	–	166.0	38	Improved alternative 2
4	2.3	11.3	160.3	33	Improved alternative 3
5	2.4	11.4	134.0	33	Cost improvement of alternative 4
6	2.5	11.5	90.8	43	Improved alternative 1
7	2.6	11.6	91.4	39	Improved alternative 6
8	2.7	11.7	91.25	39	Two shifts for alternative 1
9	2.7	11.8	120.8	30	Splitting the order
AI!.					
1	2.1	11.2	87.6	50	Minimum cost process plan
2	2.5	11.5	90.8	43	Improved alternative I
3	2.7	11.7	91.25	39	Two shifts for alternative 1
4	2.6	11.6	91.4	39	Improved alternative 6
5			98.6	48	not in text
6			99.6	47	not in text
7			101.2	41	not in text
8			108.4	34	not in text
9	2.7	11.8	120.8	30	Splitting the order
10	2.4	11.4	134.0	33	Cost improvement of alternative 4
11	2.3	11.3	160.3	33	Improved alternative 3
12			166.0	38	Improved alternative 2
13			183.0	48	Maximum production process plan
All.					
1	2.7	11.8	120.8	30	Splitting the order
2	2.4	11.4	134.0	33	Cost improvement of alternative 4
3	2.3	11.3	160.3	33	Improved alternative 3
4			108.4	34	not in text
5		–	166.0	38	Improved alternative 2
6	2.7	11.7	91.25	39	Two shifts for alternative 1
7	2.6	11.6	91.4	39	Improved alternative 6
8			101.2	41	not in text
9	2.5	11.5	90.8	43	Improved alternative 1
10			99.6	47	not in text
11			98.6	48	not in text
12			183.0	48	Maximum production process plan
13	2.1	11.2	87.6	50	Minimum cost process plan

Appendix

Roadmap Method: Example

Assume a company that manufactures two kinds of pneumatic cylinders. Figure A11.1 shows the spring return cylinder. Figure A11.2 shows its bill of material.

The manufacturing plant has the resources, as shown in Table A11.1.

Transforming the Theoretical process plan, as shown in Table A11.2, is shown in Table A11.3.

The time can be transformed into cost base, as shown in Table A11.4.

This example assumes that the company got two orders: one for 120 units of spring return cylinder to be delivered on day 40; and the other for 35 units of double acting cylinder to be delivered on day 35.

Furthermore, it is assumed that the following items are in stock:

Item	1	4	5	6	8	9	10	11	12
Quantity	40	10	18	9	11	20	28	20	15

The first step in capacity planning is to transform the product structure into a working time-based product structure, i.e., to perform stock allocation, in order to compute what should be processed. The algorithm is to allocate available stock to the critical order. The critical order is established by using the road map and the bill of materials. However, a critical order might be changed after each allocation. The example in Table A11.5 shows the 3 stages, with the row on the right indicating the final product structure. It includes the time during which each item should be processed and the quantity required.

In this example, the effect of the recommended process plan through a different criterion of optimization on throughput is examined.

Figure A11.3 shows the load profile when the process plan for maximum production (minimum process time) is selected.

In this case, it will take 35 periods and cost 162 units.

Figure A11.4 shows the scheduling load profile when the process planning for minimum cost is selected.

In this case it will take 32 periods and cost 76.2 units.

The total processing number of periods is as indicated. How can maximum production take more time to produce a product than the minimum cost? Examining the load profile supplies the answer. The best machine available is the milling machining center (#1). The process planner selected this machine as the “best” machine for the job, and rightfully so. This selection caused a long queue and jobs had to wait. It

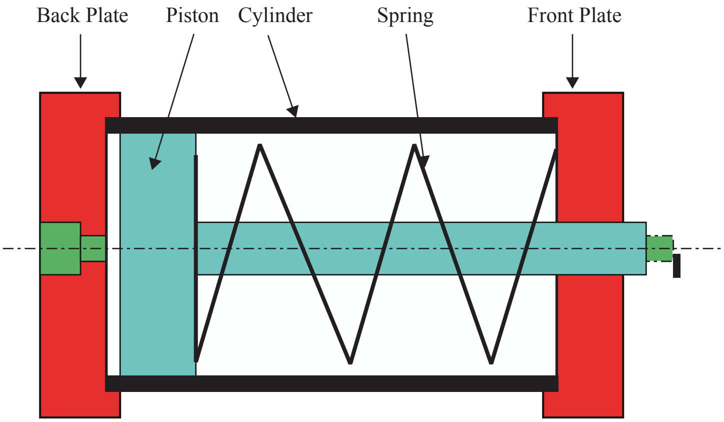
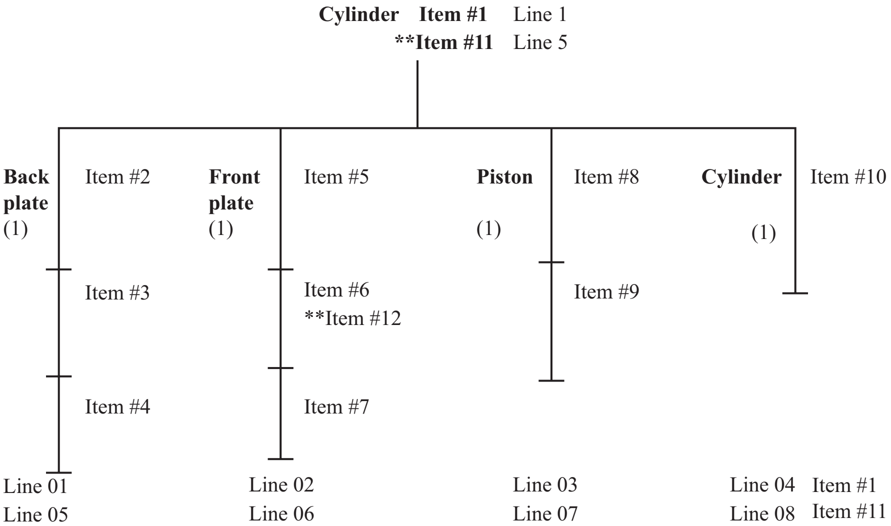


Fig. A11.1 Pneumatic cylinder spring return



** Item #11 & #12 are for the double acting cylinder

* The line numbers are for load profile indications

Fig. A11.2 Bill of materials of cylinder

means that the criterion of maximum production is a misleading term; it refers only to a single operation processing of a part or product processing.

The total cost result is reasonable; however, one should not expect such a significant cost difference. The reason why the lead time is shorter (maximum production) is because it selects several machines, and therefore, the queue at each machine is shorter, resulting in a shorter lead time.

Table A11.1 Theoretical process plan items 5, 6, 7

	Operation	No.	Pr	Tool	L	a	Feed	V	KW	T min
Cut	Raw material	*Item #7*								
010	Sawing	10	00	band						2.8
Mill	External side	*Item #6*								
020	Side milling	10	00	50	113×2	2.5	304	88	1.0	2.02
030	Face milling—R	20	10	80	76	1.59	1428	118	6.63	0.05
040	Face milling—F	30	20	80	143	0.41	900	147	1.34	0.16
050	Assembly holes	40	10	10	20×4		0.2	25	0.6	0.96
Mill	Internal side	*Item #5*								
060	Side milling	10	00	50	113×2	2.5	304	88	1.0	2.02
070	Face milling—R	20	00	80	76	1.79	1401	116	7.34	0.05
080	Face milling—F	30	20	80	143	0.21	370	164	0.37	0.39
090	Drill U 46Ø	40	10	44	40		0.27	114	10.3	0.2
100	Börnig 46Ø—Mr	50	40	40	40		804	93	0.22	0.18
110	Boring 46Ø—Mf	60	50	40	40		359	106	.07	0.41
120	Piston hole	70	60	16	16				2.0	0.34

Table A11.2 The available resources

Machine number	Machine description	Power KW	Speed RPM	Handle time, min.	Relative cost
1	Milling machining center	35	1500	1.10	4
2	Large CMC milling	35	1200	1.15	3
3	Manual milling machine	15	1500	1.66	1.4
4	Small drill press	2.5	1200	1.50	1
5	Old milling machine	15	2400	2.00	1
6	Small CNC milling	10	3000	1.25	2
7	CNC lathe	25	3000	1.15	3
8	Manual lathe new	15	3000	1.42	2
9	Manual lathe old	10	2400	1.66	1
10	Circular saw				1
11	Band saw				1
12	Hack saw				1
13	Manual assembly				1
14	Machine assembly				1.5
15	Robotics assembly				3

Conclusion—The optimization terms are misleading. The two process plans must be generated and the user (scheduler) must be allowed to decide which one to use.

Combination Scheduling A product is defined by a product structure. The items of the product are specified as branches of the product tree. It was proposed that, in order to reduce the queue on the “best” machine (#1), the process should interchange at each branch of the product tree. The first branch uses the minimum cost process plan and the next uses the maximum production process plan; the two are then interchanged back, and so on.

Table A11.3 Time base of the roadmap

Op	PR	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
BACK PLATE #4																
10	00	99	99	99	99	99	99	99	99	99	7.8	6.6	12.2	99	99	99
BACK PLATE #3																
10	00	3.12	3.17	3.68	99	4.02	3.27	99	99	99	99	99	99	99	99	99
20	10	1.15	1.2	1.71	99	2.05	1.3	99	99	99	99	99	99	99	99	99
30	20	1.26	1.31	1.82	99	99	1.41	99	99	99	99	99	99	99	99	99
40	10	1.57	1.62	2.13	2.53	2.47	1.72	99	99	99	99	99	99	99	99	99
50	10	2.06	2.11	2.62	2.62	2.96	2.21	99	99	99	99	99	99	99	99	99
BACK PLATE #2																
10	00	3.12	3.17	3.68	99	4.02	3.27	99	99	99	99	99	99	99	99	99
20	00	1.15	1.2	1.71	99	2.05	1.3	99	99	99	99	99	99	99	99	99
30	20	1.49	1.53	2.05	99	99	1.64	99	99	99	99	99	99	99	99	99
40	10	1.30	1.35	1.86	1.86	2.2	1.45	99	99	99	99	99	99	99	99	99
50	40	1.28	1.33	1.84	99	2.18	1.43	99	99	99	99	99	99	99	99	99
60	50	1.51	1.56	2.07	99	99	1.66	99	99	99	99	99	99	99	99	99
FRONT PLATE #7																
10	0	99	99	99	99	99	99	99	99	99	7.8	6.6	12.2	99	99	99
FRONT PLATE #6 #12																
10	0	3.12	3.17	3.68	99	4.02	3.27	99	99	99	99	99	99	99	99	99
20	10	1.15	1.2	1.71	99	2.05	1.3	99	99	99	99	99	99	99	99	99
30	20	1.26	1.31	1.82	99	99	1.41	99	99	99	99	99	99	99	99	99
40	10	2.06	2.11	2.62	2.62	2.96	2.21	99	99	99	99	99	99	99	99	99
FRONT PLATE #5																
10	0	3.12	3.17	3.68	99	4.02	3.27	99	99	99	99	99	99	99	99	99
20	0	1.15	1.2	1.71	99	2.05	1.3	99	99	99	99	99	99	99	99	99
30	20	1.49	1.53	2.05	99	99	1.64	99	99	99	99	99	99	99	99	99
40	10	1.30	1.35	1.86	1.86	2.2	1.45	99	99	99	99	99	99	99	99	99
50	40	1.28	1.33	1.84	99	2.18	1.43	99	99	99	99	99	99	99	99	99
60	50	1.51	1.56	2.07	99	99	1.66	99	99	99	99	99	99	99	99	99
70	60	1.44	1.49	2.00	99	99	1.59	99	99	99	99	99	99	99	99	99
PISTON #9																
10	0	99	99	99	99	99	99	2.03	2.33	2.57	99	99	99	99	99	99
20	10	99	99	99	99	99	99	1.91	1.85	99	99	99	99	99	99	99
PISTON #8																
10	0	99	99	99	99	99	99	1.45	1.72	1.96	99	99	99	99	99	99
20	10	99	99	99	99	99	99	1.45	1.72	99	99	99	99	99	99	99
CYLINDER #10																
10	0	99	99	99	99	99	99	2.86	3.12	99	99	99	99	99	99	99
ASSEMBLY #1 & #11																
10	0	99	99	99	99	99	99	99	99	99	99	99	99	5.0	4.0	3.0

Table A11.4 Cost base of the roadmap

Op	PR	R1	R2	R3	R4	R5	R6	R7	R8	R9	R 10	R 11	R 12	R 13	R 14	R 15
BACK PLATE #4																
10	00	99	99	99	99	99	99	99	99	99	7.8	6.6	12.2	99	99	99
BACK PLATE #3																
10	00	12.5	9.51	5.15	99	4.02	6.54	99	99	99	99	99	99	99	99	99
20	10	4.60	3.60	2.39	99	2.05	2.60	99	99	99	99	99	99	99	99	99
30	20	5.04	3.93	2.55	99	99	2.82	99	99	99	99	99	99	99	99	99
40	10	6.28	4.86	2.98	2.53	2.47	3.44	99	99	99	99	99	99	99	99	99
50	10	8.24	6.33	3.67	2.62	2.96	4.42	99	99	99	99	99	99	99	99	99
BACK PLATE #2																
10	00	12.5	9.51	5.15	99	4.02	6.54	99	99	99	99	99	99	99	99	99
20	00	4.6	3.60	2.39	99	2.05	2.60	99	99	99	99	99	99	99	99	99
30	20	6.0	4.59	2.87	99	99	3.28	99	99	99	99	99	99	99	99	99
40	10	5.2	4.05	2.60	1.86	2.2	2.90	99	99	99	99	99	99	99	99	99
50	40	5.12	3.99	2.58	99	2.18	2.86	99	99	99	99	99	99	99	99	99
60	50	6.04	4.68	2.90	99	99	3.32	99	99	99	99	99	99	99	99	99
FRONT PLATE #7																
10	0	99	99	99	99	99	99	99	99	99	7.8	6.6	12.2	99	99	99
FRONT PLATE #6 #12																
10	0	12.5	9.51	5.15	99	4.02	6.54	99	99	99	99	99	99	99	99	99
20	10	4.60	3.60	2.39	99	2.05	2.60	99	99	99	99	99	99	99	99	99
30	20	5.04	3.93	2.55	99	99	2.82	99	99	99	99	99	99	99	99	99
40	10	8.24	6.33	3.67	2.62	2.96	4.42	99	99	99	99	99	99	99	99	99
FRONT PLATE #5																
10	0	12.5	9.51	5.15	99	4.02	6.54	99	99	99	99	99	99	99	99	99
20	0	4.6	3.60	2.39	99	2.05	2.60	99	99	99	99	99	99	99	99	99
30	20	5.96	4.59	2.87	99	99	3.28	99	99	99	99	99	99	99	99	99
40	10	5.20	4.05	2.60	1.86	2.20	2.90	99	99	99	99	99	99	99	99	99
50	40	5.12	3.99	2.58	99	2.18	2.86	99	99	99	99	99	99	99	99	99
60	50	6.04	4.68	2.90	99	99	3.32	99	99	99	99	99	99	99	99	99
70	60	5.76	4.47	2.8	99	99	3.18	99	99	99	99	99	99	99	99	99
PISTON #9																
10	0	99	99	99	99	99	99	6.09	4.66	2.57	99	99	99	99	99	99
20	10	99	99	99	99	99	99	5.73	3.70	99	99	99	99	99	99	99
PISTON #8																
10	0	99	99	99	99	99	99	4.35	3.44	1.96	99	99	99	99	99	99
20	10	99	99	99	99	99	99	4.35	3.44	99	99	99	99	99	99	99
CYLINDER #1 0																
10	0	99	99	99	99	99	99	8.58	6.24	99	99	99	99	99	99	99
ASSEMBLY #1 & #11																
10	0	99	99	99	99	99	99	99	99	99	99	99	99	5.0	6.0	9.0

Table A11.5 Final stage of stock allocations

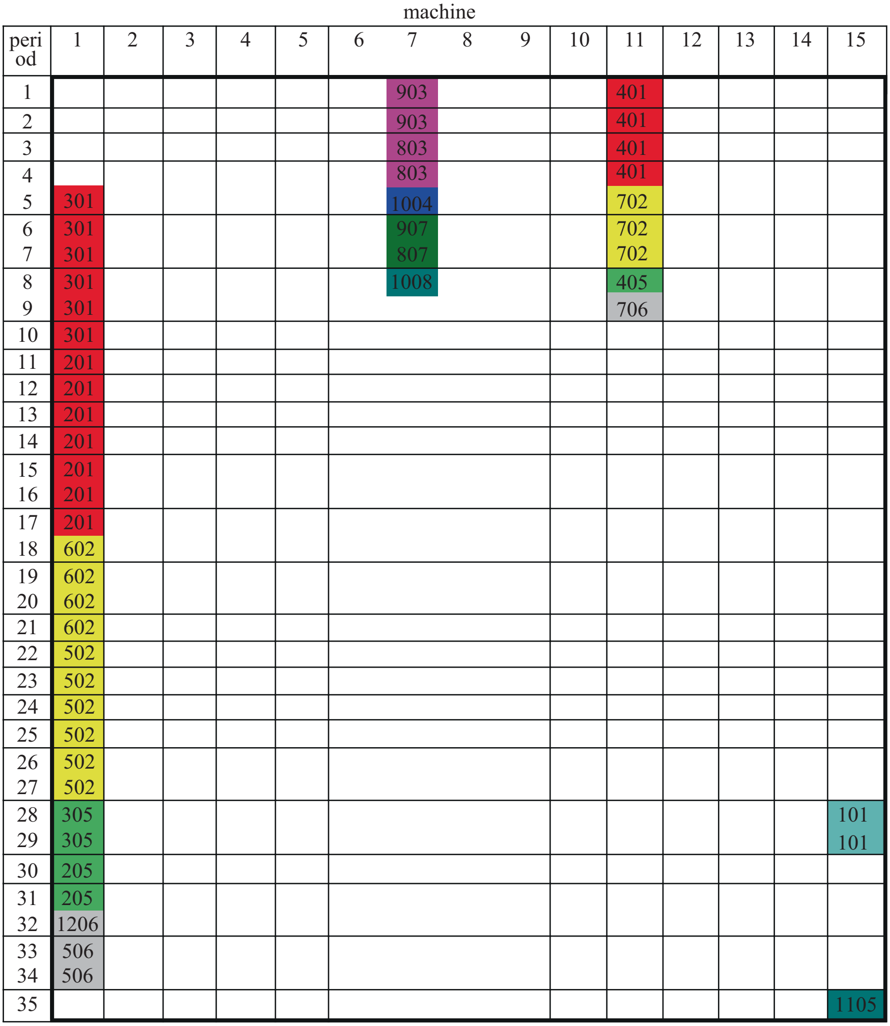
Order	**Due Date**	**Item**	Quantity	**Start date**	Quantity	**Start date**	Quantity	**Start date**
1	**40**		**120**					
		Assembly #1	80	39.10	80	39.10	**80**	**39.10**
		Back plate #2	80	36.55	80	36.55	**80**	**36.55**
		Back plate #3	80	34.20	80	34.20	**80**	**34.20**
		Back plate #4	70	33.17	**70**	**33.17**	**70**	**33.17**
		Fr. plate #5	80	36.22	62	36.93	**62**	**36.93**
		Fr. plate #6	80	34.28	53	35.58	**53**	**35.58**
		Fr. plate #7	80	**33.12**	53	34.79	**53**	**34.79**
		Piston #8	80	38.37	69	38.45	**69**	**38.45**
		Piston #9	80	37.50	49	37.87	**49**	**37.87**
		Cylinder #10	80	38.52	52	38.70	**52**	**38.70**
2	**35**		40					
		Assembly #11	20	34.73	20	34.73	**20**	**34.73**
		Back plate #2	20	34.12	20	34.12	**20**	**34.12**
		Back plate #3	20	33.56	20	33.56	**20**	**33.56**
		Back plate #4	20	33.22	20	33.22	**20**	**33.22**
		Fr. plate #5	20	34.03	20	34.03	**20**	**34.03**
		Fr. plate #12	20	33.56	20	33.56	**5**	**33.87**
		Fr. plate #7	20	33.22	20	33.22	**5**	**33.74**
		Piston #8	20	34.52	20	34.52	**20**	**34.52**
		Piston #9	20	34.21	20	34.21	**20**	**34.21**
		Cylinder #10	20	34.54	20	34.54	**20**	**34.54**

The load profile for such a method is shown in Fig. A11.5 (Fig. A11.6).

In this case, it will take 23 periods and cost 131 units.

Scheduling with a Variable Process Plan In the previous sections, process plan optimization was restricted to two options, maximum production and minimum cost. The method for arriving at the appropriate process plan was described in Chap. 10. It was regarded as a combination, and as a mathematical problem, not a technological one. Table A11.6 shows one of the roadmaps used in computing the appropriate process plan used before.

Examining the roadmap's content shows that seeking the mathematical minimum or maximum is valid from a mathematic point of view; however, from a practical or technological point of view, it misses the purpose. For example: the differ-

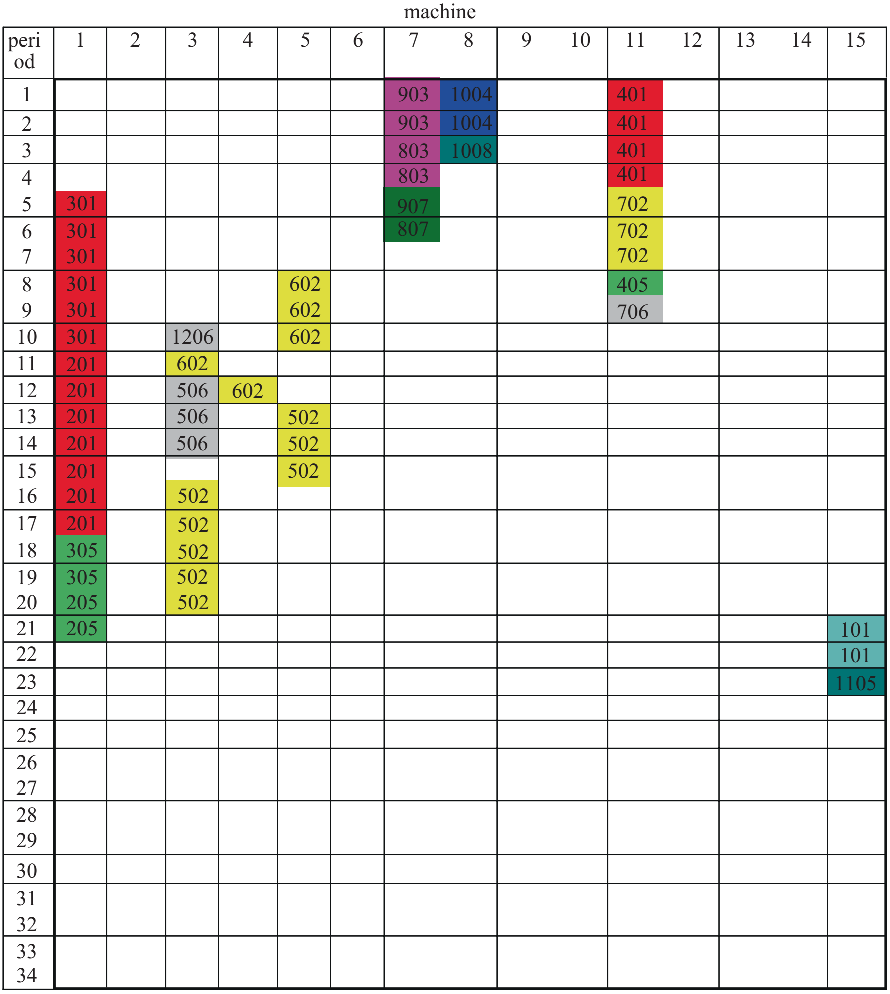


	machine														
period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							903				401				
2							903				401				
3							803				401				
4							803				401				
5	301						1004				702				
6	301						907				702				
7	301						807				702				
8	301						1008				405				
9	301										706				
10	301														
11	201														
12	201														
13	201														
14	201														
15	201														
16	201														
17	201														
18	602														
19	602														
20	602														
21	602														
22	502														
23	502														
24	502														
25	502														
26	502														
27	502														
28	305														101
29	305														101
30	205														
31	205														
32	1206														
33	506														
34	506														
35															1105

Total relative cost = 162

Fig. A11.3 shows the load profile when the process plan for maximum production (minimum process time) is selected.

ence in machining time between machine R1 and R2 is not significant. Machine R1 will be selected for maximum production by mathematic algorithm. But if jobs have to stand in the queue, it is better to shift the job to machine R2. (Notice that the hourly rate of R2 is 75 % of R1.) For a batch size of 150 PCs, the time difference for Operation 010 will be: (3.17–3.12) * 150 = 7.5 min = 7.5/120 = 0.0625 additional periods (A period = 120 min.). This negligible additional time will save 3.9 periods



	machine														
period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							903	1004			401				
2							903	1004			401				
3							803	1008			401				
4							803				401				
5	301						907				702				
6	301						807				702				
7	301										702				
8	301				602						405				
9	301				602						706				
10	301		1206		602										
11	201		602												
12	201		506	602											
13	201		506		502										
14	201		506		502										
15	201				502										
16	201		502												
17	201		502												
18	305		502												
19	305		502												
20	205		502												
21	205														101
22															101
23															1105
24															
25															
26															
27															
28															
29															
30															
31															
32															
33															
34															

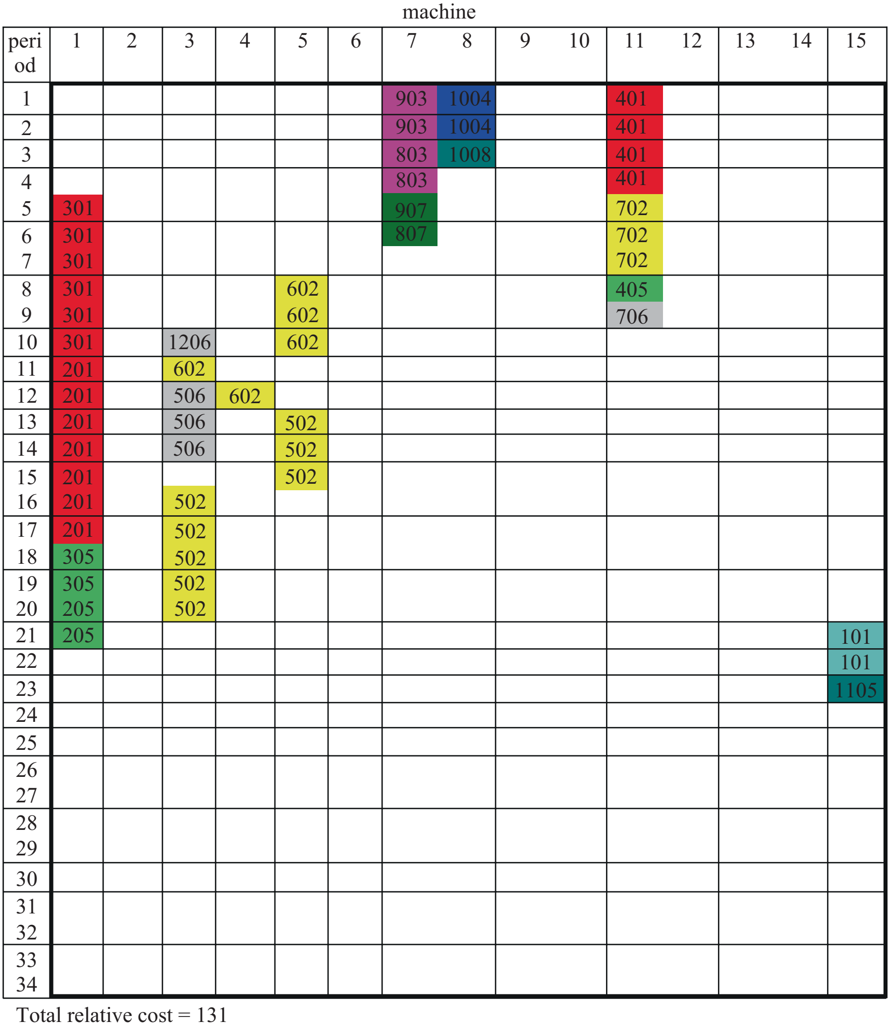
Total relative cost = 131

Fig. A11.4 Load profile for Min/Max process plans

(see Fig. 11.3); in other words, instead of staying in the queue for 3.9 periods (3.12 * 150=468 min.) to work "inefficiently" and shifting the job to R2. This algorithm was tested and the results are shown in Table A11.6.

In this case, it will take 21 periods and cost 101 units.

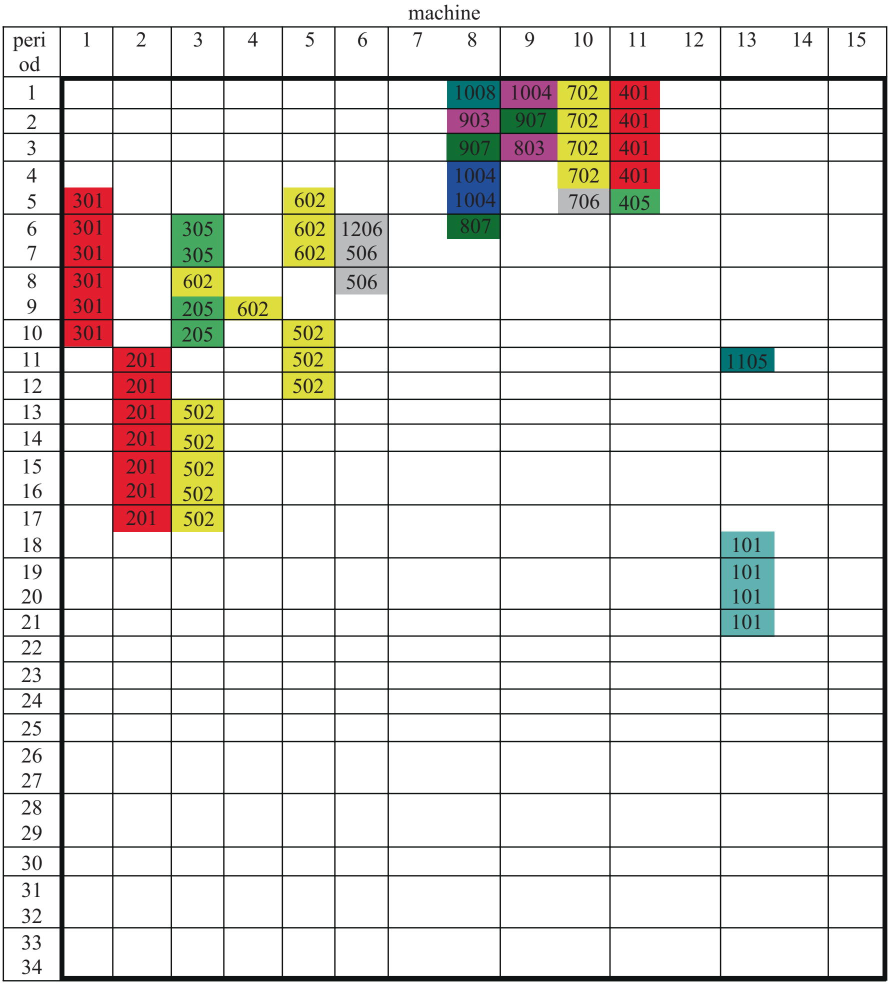
Conclusion—The best results for scheduling are when the process planner presents a roadmap of possible processes but leaves the decision of which plan to use to the user.



	machine														
period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							903	1004			401				
2							903	1004			401				
3							803	1008			401				
4							803				401				
5	301						907				702				
6	301						807				702				
7	301										702				
8	301				602						405				
9	301				602						706				
10	301		1206		602										
11	201		602												
12	201		506	602											
13	201		506		502										
14	201		506		502										
15	201				502										
16	201		502												
17	201		502												
18	305		502												
19	305		502												
20	205		502												
21	205														101
22															101
23															1105
24															
25															
26															
27															
28															
29															
30															
31															
32															
33															
34															

Total relative cost = 131

Fig. A11.5 Load profile for Min/Max process plans



period	machine 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1								1008	1004	702	401				
2								903	907	702	401				
3								907	803	702	401				
4								1004		702	401				
5	301				602			1004		706	405				
6	301		305		602	1206		807							
7	301		305		602	506									
8	301		602			506									
9	301		205	602											
10	301		205		502										
11		201			502								1105		
12		201			502										
13		201	502												
14		201	502												
15		201	502												
16		201	502												
17		201	502												
18													101		
19													101		
20													101		
21													101		
22															
23															
24															
25															
26															
27															
28															
29															
30															
31															
32															
33															
34															

Total relative cost = 101

Fig. A11.6 Load profile for variable process plan

Table A11.6 Front plate operation time roadmap

Op	PR	R1	R2	R3	R4	R5	R6	R7	R8	R9	R 10	R 11	R 12	R 13	R 14	R 15
FRONT PLATE #5																
10	0	3.12	3.17	3.68	99	4.02	3.27	99	99	99	99	99	99	99	99	99
20	0	1.15	1.2	1.71	99	2.05	1.3	99	99	99	99	99	99	99	99	99
30	20	1.49	1.53	2.05	99	99	1.64	99	99	99	99	99	99	99	99	99
40	10	1.30	1.35	1.86	1.86	2.2	1.45	99	99	99	99	99	99	99	99	99
50	40	1.28	1.33	1.84	99	2.18	1.43	99	99	99	99	99	99	99	99	99
60	50	1.51	1.56	2.07	99	99	1.66	99	99	99	99	99	99	99	99	99
70	60	1.44	1.49	2.00	99	99	1.59	99	99	99	99	99	99	99	99	99

Chapter 12
Company's Level of Performance

Abstract The overall rating of a company's performance does not reveal the reasons for the rating. To be able to evaluate the contribution of each chain of the manufacturing process, the rating must consider the individual elements.

This chapter presents a performance measurement ratio method that is based on setting reference values, which are the "best" performance for each stage. It sets a ratio of actual performance value with relationship to the reference value, such as the effect of the suitability of resources to the product mix and the effect of the production planning method selected. Furthermore, improvements to the computed performance value are presented.

1 Introduction

A competitive environment compels companies to be the best at the work they do. Research shows that about 90 % of the incurred cost of manufacturing is established at the design and process planning stages. Therefore, a great deal of attention must be given to these stages. Process planning is an important link in the manufacturing cycle. It defines in detail the process that transforms raw material into the desired form. More precisely, process planning defines the operations, sequence of operations, facilities for each operation, and operation details.

Management of an enterprise is overwhelmingly based on economic considerations. Managing a company calls for many economic decisions, such as capital investment, product line, product mix, and resource selection.

Resource selection is crucial, as machining efficiency establishes a plant's level of performance, and thus, the ability to compete. In order to make a sound decision for resource replacement, management relies on economic models and techniques (e.g., total value analysis, return on investment, etc.). However, an organization or operation is continually undergoing modification and changes in both the product mix and the quantities of products manufactured. New resources and technologies are introduced and developed. A sound economic decision made in the past might not be a sound decision in the present, in view of the changes and modifications that have occurred. Periodic evaluation of machining efficiency might indicate the level of competitiveness of a company compared to other companies in the market or presently available technology. Such an evaluation requires a lot of expense and

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work, which probably would not be economically justified. Therefore, it is done only in cases of crisis (or value analysis) and on a limited scale.

The roadmap method presents a computerized method to perform the evaluation in a short and reasonable length of time. Thus, management can periodically evaluate machining efficiency at a very low cost. Based upon these evaluations, management can make decisions at the right time, without waiting for a crisis. The roadmap method and its application in the resource-evaluating task are described in the following sections.

The trend in resource development is toward computerized resources and machining centers. The new resources are better qualified and more efficient, but their price is accordingly high. There is no doubt that employing such modern resources may save set-up time, increase uptime and quality, reduce material handling, and simplify production planning. However, is questionable as to whether they reduce production costs. In many cases, a 35-kW machine with 5 degrees of freedom that costs about $700,000 is employed in drilling a series of quarter-inch holes. Such an operation may be carried out more efficiently by a $1000 drill press.

In the metal-cutting process, a rough cut usually precedes a finished cut. A rough cut does not require accuracy and may be produced by an old inaccurate machine that was probably fully depreciated. Employing modern machines for all operations no doubt will reduce manufacturing time and result in ease of managing. However, it will not always result in the minimum production cost. Therefore, the process planning of all products should be reevaluated to supply management with a coefficient of competitiveness. It is ***up to management*** to make an operating decision, but the decision must be based on sound data. The concept of the coefficient of competitiveness is explained in the following sections.

2 Performance Measurement

Machining efficiency is not the only parameter that affects competitiveness, but it is the only one that will be treated in this chapter. Comparing machining performance to that of competitors is a relative measurement. Use of an absolute measurement method is proposed here. This proposal is based on the belief that there exists a theoretical process. Such a process probably cannot be met in reality, but it can serve as a reference point to measure how close existing machining performance is to the absolute reference point.

Different organizations and different management control methods might use different controlling performance measurement ratios and parameters. The proposed roadmap method, by its nature, can supply objective measuring ratios for any desired method.

In this chapter, several performance measurement ratios will be given. The user can adapt the appropriate ratio or a combination of them.

Reference points are used to establish the ratio of plant performance. The following reference points will enable the user to direct responsibility to a specific stage of the manufacturing process:

1. The effect of the suitability of the resources to the product mix (ratio of theoretical process to practical process).

2. The effect of production planning methods (ratio of practical process to practical optimum).
3. The effect of shop floor efficiency (ratio of practical optimum to actual performance).

3 Reference Point

3.1 Basic (Theoretical) Process

The basic (theoretical) process (TP) is a fixed universal reference point. Its value is based on actual available technologies. It considers real strength and technical constraints. It assumes an ***imaginary machine,*** that is, no machine constraints are considered. Thus, the basic process plan is practical from an engineering standpoint and theoretical from a specific shop standpoint. Its value does not include set-up cost. Consequently, it is free from sales, lot sizing, grouping, and scheduling effects. It is a theoretical value that will most probably never be achieved. However, it is a fixed value, representing the ***state of technology***. It can be used as a fixed measuring reference point.

The value is expressed in time units. For comparison purposes, it is necessary to use a common denominator, which is cost. The conversion from time units to cost is accomplished by multiplying the machining time by its hourly rate. An arbitrary hourly rate for the imaginary machine can be assumed. The lowest hourly rate used in the shop is recommended as the assumed value. This guarantees that the dispersion will be to only one side of the fixed reference point.

3.2 Practical Process

A **practical process (PP)** is a fixed specific shop reference point. Its value is based on the available resources in a specific shop. The PP is practical from the standpoint of technology and available facilities and theoretical with regard to production and capacity planning (i.e., the availability of the required machine at the *required time*). Moreover, it considers a theoretical optimum quantity and not the actual quantity. The theoretical optimum quantity (economic order quantity [EOQ]) is defined as that quantity which, when increased, will have a negligible effect on item cost. This EOQ can be established by solving the roadmap while increasing the quantity and recording part cost. The point where the differential cost becomes negligible is the EOQ.

3.3 Practical Optimum

The practical optimum (PO) is the planned cost of producing a known product mix in a given period. The *product mix* planned for each department or work center is defined by production planning and is regarded as practical. Production planning employs its techniques to balance work center load. The planned load is available from the work center profile. The total cost of producing the planned product mix is equal to the total department (or work center) expenses for the period. The planned product mix can be introduced to the roadmap system and its PO computed.

3.4 Actual Performance (AP)

The total expenses of the department or work center and the deviation from the plan in terms of items and quantities constitute actual performance (AP). The job recording system should supply data about completion of planned jobs and accumulated cost in producing the product mix.

4 Machine Level Competitiveness

4.1 Multiple Parts

Machine level of competitiveness is defined as the suitability of the available resources to the planned product mix. A company that has the most suitable resources has an edge in competing in the market. The level of competitiveness is defined as a ratio, the machining ratio (MR). MR is measured on a scale from zero to one, where one is the most suitable resources. The method of computing MR for different cases follows.

The ratio of time (cost) to produce a part with the existing resources (PP) to time (cost) to produce the part by existing technology (and ignoring the resources that were acquired by the specific company, TP) establishes the MR for a single part:

$$\mathrm{MR} = \mathrm{TP} = \mathrm{PP} \tag{12.1}$$

The value of PP is a function of the process planning method and expertise. For several process planners, it is possible to rate them one against the other. The higer the rating, the better the process planner:

$$\mathrm{Rating} = \mathrm{PPi} / \mathrm{PP}$$

where PP is the best process plan, the one to be used in the MR equation. PPi is the process plan set by process planner i.

The machine rating for products, or several individual parts, follows the logic of the single part MR equation. The rating is calculated Through:

$$MR = \frac{1}{p}\sum_{i=1}^{p}\frac{TPi}{PPi} \tag{12.2}$$

where:

MR – Machinability Rating
P – Number of parts

PPi – Practical Process of machining part i
TPi – Theoretical Process of machining part i

This equation assumes that the quantity of all parts to be manufactured is the same. This is a doubtful assumption that probably does not correspond with real life. To consider the quantities of each part, a modification to the equation is made. MR is replaced by MRQ, and the individual part gets a weight according to its quantity. To arrive at MRQ for an individual part, its MR is multiplied by its quantity. The sum of the individual MRQs is divided by the total quantity to arrive at the plant MRQ value:

$$MRQ = \frac{1}{\sum_{i=1}^{p} Qi} \sum_{i=1}^{p} \frac{TPi}{PPi} \times (Qi) \tag{12.3}$$

where:

MRQ – Machinability Rating with quantity effect
P – Number of parts
PPi – Practical Process of machining part i
TPi – Theoretical Process of machining part i
Qi – Quantity of part i

A company might have the best resources for producing parts, considering the quantities, yet its competitiveness could still be jeopardized by machine idleness (i.e., not having enough loads to keep the machines occupied). To arrive at overall optimization, management must have a load profile and data on the machine utilization rating (MUR), measured on a scale from zero to one, in which one is the utmost utilization.

MUR is defined as the average load rating of all machines. Single-machine load rating is defined as the ratio of machine load to the "maximum load machine" value. Load is defined as the machining time on a machine. This definition is best explained by an example.

4.1.1 MUR Definition Example

Part "PLATE", as shown in Fig. 12.1, is manufactured in a plant that has six machines, as specified in Table 12.1.

Table 12.2 gives the PP process. It calls for 4 operations and 4 machines. The load on machine #3 is the greatest at 7.37, and will be called the **MAX**—"maximum load machine".

The MUR on:
machine #5 is 1.62/7.37 = 0.22;
machine #2 is 0.71/7.37 = 0.096;
machine #6 is 1.76/7.37 = 0.239;
machine #3 is 7.37/7.37 = 1.00.
The average load is: (0.22 + 0.096 + 0.239 + 1)/6 = 0.259.

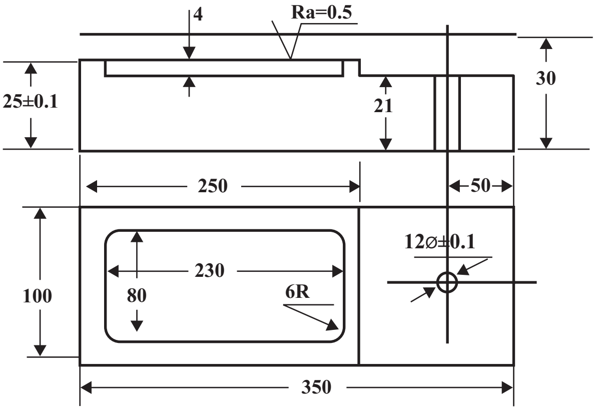


Fig. 12.1 Sample part "PLATE"

Table 12.1 Machine specifications

Mach Nunber	Machine description	Power KW	Seed RPM	Handle time Min	Relative cost $
1	Machining Center	35	1500	0.10	4
2	Large CNC Milling	35	1200	0.15	3
3	Manual milling machine	15	1500	0.66	1.4
4	Small drill press	1	1200	0.66	1
5	Old milling machine	15	2400	1.0	1
6	Small CNC machine	10	3000	0.25	2

Table 12.2 Routing for part "Plate"

Operation	Machine	Cost	Time
010	5	1.62	1.62
020	2	2.13	0.71
030	6	3.52	1.76
040	3	10.32	7.37
Total		17.59	11.46

For multiple parts, the MUR computation will refer to the machine load, as the sum of machine load on all parts. The general equation to compute the MUR is done in three steps.

Step 1: Sum up the load on each machine:

$$\mathrm{SM}_j = \sum_{i=1}^{\mu} \mathrm{MT}_i \tag{12.4}$$

Where: MTj = Total machining time of part i on machine M

Step 2: Determine the machine with maximum load, mark its load as MAX.

$$\text{MAX} = \text{Maximum value of SM}$$

$$MUR = \frac{1}{M} \sum_{j=1}^{M} \frac{SMj}{MAX} \tag{12.5}$$

Step 3: Compute MUR by Eq. 12.5:
Where:

MUR – Machining Utilization Rating
M – Number of machines
P – Number of parts

The general MUR equation considering quantity is

$$MUR = \frac{1}{M}\sum_{j=1}^{M} \frac{\{\sum_{i=1}^{p} MTi * Qi\} j}{\{\mathrm{MAX}\sum_{i=1}^{p} MTi * Qi\} j} \tag{12.6}$$

4.2 Machine Level of Competitiveness Variations

In the previous sections, the terms PP and MT were used freely. These terms have different values depending on the criterion of optimization, i.e., maximum production or minimum cost. Each criterion will result in a different process, different PP value, and different machine selection. Therefore, different values of MR and MUR will result. The decision as to which rating to use is up to management. The purpose of this method is to supply data to management, and not to make decisions.

The definition of machine level of competitiveness might have three forms:

a. Competitiveness ratio of machining time (MRT)
   MRTT—Machining Time in case of maximum production criteria of optimization
   MRTC—Machining Cost in case of maximum production criteria of optimization

b. Competitiveness ratio of machining cost (MRC)
   MRCT—Machining Time in case of minimum cost criteria of optimization
   MRCC—Machining Cost in case of minimum cost criteria of optimization

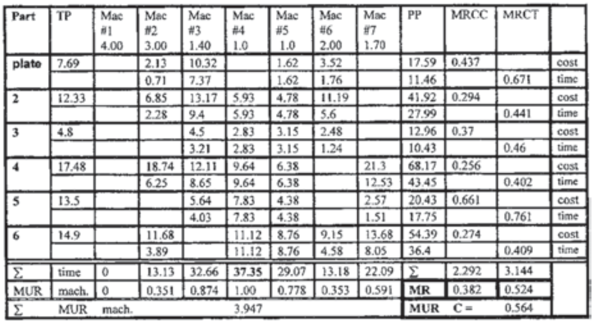
c. Competitiveness ratio of machine utilization (MUR)
   MURT—Machine utilization in case of maximum production criteria of optimization
   MURC—Machine utilization in case of minimum cost criteria of optimization

5 Example of Machine Level Competitiveness

Assume that six parts have to be manufactured, and seven machines are available. The procedure of the roadmap format was followed and the routing of each one of the parts is as shown in Table 12.3 for the case of minimum cost optimization, and Table 12.4 for the case of maximum production optimization.

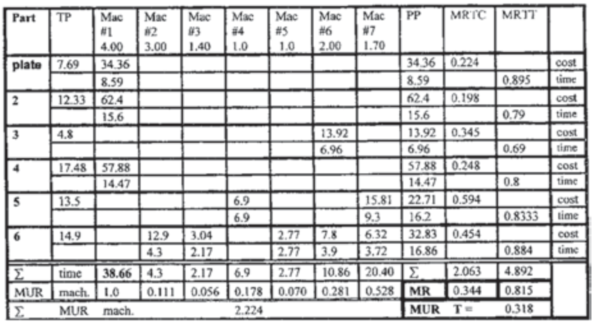
The numbers in the machine row indicate the machining relative hourly rate (e.g., hourly rate for machine#1 is 4.00 and for machine #3 is 1.4). The numbers in the TP column indicate TP machining time and cost (relative hourly rate is one). For

Table 12.3 Data and example of computing Minimum cost Rating



Part	TP	Mac #1 4.00	Mac #2 3.00	Mac #3 1.40	Mac #4 1.0	Mac #5 1.0	Mac #6 2.00	Mac #7 1.70	PP	MRCC	MRCT	
plate	7.69		2.13	10.32		1.62	3.52		17.59	0.437		cost
			0.71	7.37		1.62	1.76		11.46		0.671	time
2	12.33		6.85	13.17	5.93	4.78	11.19		41.92	0.294		cost
			2.28	9.4	5.93	4.78	5.6		27.99		0.441	time
3	4.8			4.5	2.83	3.15	2.48		12.96	0.37		cost
				3.21	2.83	3.15	1.24		10.43		0.46	time
4	17.48		18.74	12.11	9.64	6.38		21.3	68.17	0.256		cost
			6.25	8.65	9.64	6.38		12.53	43.45		0.402	time
5	13.5			5.64	7.83	4.38		2.57	20.43	0.661		cost
				4.03	7.83	4.38		1.51	17.75		0.761	time
6	14.9		11.68		11.12	8.76	9.15	13.68	54.39	0.274		cost
			3.89		11.12	8.76	4.58	8.05	36.4		0.409	time
Σ	time	0	13.13	32.66	**37.35**	29.07	13.18	22.09	Σ	2.292	3.144	
MUR	mach.	0	0.351	0.874	1.00	0.778	0.353	0.591	**MR**	0.382	0.524	
Σ	MUR	mach.			3.947				**MUR**	**C =**	0.564	

Table 12.4 Data and example of computing Naximum production Rating



Part	TP	Mac #1 4.00	Mac #2 3.00	Mac #3 1.40	Mac #4 1.0	Mac #5 1.0	Mac #6 2.00	Mac #7 1.70	PP	MRTC	MRTT	
plate	7.69	34.36							34.36	0.224		cost
		8.59							8.59		0.895	time
2	12.33	62.4							62.4	0.198		cost
		15.6							15.6		0.79	time
3	4.8						13.92		13.92	0.345		cost
							6.96		6.96		0.69	time
4	17.48	57.88							57.88	0.248		cost
		14.47							14.47		0.8	time
5	13.5				6.9			15.81	22.71	0.594		cost
					6.9			9.3	16.2		0.8333	time
6	14.9		12.9	3.04		2.77	7.8	6.32	32.83	0.454		cost
			4.3	2.17		2.77	3.9	3.72	16.86		0.884	time
Σ	time	**38.66**	4.3	2.17	6.9	2.77	10.86	20.40	Σ	2.063	4.892	
MUR	mach.	1.0	0.111	0.056	0.178	0.070	0.281	0.528	**MR**	0.344	0.815	
Σ	MUR	mach.			2.224				**MUR**	**T =**	0.318	

each part, there are two rows in the table. The first row indicates the cost of processing on each participating machine, and the second row the time of each participating machine (the time multiplied by the relative cost is the cost of the operation). The PP column indicates total machining cost or time on all machines. The next two columns indicate the computed relevant MR value for a single part, the MRCC Machining Cost in the case of minimum cost criterion of optimization and MRCT Machining Time in the case of minimum cost criterion of optimization.

The last three rows hold computation values. The first row, below the table, under the machine columns, holds the SM value, as computed. The bold type indicates the MAX value. The next row indicates the MUR for individual machine. The next row indicates the sum of the individual machine MUR, divided by seven (the number of machines), and results in the MUR, which is listed on the right side of the last row. The first row below the MR columns indicates the sum of the MR values of the individual part. The next row indicates the appropriate MR values, as computed.

The single part machine rating will be best demonstrated by using part "PLATE" (Fig. 12.1). In Table 12.3, the first part (PLATE) with minimum cost criterion of optimization calls for 4 machines: machine 2 for 0.71 min, machine 3 for 7.37 min, machine 5 for 1.62 min, and machine 6 for 1.76 min. These values and the subsequent total are entered into the time row of this part.

The total is: $0.71 + 7.37 + 1.62 + 1.76 = 11.46$ min.

Similarly, the total cost is $2.13 + 10.32 + 1.62 + 3.52 = 17.59$.

These two values are, therefore, the cost PP and the time PP, and are entered into the PP column of part "PLATE". The TP value is 7.69, therefore, the machine rating of cost is **7.69/17.59 = 0.437** and the time machine rating is 7.69/**11.46 = 0.671**. These two values are registered in the MRCC and MRCT columns of part "PLATE".

Similarly, computations are made for parts 2 to 6, and the PP and MR are recorded. For part 6, the cost PP is 54.39 and the TP is 14.9, therefore, the MRCC is 14.9/54.39 = 0.274.

For multi-part rating, Eq. (12.2) is used. The MRCC is summed up for all six parts.

Its value is: 0.437 + 0.294 + 0.370 + 0.256 + 0.661 + 0.274 = 2.292.

This figure appears as the sum of MRCC; similarly, the sum of MRCT is 3.144. As there are 6 parts, the multi-part machine rating is the sum divided by the number of parts:

$$\text{MRCC} = 2.292/6 = 0.382; \text{ and the MRCT} = 3.144/6 = 0.524$$

To compute the machine utilization rating equation, SMj is used to compute the total machining time of each machine required to produce all parts. Therefore, the sum of the machine column is calculated and the results are given in the first row below the part. For minimum cost criterion of optimization, none of the parts use machine 1; therefore, the summation is zero.

Machine 2 is used by: part 1 for 0.71 min; part 2 for 2.28 min; part 4 for 6.25 min; and part 6 for 3.89 min; the total, therefore, is 0.71 + 2.28 + 6.25 + 3.89 = 13.13 min.

Similarly, the sum of machine 3 is 32.66; machine 4, 37.35; machine 5, 29.07; machine 6, 13.18; and machine 7, 22.09.

The maximum value is on machine 4, with 37.35 min, therefore, this value is marked as MAX, and the machine utilization rating for each individual machine is computed.

The MUR of machine 4 is 1.00, as it is the MAX value. The MUR of machine 2 is 13.13/37.35 = 0.351; for machine 3, 32.66/37.35 = 0.874; for machine 5, 29.07/37.35 = 0.778; for machine 6, 13.18/37.35 = 0.353; and for machine 7, 22.09/37.35 = 0.591.These values are shown in the second row, below the row for parts.

The average MUR is computed through Eq. (12.6), and is the sum of all individual machine MURs divided by the number of machines. The sum is:

$$0 + 0.351 + 0.874 + 1.0 + 0.778 + 0.353 + 0.591 = 3.947.$$

This value appears in the last row; the MUR = 3.947/ 7 = 0.564 and appears in the lower right corner of the table.

The ratings for the data given in the example are:

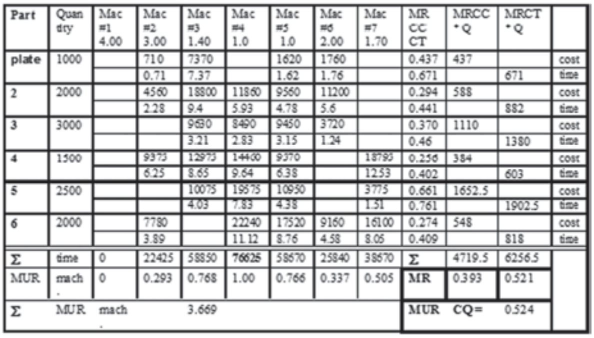
For the case of minimum cost criterion of optimization:

$$\text{MRCT} = 0.524 \text{ MRCC} = 0.382 \text{ MRUC} = 0.564.$$

For the case of maximum production criteria of optimization:

$$\text{MRTT} = 0.815 \text{ MRTC} = 0.344 \text{ MRUT} = 0.318.$$

Table 12.5 Data and example of computing minimum cost rating and quantitu



Part	Quantity	Mac #1 4.00	Mac #2 3.00	Mac #3 1.40	Mac #4 1.0	Mac #5 1.0	Mac #6 2.00	Mac #7 1.70	MR CC CT	MRCC *Q	MRCT *Q	
plate	1000		710	7370		1620	1760		0.437	437		cost
			0.71	7.37		1.62	1.76		0.671		671	time
2	2000		4560	18800	11860	9560	11200		0.294	588		cost
			2.28	9.4	5.93	4.78	5.6		0.441		882	time
3	3000			9630	8490	9450	3720		0.370	1110		cost
				3.21	2.83	3.15	1.24		0.46		1380	time
4	1500		9373	12973	14460	9370		18793	0.256	384		cost
			6.25	8.65	9.64	6.38		12.53	0.402		603	time
5	2500			10075	19575	10950		3775	0.661	1652.5		cost
				4.03	7.83	4.38		1.51	0.761		1902.5	time
6	2000		7780		22240	17520	9160	16100	0.274	548		cost
			3.89		11.12	8.76	4.58	8.06	0.409		818	time
Σ	time	0	22425	58850	76625	58670	25840	38670	Σ	4719.5	6256.5	
MUR	mach.	0	0.293	0.768	1.00	0.766	0.337	0.505	**MR**	0.393	0.521	
Σ	MUR	mach.		3.669					**MUR**	**CQ=**	0.524	

5.1 *Management Control*

The results clearly indicate that the available machines are in good competitive standing, in the case of competition on fast deliveries; however, this results in a penalty of excessive production cost and idle machines. It is up to management to decide on the most profitable compromise for plant operation. The roadmap method may be used in deciding on such a compromise. The next section will demonstrate this feature.

5.2 *The Quantity Effect*

The quantity effect was checked by using the data given in Tables 12.3 and 12.4 and assuming the following quantities:

$$\text{Part}\,\#1-1000,\text{P}\,\#2-2000,\text{P}\,\#3-3000,\text{P}\,\#4-1500,$$
$$\text{P}\,\#5-2500,\text{P}\,\#6-2000.$$

The results of computing with Eqs. (12.3) and (12.6) are shown in Tables 12.5 and 12.6.

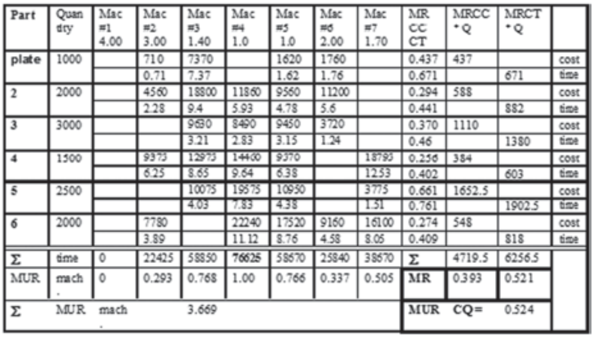
The table is similar to Table 12.3, with the following changes:

- The TP column is changed to the quantity ordered for each part.
- The PP column is changed to list the MRCC value from Table 12.3 in the first line of each part, and the MRCT value from Table 12.3 in the second line.
- The MRCC column holds the MRCC multiplied by the quantity.
- The MRCT column holds the MRCT multiplied by the quantity.
- The $\sum$ of the MR columns holds the total value of all parts.

The total quantity of all parts is 12,000, therefore, according to equation MRQ, the machining ratio for minimum cost is

For cost MRCCQ = 4719.5/ 12000 = 0.393,
And for time MRCTQ = 6256.5/ 12000 = 0.521.

Table 12.6 Data and Example of Computing maximum production Rating and Quantity



Part	Quantity	Mac #1 4.00	Mac #2 3.00	Mac #3 1.40	Mac #4 1.0	Mac #5 1.0	Mac #6 2.00	Mac #7 1.70	MR CC CT	MRCC *Q	MRCT *Q	
plate	1000		710	7370		1620	1760		0.437	437		cost
			0.71	7.37		1.62	1.76		0.671		671	time
2	2000		4560	18800	11860	9560	11200		0.294	588		cost
			2.28	9.4	5.93	4.78	5.6		0.441		882	time
3	3000			9630	8490	9450	3720		0.370	1110		cost
				3.21	2.83	3.15	1.24		0.46		1380	time
4	1500		9373	12973	14460	9370		18793	0.256	384		cost
			6.25	8.65	9.64	6.38		12.53	0.402		603	time
5	2500			10075	19575	10950		3775	0.661	1652.5		cost
				4.03	7.83	4.38		1.51	0.761		1902.5	time
6	2000		7780		22240	17520	9160	16100	0.274	548		cost
			3.89		11.12	8.76	4.58	8.05	0.409		818	time
Σ	time	0	22425	58850	76625	58670	25840	38670	Σ	4719.5	6256.5	
MUR	mach.	0	0.293	0.768	1.00	0.766	0.337	0.505	**MR**	0.393	0.521	
Σ	MUR	mach.		3.669					**MUR**	**CQ=**	0.524	

Machine utilization is computed by Equation MUR. The second row of each part and each machine indicates the machining time on that machine, just as in Table 12.3. The first row is the product of multiplying the quantity by the machining time. The Σ for each machine is the total of the first row for each machine [(∑(MTi *Qi)].

The maximum value, as seen in the table, is that of machine 3, and is the variable MAX; its value is 76,625.

The MUR of each machine is its total value divided by MAX. Therefore, the value for machine 1 is 22425/76625 = 0.293; for machine 2, 58850/76625 = 0.768; for machine 4, 1.00, and so forth.

The total on the last line is the total of all individual MUR values:

$$\sum \mathrm{MUR} = 0.293 + 0.768 + 1.00 + 0.766 + 0.337 + 0.505 = 3.669.$$

Therefore, the average MUR value for the seven machines is:

$$\mathrm{MURCQ} = 3.669/7 = 0.524.$$

The rating for the data given in the example is as follows:

For the case of maximum production criteria of optimization:

$$\mathrm{MRTTQ} = 0.797\ \mathrm{MRTCQ} = 0.368\ \mathrm{MRUTQ} = 0.389.$$

For the case of minimum cost criteria of optimization:

$$\mathrm{MRCTQ} = 0.521\ \mathrm{MRCCQ} = 0.393\ \mathrm{MRUCQ} = 0.524$$

6 Improvement of Competitiveness Level

The Machinability Rating indicates the overall rating of the plant. However, in order to evaluate and search for ways to improve the competitiveness level, additional information is needed. Such information is available through the roadmap method. Examples of such additional information and improvement methods follow.

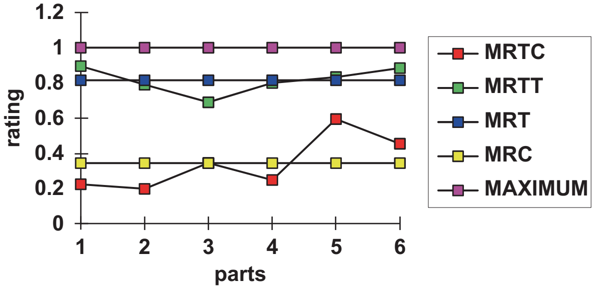


Fig. 12.2 Machinability rating for machining time

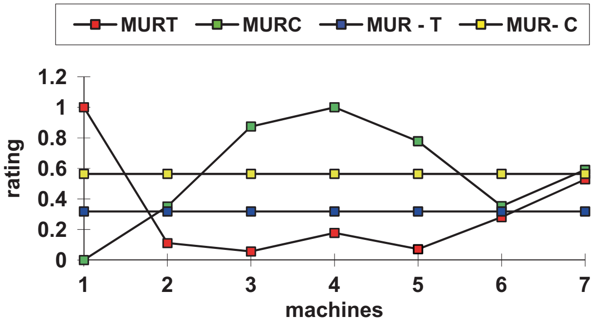


Fig. 12.3 Machine utilization vs. machine rating

The overall rating does not reveal the causes of the rating. To be able to evaluate the effect of each part and each machine on the rating, one must look at the individual values in the tables above or build a diagram that illustrates the individual ratings. Figures 12.2 and 12.3 serve this purpose.

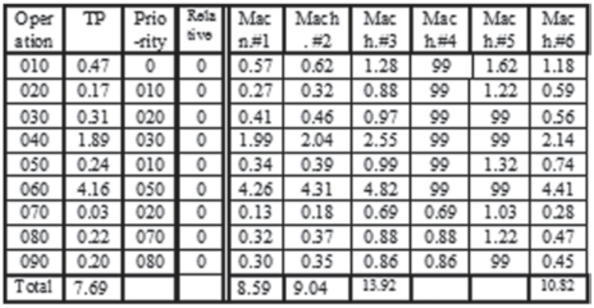
Figure 12.2 shows the overall rating and the individual part rating for the case of computing the maximum production rating as detailed in Table 12.4. (values from Table 12.4). The MRT and MRC are the respective plant ratings (average of all parts), while the MRTT shows the individual part rating for time and the MRTC for the cost criterion.

Figure 12.3 shows the overall MUR rating and the individual machine rating (the values for MURT are those of Table 12.4, while those of MURC are those of Table 12.3). MURT and MURC represent the rating of the individual machine.

It is clearly seen that, in the case of machine rating (MUR), there is a conflict in machine selection between maximum production and minimum cost criterion of optimization.

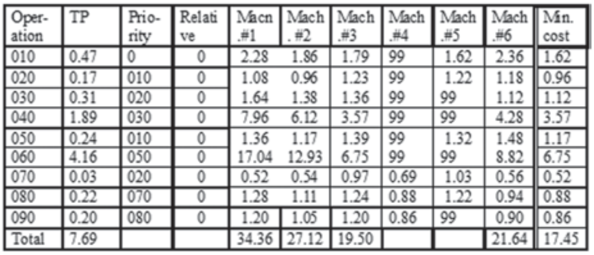
Machine #1, for example, has a rating of 1 (one) in the case of a process plan with maximum production criteria of optimization, and a rating of 0 (zero) in the case of a process plan with minimum cost criteria of optimization. Machine #4 has a low rating (0.178) in the case of a process plan with maximum production criteria of optimization, and a high rating (1.00) in the case of a process plan with minimum cost criteria of optimization.

Table 12.7 Machine-Operation Time Roadmap



Operation	TP	Prio-rity	Relative	Macn.#1	Mach. #2	Mach.#3	Mach#4	Mach.#5	Mach#6
010	0.47	0	0	0.57	0.62	1.28	99	1.62	1.18
020	0.17	010	0	0.27	0.32	0.88	99	1.22	0.59
030	0.31	020	0	0.41	0.46	0.97	99	99	0.56
040	1.89	030	0	1.99	2.04	2.55	99	99	2.14
050	0.24	010	0	0.34	0.39	0.99	99	1.32	0.74
060	4.16	050	0	4.26	4.31	4.82	99	99	4.41
070	0.03	020	0	0.13	0.18	0.69	0.69	1.03	0.28
080	0.22	070	0	0.32	0.37	0.88	0.88	1.22	0.47
090	0.20	080	0	0.30	0.35	0.86	0.86	99	0.45
Total	7.69			8.59	9.04	13.92			10.82

Table 12.8 Operation Cost Roadmap



Operation	TP	Prio-rity	Relative	Macn.#1	Mach. #2	Mach.#3	Mach.#4	Mach.#5	Mach.#6	Min. cost
010	0.47	0	0	2.28	1.86	1.79	99	1.62	2.36	1.62
020	0.17	010	0	1.08	0.96	1.23	99	1.22	1.18	0.96
030	0.31	020	0	1.64	1.38	1.36	99	99	1.12	1.12
040	1.89	030	0	7.96	6.12	3.57	99	99	4.28	3.57
050	0.24	010	0	1.36	1.17	1.39	99	1.32	1.48	1.17
060	4.16	050	0	17.04	12.93	6.75	99	99	8.82	6.75
070	0.03	020	0	0.52	0.54	0.97	0.69	1.03	0.56	0.52
080	0.22	070	0	1.28	1.11	1.24	0.88	1.22	0.94	0.88
090	0.20	080	0	1.20	1.05	1.20	0.86	99	0.90	0.86
Total	7.69			34.36	27.12	19.50			21.64	17.45

The above process planning time and cost values were taken from the solution for the best process plan according to the desired criterion of optimization. However, the roadmap method works with many alternate process plans, while selecting the best process for the specific problem at hand at the moment it is needed. This can be appreciated using part "PLATE" as an example. Its roadmaps are shown in Table 12.7 and Table 12.8.

Employing the roadmap might assist in making a reasonable decisions. Table 12.7 reveals that if, in case of maximum production, machine #2 will be employed instead machine #1, which is the optimum machine, the increase in machining time will be 5.2 % (from 8.59 to 9.04) while the decrease in cost will be 20 % (from 34.36 to 27.12).

Further balancing might be to move operation 060 from machine #2 to machine #6 (increase time from 4.31 to 4.41; decrease in cost from 12.93 to 8.82) or move operation 060 to machine #3 (increase time from 4.31 to 4.82; decrease in cost from 12.93 to 6.75). Making similar changes in the other parts indicates that there is no need for machine #1. Machine #3 is has a good rating for minimum cost criterion, and low in the maximum production criterion. All its operations can be transferred to machine #2 and #6 to balance the load between the two criterions of optimization. Machine #5 has a very low rating, but it is an old machine that may be used as a backup machine. Considering the above modifications the rating may be increased to 0.71. Figure 12.4 shows the new overall rating and the individual machine rating.

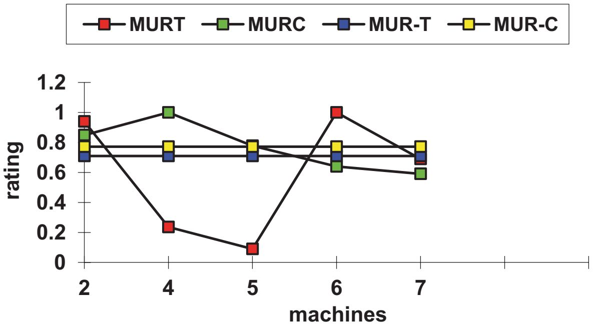


Fig. 12.4 Machine utilization vs. machine rating (improved)

7 Management Control

Management of an enterprise is overwhelmingly based on economic considerations. It calls for many economic decisions such as capital investment, product lines and mix, machine selection etc. Research shows that about 90 % of the incurred cost of manufacturing is established at the design and process planning stages. Therefore, machining selection is a crucial task, as machining efficiency establishes a plant's level of performance, and thus, the ability to compete in the market. To make a sound decision on resource planning, management relies on economic models and techniques (e.g., total value analysis, ROI, etc.). However, machine efficiency varies over time, as the product mix might change, and with the introduction of new machines possessing more and better capabilities. Therefore, a continuous evaluation of the fitness of the machines to produce the product mix must be made. This is a huge task, and, due to lack of efficient tools, it is seldom done.

A computerized method that performs the evaluation task and establishes the level of competitiveness in an honest and just way, free from improper influence, was presented in this chapter. The method employs the roadmap concept. By employing the roadmap concept, sound engineering data can be supplied to the economic models, and real economic decisions can be made. The engineering stages do not make economic decisions, as they are not economic experts.

It has been shown that local optimization does not result in overall or product mix optimization. There is a mathematical optimum but there is also a real optimum. By minute variation from the local optimum, a large savings of producing a product mix or increasing the level of competitiveness can be achieved.

The term level of competitiveness was defined and a method to measure it was proposed. The method is based upon the belief that there exists a Theoretical Process, an optimum that probably cannot be reached. However, it can be used as a yard stick to give an unambiguous and impartial rating.

Index

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