Lecture Notes in Management and Industrial Engineering

Gideon Halevi

Expectations and Disappointments of Industrial Innovations

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Gideon Halevi
CAD/CAM R&D Center
I.M. Industries
Tel Aviv
Israel

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Preface

An acceptable axiom declares that innovation is a driving force to improve the manufacturing performance. This axiom might be true in most cases but in others it might be destructive by shifting the research topics towards non-supporting path and thus blocking the progress of the main research objectives.

It is not that such destructive innovation methods were not extraordinary methods; on the contrary, they showed potential by swept industry and academic colleagues to follow their research lead which might result in new innovative technologies or end up with delay of the main objective or just waste of research time and cost.

This book presents a review of three remarkable innovation methods of the 50s, which had far-reaching impacts on the manufacturing methods: group technology, numerical control and integrated manufacturing system.

Group Technology. The method is followed to organize the factory in "work cells" instead of functional layout. A work cell is defined as a group of machines, located close to one another, and can manufacture a family of parts. The main slogan of GT is that "One solution may serve a family of problems". There is no need to solve each problem as unique, first try to relate it to a family of problems and try to use one solution to all of them. In other words "don't invent the wheel over and over again".

A variety of enterprises that adapt this manufacturing method have confirmed that within 2–3 months of changing over to work cell sections the labor productivity rises by 12–20%, the cost per unit value of finished products falls by 2–3%, the duration of the machining cycle falls by 25–35%, and the average value of work in progress falls by 15–25%.

Group technology was the leading manufacturing technology until the mid-70s. A survey by the University of Michigan researchers predicted that by 1988 more than 50% of industry will use group technology in manufacturing, while a survey by CIRP researchers indicated that by 1990 70% of industry will use group technology in manufacturing.

The concept of “groups” or family of part was accepted with enthusiasm. Thus, the main topic of research deviated from GT to conducting research on how to create families. For over a decade, the leading research topic was to form a classification system. However, such a coding and classification that may serve several industrial users could not be formalized. As a result the topic slowly disappeared and the GT faded away with it.

Numerical Control. The numerical control **technical stage** is still one of the leading innovative technologies in our days. It intruded the computerized machines which dominates today’s manufacturing resources, i.e. CNC, DNC, industrial robots, automatic storage and retrieval, AGV, machining center, FMC, etc.

Note that these incredible manufacturing resources are a single defined objective that should and could be organized as a remarkable manufacturing **system** such as flexible manufacturing, or even automatic factory. At this point a reasonable research focus should have been system organization, but it deviated to how to increase their individual capabilities. This digression contradicted with manufacturing performance objectives and delayed the dream of forming flexible and automated factory from 1980 to 1999 and then to 2015 and even further.

IMS–Integrated Manufacturing System. The task of the manufacturing management is to plan and produce products according to management orders and policy. The objectives of the task are to plan enterprise activities in a manner that ensures the following:

- Meeting delivery date
- Minimum processing lead time
- Minimum processing cost
- Maximum resource utilization
- Minimum work in process
- Minimum capital tie-down in production.

Theoretical production planning and scheduling is actually a very simple task. The plant gets orders which define the product, the quantity and the delivery dates. The resources of the plants are known and 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.

Therefore, it seems strange that in order to meet this **simple** task, over 130 innovation production planning methods were proposed such as: Agile Manufacturing; Just-in-time; Kanban system; Lean manufacturing; OPT; Outsourcing; TQM; Virtual manufacturing; and others keep coming at an ever-increasing pace. Any one of the proposed methods improves a certain aspect or several aspects of the manufacturing cycle. However, none of the proposed methods improve all disciplines’ aspects and area of activities of the manufacturing cycle.

A common shared justification is that production planning is a very complex task. Research proves that the manufacturing process is flexible by nature.

However, the structure of the proposed manufacturing system makes it rigid and complex. Analyzing the reasons for the rigidity shows that:

The complexity is a result of the rigidity which is caused by using one (or two) routine and attempting to solve disruptions by mathematics and not by technology.

Moreover by being a system in which decisions are being made too early in the manufacturing process. Some decisions (routine) were made several years before the execution time. Therefore, they cannot comply with the dynamic situation of the manufacturing process.

IMS approach was misleading and adverse to the objectives. The planning and execution regards the routing as static and unalterable; therefore the capacity planning is simple, but it robs the shop of production flexibility and efficiency. The basic notions of the hierarchical approach techniques are:

- Use the "best" routing for the job
- Using the "best" routing for maximum production optimization will result in the shortest throughput.
- The larger the batch quantity, the better the productivity.
- Job release to shop floor based on MRP (or ERP) will assure maximum efficiency and meeting delivery dates.

These notions (that none of them meets cost and profit objection) appear to be logical and were accepted without justification. However, research leads to the conclusion that these notions are in many cases incorrect.

The term "best" routing is obscure; routing can generate over 20 routing for each job, each one to serve a different objective (maximum production, minimum cost, maximum profit, etc.).

Using maximum production criterion of optimization for scheduling a random product mix showed that this criterion usually resulted in the longest throughput as compared to others criteria.

CAD—Computer-Aided Design. The extraordinary impact of electronic computers on enterprise management has been everywhere, extending into product-process technology; information systems and decision making; control technology and resource member. Lately, in addition to CAD—computer-aided design, with its remarkable simulation capabilities and impressive display—new incredible Additive Technologies and 3D picture have materialized. They are completely new processing technologies and open up new horizons in manufacturing methods. However, these useful new technologies caused fading away of the incredible innovations that dominated manufacturing from 1940s to mid-1970s.

Using present-day capabilities CAD can be a tool to redirect research in order to restore the remarkable potential of the above-mentioned three manufacturing methods.

The book chapters are as follows:

Chapter 1 presents introduction to group technology, numerical control and industrial management system.

Chapter 2 presents in detail the history of group technology, its objectives, expectations and technology. This chapter also details the great efforts that were made for over 30 years by the industries and academia in order to make it work, till it was abandoned.

Chapter 3 presents in detail the history of numerical control systems, its objectives, expectations and technology. Numerical control actually revolutionized the hardware (facilities) used by industry. An attempt to keep on this innovation technology to create an automated factory failed.

Chapter 4 presents the history of industrial management system (IMS) its great efforts to establish a method that will be flexible and efficient, but unfortunately such a system was not discovered yet.

Chapter 5 is devoted to analyze the reasons for the decline of the remarkable technology after dominating the market for several decades. It concluded that the dominating research topic; the run for "routine" was a slip-up and climbing on a wrong tree. Routine is **not** the missing link between design and production planning (manufacturing). The missing link is process planning, and setting objectives to CAD—computer-aided design.

This chapter describes a restoration method which may revive the incredible group technology, numerical control integrate manufacturing system, and may assist in making the dream of automated factory come true.

I would like to express my gratitude to Marc Beschler for his special review efforts.

Tel Aviv, Israel
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Gideon Halevi

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Chapter 1
Introduction

Abstract Manufacturing has been represented over time by a number of different technique. The initial craftsman technique involved tailoring production to individual customer needs. The craftsman technique was succeeded by the ***remarkable innovation*** of the mass production technique, in which a small set of products could be made in large volumes. This, in turn, led to batch production for smaller volumes and varied products. But a number of industries were dissatisfied with the results of their contemporary production management and were looking for other methods that would enable them to increase production efficiency, particularly the metal-cutting manufacturing industries; it is an amazing fact that two different methods, group technology and numerical control, were proposed in two different parts of the world at around the same time (circa the 1950s) with the same objective, i.e., reducing throughput time. These methods are discussed in this chapter.

1.1 Introduction

Manufacturing has been represented over time by a number of different techniques. The initial craftsman technique, in which production was tailored to individual customer needs, was replaced by different methods reflecting the fact that modern production and operation management was turning into more and more of a science.

This trend started with the publication of F.W. Taylor's book "Principles of Scientific Management" (1919). At that time, the owner-manager of a business remained aloof from the manner in which the production process was carried out. The workers themselves did whatever production planning seemed minimally necessary and determined how to produce, based on their skills and experience. In the true spirit of Taylor's scientific management philosophy, there were early formulations of models of operation problems. F.W. Harris formulated the classic EOQ inventory model. W. Shewhart introduced statistical quality control, which not only impacted the field of quality control, but also paved the way for the

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acceptance of probability and statistical concepts in forecasting, inventory control, and many other fields.

The extraordinary impact of computers on operation management is in evidence everywhere, their use extending into product-process technology, information systems and decision-making and control technology, as well as acting as machine members themselves. For example, without computers, linear programming would have had a very small field of application. PERT, CPM, and Simulation are all computer dependent systems, as are CNC machines and CAD/CAM systems. In the future, the development of a completely automated factory is logically to be expected. The product-process technology is already fairly well in place. What remains to be done is the integration of computers into decision-making and control and the merging of managerial technology with product process technology in a practical system of operations that functions automatically, without direct labor.

Modern production and operation management have turned out to be a science. Management relies on scientific models and techniques (e.g., Total Value Analysis, ROI, etc.) in making its decisions. Different concerns will adapt different scientific economic models. However, no matter what model is employed, the decisions are restricted by the engineering data fed into it. Thus, engineering actually performs the initial screening of the data to be considered. Furthermore, engineering passes on its decisions, but not the reasons that caused them to arrive at such decisions, nor the alternatives considered. Engineering, no doubt, is doing the best they can. However, the considerations and optimization prioritized by engineering are not always the same as those prioritized by management. Thus, the data fed into the scientific model are incomplete, and uneconomical decisions might be reached despite the employment of advanced economical models.

IFIP (International Federation of Information Processing) AICT (Advances Information and Communication Technology-1995 Springer Journal) series publishes state-of-the-art results in the sciences and technologies of information and communication. It indicates that today's competitive environment is compelling companies to be the best at the work they do. Competition on a conventional basis has lost its individual distinction, as most companies are using similar machinery, similar quality control, similar inventory control, etc. Thus, the objective for competitive manufacturing has changed as well, focusing on customer service and satisfaction, quick response to market demands, and new product sophistication and options. These competitive fields have spurred the need for a re-evaluation of manufacturing methods. Many new methods, such as: Concurrent Engineering, Total Quality Management (TQM), Business Process Modeling, World Class Manufacturing, Value Engineering, Agile manufacturing, Lean manufacturing, Bionic manufacturing, Mission statements, etc., have been proposed. Most of the proposed methods emphasize the need for each stage and each discipline of the manufacturing process to consider the objectives and problems of the others. They may very well differ in how to implement these objectives. The commonly-suggested method is based on team-work, committees and group discussions. But for all the ideas put forward, very few methods offer, beside ideas, a computerized method of implementation.

But first, let us look at the ways in which manufacturing developed before the use of computers. The above-mentioned craftsman technique was succeeded by the ***remarkable innovation*** of the mass production technique, in which a small set of products could be made in large volumes.

1.2 Remarkable Innovation: Mass Production

Mass production is perhaps most appreciated for its facilitation of singular focus, a positive boon in manufacturing when you have one product that needs to be produced on a significant scale. It is comparatively easy to map out, it allows for a large number of work products to be produced in a shorter amount of time, it creates a sense of flow and connectivity that enables greater efficiency, and it has other benefits such as being easily adaptable to automation and ensuring that specialized machines that might otherwise be used sparingly are put to greater use. On the other hand, it also has its pitfalls: it can be expensive to set up, the reliance on one carefully planned system means that any problem that arises within that system can bring work to a dead stop, the focus on one product means that flexibility in production is essentially nil, and, corresponding with that last point, even a minor change in the product design can necessitate the entire production process being overhauled.

As is almost universally acknowledged, mass production became a genuine reality with Henry Ford's establishment of the assembly line. The good results of this approach were almost unbelievably widespread, with everyone benefitting. The process allowed for far faster production of Model Ts, saving time and money, which allowed Ford both to sell the cars at a lower price (thereby increasing the company's potential customer base) and pay his workers a better wage (an unheard of for the time $5 a day), which not only improved their quality of life but also made it possible for them to buy cars themselves, benefitting the company even more. The better pay also meant that the workday could be shortened without harming the workers' income, which paved the way for the creation of a schedule divided into three shifts.

The mass production technique is based on building a production line. The resources on the line are dedicated to performing a predefined operation. They have to be operated automatically, simple control being exercised by having a signal to start the operation, and an automatic stop when the operation is complete. A transfer mechanism then transfers the parts from one operating machine to the next in an intermittent motion. The simple control may be based on time. A more sophisticated control can be based on signals from all individual machines that the operation is complete. The line is mechanical, with electronic control, and operates without human intervention.

A raw material is loaded into the first working station, and is transferred from one machine to another until it reaches the last machine. Assuming that the time of each operation is 6 min, and there are 20 machines in the line, the machining time is

$20 \times 6 = 120$ min = 2 h. This means that from the time that the line is started, it takes 2 h to complete the first part, with a new part being completed every 6 min after that.

To produce 100 parts, it will take $100 \times 6 = 600$ min = 10 h, meaning 12 h altogether. The work in process will be equal to the number of working stations, i.e., 20 units.

The efficiency of mass production relies on the production line being designed with a great degree of logic, ensuring that the product progresses from each station to the next in as sensible (and therefore cost- and labor-efficient manner) as possible.

1.3 Batch Production

> Batch production is defined by the American Production and Inventory Control Society (APICS) "as a form of manufacturing in which the job passes through the functional departments in lots or batches and each lot may have a different routing." It is characterized by the manufacture of a limited number of products produced at regular intervals and stocked awaiting sales.

Research reveals that over 75% of manufactured products are produced in small to medium quantities. That means that mass production is not a good fit for manufacturing such items and other methods should be used.

Batch production is a name that covers several shop production techniques. The main characteristic is the manufacturing of between one and a few products designed and produced as per the specification of customers within a pre-fixed time and for a pre-fixed cost. It is further characterized by a tendency towards a large number of individual products, but a small number of individual batches, which are then often stored for later sale. Thus, while batch production lacks the uniformity of mass production, by its very nature, the former allows for flexibility that is simply impossible in the latter.

Batch production is effected with standard universal machines. Usually, it is organized by machine capabilities, i.e., turning department, milling, grinding, etc. Universal machines are required to be set up for each individual job. Contrary to the case of machines in mass production, it takes time to set up each machine for its job. Therefore, out of economical consideration, once the machine is ready to begin the job, it will be used to machine a batch of parts, whose size will be determined by Economic Order Quantity (EOQ). The transfer of the batch from one machine to the other will be done by manual means (or lift track). But the use of such standard machines is also a benefit, since they are ones that a manufacturing company is likely to own already, reducing expenses (a particularly good thing given the extra cost that may be incurred as a result of frequent changes in set-up and the need to store inventory over time.

Consider the previous example of 20 operations, each 6 min long, and working with an economic batch size of 100 PCs. Each machine finishes the batch in 100 × 6 = 600 min = 10 h. Adding the rest of the day for transferring the batch between operations means that each operation will take 2 days. Therefore parts will be finished in 2 × 20 = 40 days. Compare this to the 12 h required in the mass production technique. The WIP (work in process) will be 19 stations × 100 batch size = 1900 PCs. Compare this to the 20 PCs in the mass production technique.

The production planning and control in mass production is simple. The production rates are the line capability. In batch production, each operation has to be planned separately. A batch production is comprised of general purpose machines arranged into different departments. The challenge of batch production is the variability from job to job, with each having its own technological specifications and sequence requirements. This can also be seen as an advantage, as it represents opportunities for the workers both to learn as they work and to come up with innovative ideas that increase efficiency.

The major processing time difference between mass production and batch production is that of operation time. In mass production, it is the pure machining time of each operation, while in batch production, the operation time taken for production planning is the pure machining time with the addition of waiting time in the queue (there must be a queue if JIT (Just in Time) policy has not been implemented), set-up time, operation time multiplied by batch size, tear down time, and time spent waiting for transportation. Thus, the machine is available to process its next job.

1.4 Improving Productivity of Batch Production

This section presents three methods with the objective of increasing productivity while organizing batch manufacturing:

- Manufacturing—production information and control system.
- Group technology—processing by family of parts.
- Numerical control machines—processing by computerized machines and auxiliary devices.

All three came into practice at about the same time (the early 1950s) and were the favorite technology of their time for over 30 years, before fading away. Individual sections are devoted to describing each of these methods, with indication of their objectives and disappointments.

1.4.1 Manufacturing

The manufacturing method is an attempt to increase productivity through procedural means, such as scheduling, economic batch size, and information technology.

Production management is the component that makes decisions about planning and controlling operations, including maintenance of equipment, product quality, assorted costs and how best to utilize available human labor.

Production Management Planning is considered to mean “preplanning” or the systematization in advance of the various industrial factors vital to production. Planning thus includes any and all activities that determine the manufacturing techniques to be used before any actual manufacturing begins. It decides what has to be done, and where, when, and how it is to be done. One phase of planning is the analysis of products and parts, as well as the required manufacturing operations, to foresee the sequence of steps necessary for the completion of each article and to set up routines that will cause each step to be performed in a stipulated manner and at a designated time.

As such, planning is a major activity for the production department in its control of production. But the function of planning embraces more than just production control, for it is also a coordinating function—one that is designed to affect a concerted effort from a series of disassociated departments. The quantitative planning of purchased materials and supplies as a cooperative venture of the material control, production, and purchasing departments constitutes a vital part of production planning. The activities of the plant and industrial engineering departments in planning the procedures needed to maintain the quality standards established, the development of methods and work simplification techniques as applied to the contemplated manufacturing processes, and the set-up of the tools, jigs, and fixtures not only as to type but also as to quantity required to accomplish the desired production are all an integral part of the overall plan necessary to achieve a smoothly operating industrial enterprise.

Thus, in summation, it can be said that production planning is a series of related activities performed by not one but a number of different departments, each activity being designed to systematize in advance and to coordinate the manufacturing efforts of the entire enterprise.

The best evidence of effective planning procedure is the elimination of the wasteful conditions noted in the following list:

- Idle men
- Idle machines
- Idle materials
- Idle money
- Idle delivery promises
- Idleness of the product.

Thus, good planning procedure aims to eliminate the idleness that may evolve from the foregoing factors. Men and machines which are busy and which have a moderate bank of work ahead of them at all times, materials progressing through the plant from one operation to the next in what approximates a thin, smoothly flowing stream of work, money turning over at a rate commensurate with the length of the manufacturing cycle, delivery promises that are based on fact rather than on fancy, and a product that is invoiced rather than inventoried; these are the dynamic factors indicative of effective planning.

Technology is affected by the capability of the available tools, and the imagination of those who build and drive it. For many years, production management was built around a chain-of-activities philosophy. In this chain-of-activities approach, there are hierarchical levels, each level having a specific task to perform. Each level receives input that acts as a constraint, performs its algorithms by some method, and generates output. The output of a certain level (stage) acts as the input to the next level. The main production planning stages and their tasks are as follows.

1.4.1.1 Master Production Schedule (MPS)[1]

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.

The decisions in this phase depend either on the forecast or on confirmed customer orders, and the optimization criteria are the meeting of due dates, a 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 phase.

The master production schedule is a long-range plan. Decisions concerning lot size, make or buy, addition of facilities, overtime work and shifts, and confirmation or alteration of due dates are considered and finalized until a plan is realized under which the objectives can be met.

1.4.1.2 Material Requirements (Resource) Planning (MRP)[1]

The purpose of this phase is to plan the manufacturing and purchasing activities necessary to meet the targets of the master production schedule. A quantity and date are set for each part of the final production. The decisions in this phase are confined to the demands of the master production schedule, and the optimization criteria are:

- Meeting due dates
- Minimum level of inventory

[1]The material in this section has been adapted from ‘The Role of Computers in Manufacturing Processes.’ Author: Gideon Halevi. A Wiley-Interscience Publication. John Wiley & Sons, book ISBN 0-471-04383-4, 1980, p. 18 with permission.

- Minimum work-in-process
- Meeting department load balance.

The parameters are on-hand inventory, in-process orders, and on-order quantities.

1.4.1.3 Capacity Planning System (CPS)[1]

The goal here is to transform the manufacturing requirement, as set forth in the requirement planning phase, 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 phase are confined to the demands of the MRP, and the optimization criteria are:

- Capacity balancing
- Meeting due dates
- Minimum level of work-in-process
- Minimum manufacturing lead time.

The parameters are plant capacity, tooling, on-hand materials and employees.

The division between the stages is straightforward and logical. However, it suffers from a practical problem. In a way, all three stages are doing the same thing, but with a different degree of accuracy. The MPS assumes infinite inventory and capacity. The MRP realizes that there is a finite inventory, but assumes an infinite capacity. The CPS assumes finite capacity. But by introducing the actual, or finite, available resources, infinite planning might become unrealistic. This blindness to capacity is one of the main problems with MRP. Several methods have been used to get around this problem. The most universal one is rough-cut capacity planning in the MRP. Rough-cut is typically used to measure the fit of a master schedule. This technique translates a master schedule (end-item requirements) into a common resource unit of measure, such as work hours. Available capacity at *key* resources is compared with the plan to check for potential overload. Resolving the overload is a *manual* process. There are many philosophies, methods, and ideas as to how to resolve these practical problems. Some of them are of a mathematical nature, but the trend is toward "supplying information to the person in charge and letting him make the manual decisions based on the information supplied to him".

One dominating feature in any of the suggested systems is the separation of technical data from the production planning phases, i.e., **the bill of materials and the routing are given axiomatic data externally**. One may have alternatives, but even they are externally fixed—given beforehand without knowing whether or not they are required. Thus, production planning loses some of the flexibility inherent in the manufacturing process and ignores many possible solutions.

Moreover, production management is compulsory for the smooth, efficient operation of industrial enterprise. However, its production cost is restricted by the technical data, which are out of its scope. The technical data establish the optimum processing cost of a product. Production management may aim to adhere as closely as possible to that established cost, but can never meet it. Their objectives are to eliminate any wasteful conditions engendering idleness, which may cause cost increase.

Production management can: determine operation batch size by economic order quantity (EOQ); plan a plant layout that will result in minimum transfer time between operations; select manufacturing resources; set priorities for orders competing over resources, etc.

None of these decisions can reduce the manufacturing cost below the one set by the technical data.

1.5 Favorite Innovation: The Search for Production Efficiency

At one point, a number of industries, mainly those in metal-cutting manufacturing, found themselves dissatisfied with the production management results that they had obtained thus far and were looking for other methods for increasing production efficiency. Amazingly, two different methods were proposed in two different parts of the world at about the same time (circa the 1950s) with the same objective, i.e., reducing throughput time.

In the United States, the focus was on moving set-up to the office from the shop floor with the introduction of machines that functioned under principles of numerical control, while manufacturing in the Soviet Union targeted inter-operational transfer time with a new idea called Group Technology.

The objectives of both methods were not those of traditional production management, which are:

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

This methodology represents an attempt to eliminate wasteful conditions throughout the stages of manufacturing, meet due dates, and establish a minimum level of work-in-process. However, it does not consider throughput time as one of its objectives.

In manufacturing, throughput time represents the time necessary for a material, part or sub-assembly to pass through a manufacturing process after the manufacturing floor receives an order.

Throughput time, also known as manufacturing cycle time, comprises four individual periods in the manufacturing process. The first, process time, constitutes the actual work time spent making the product. Next comes inspection time; the work that has just been done is evaluated and the product/material is (hopefully) cleared to move on to the next workstation. Assuming that is what happens, the time it takes to move it is known, not surprisingly, as move time. But since that move may not occur immediately, we have our final period during which the product/material waits to be moved, known as queue time.

In many cases, more than 95% of the total throughput time is taken up by waiting time, an amount that needed to be shortened drastically. The primary ideas for the purpose of shortening throughput time are:

- Increasing flexibility
- Improving delivery reliability
- Decreasing stock levels.

However, the shortening of throughput times is more difficult than simply pushing a button. A significant number of coherent measures have to be taken in regard to work methodology and organization, the two main culprits behind our present long throughput times.

1.5.1 Outcome of Long Throughput Times

- The result of long throughput times, both in the information transfer and in the physical process, is the necessity of forecasting far ahead. The more dynamic the market circumstances and the longer the horizon, the greater the uncertainty and, as a consequence, the more the reliability of our plans leaves to be desired. The longer the throughput time in the physical area, the more the amount of work-in-process will increase.
- The longer the manufacturing throughput time, the more difficult the capacity control, especially if the production takes place at a number of assembly and sub-assembly levels.
- The longer the throughput time, the bigger the risk of obsolescence at the end of the life cycle of a product. Material procurement and production have to take place in anticipation of the throughput time, and the end of the life cycle of a product is difficult to forecast. In addition, we have to realize that the life cycles of our products nowadays are much shorter than in the past, meaning we are more and more often confronted with the above-mentioned risk of obsolescence.
- As a consequence of long throughput times, longer than the delivery times accepted by the market, we have to have decoupling stocks (buffer stocks). The difference between the accepted delivery times in the market and our internal throughput time has to be bridged. For every product/market combination, there exists a delivery time accepted by the market, which can vary from immediate availability to a delivery time of a number of weeks, months or even years.
- As a consequence of long throughput times, there is a slow reaction to changes in market circumstances and technology.
- As a consequence of long throughput times, effective quality control (fast feedback) is often hampered and may even become impossible.

Anyone who has studied throughput time can tell you that its level of efficiency comes down to one single question: are the system's assorted facets, human, mechanical and intellectual, being utilized in the best possible manner? When a machine that could otherwise be working is sitting idle, throughput time suffers. When the stock of a needed material turns out to have run dry, throughput time suffers. When a process runs into a snag unforeseen because the process designer did not take a crucial factor into account…you get the picture.

Surveying the job shop, a manufacturing company may reduce throughput time by minimizing the time consumed by inspecting, moving and queuing activities, or what is commonly referred to as non-value-added time. The more non-value-added-time is reduced, the more actual production time follows suit, and the faster you can get the product out of the door on its way to the customer.

1.5.2 Remarkable Innovation: Group Technology

Group Technology (GT) was the first technique the recommended aim of which was reducing throughput time. Surveying job shop time distribution shows that only 5% of the time that a part spends in the manufacturing cycle is in actual process. The rest of the time, it just sits stored on the shop floor waiting to be processed. Moreover, 50% of the processing time is dedicated to non-manufacturing activities, such as inspection, loading and unloading. Hence, only about 2.5% of the lead time is dedicated to actual manufacturing.

The main objective of GT is to increase the actual processing time, and thereby reduce the throughput time in the job shop manufacturing technique. GT aims to increase the 5% processing time by way of reducing the 95% waiting time.

The method involves organizing the factory layout into ***work-cells***. A work-cell is a cell of up to 9 machines that can manufacture a family of parts from start to finish. A ***family of parts*** is defined as the parts that can be produced in a single cell. An individual part in the family may not use all the machines in the cell. The number of machines in a cell is restricted, so that the machines may be positioned close together. A shelf is installed between the machines to act as a transfer mechanism. The transfer of a part between operations can be done manually. This method simulates the mass production manufacturing technique. The difference is that a work-cell uses universal machines and a simple and low cost transfer mechanism, processing operations without a batch size buffer. It also simulates the job shop manufacturing technique, as it may process many parts, as long as they belong to a certain family. A shop will consist of several work-cells, covering all plant product requirements. Another advantage of the GT methodology is that production planning is accomplished simply by directing the part to the appropriate work-cell, leaving the responsibility for meeting the delivery dates and quality to the individuals in the cell.

Reviewing batch-type production cost distribution reveals that the main cost elements are set-up time (35–40%) and transfer time.

The website strategosinc.com lists the following statistics on improvements as a result of the use of GT (http://www.strategosinc.com/group_technology.htm):

- Set-up Time 35–40%
- Tooling Cost 40%
- Inventory 15–35%
- Throughput Time 80%
- Purchased Items 15%.

For more on Group Technology, see Chap. 2.

1.5.3 Remarkable Innovation: Numerical Control Machines

Numerical Control, NC, is a method by which manufacturing machine operations are moved from manual control to electronic control based entirely on a numerical code that tells the machine where it is supposed to go and what it is supposed to do. The computer into which these codes are programmed and which subsequently runs the machine is often built right into the machine itself. The technology was further improved with the introduction of the servomechanism, a device that uses feedback to correct a machine automatically when any aspect of its performance strays from the plan.

The NC concept was so strange to manufacturers, and so slow to catch on, that the US Army itself finally had to build 120 NC machines and lease them to various manufacturers to begin popularizing its use.

An MIT team concluded that servomechanisms could be greatly beneficial technology for such industries as metal cutting, for example, milling machines. The great innovation was the machine's ability to cut entire curved lines by itself instead of relying on the ability to cut at certain set points in order to create the facsimile of a line.

MIT subsequently initiated a joint project with the Air Force to continue development of this new technology. They built a machine, a quite large one at that, by refashioning a milling machine purchased from a company in Cincinnati. The machine's axes were moved according to codes punched into tape housed in one of the five cabinets that comprised the machine's control center. The speed with which the machine operated was determined by a clock in one of the cabinets that used electric pulses to determine what speed was needed at any given time.

The machine made quite an impression on those who witnessed its ability to make cuts that no other machine, nor human hand for that matter, could attain with nearly as much ease. Nonetheless, despite the impressive results and some very positive evaluations, such as the one issued by Boeing, the technology was slow to be embraced by the greater manufacturing community owing to its complexity and significant cost.

Today NC is the leading technology and most of the manufacturing resources and facilities are based on it.

For more on Numerical Control, see Chap. 3.

1.6 Conclusions

The innovation technologies developed in the 1950s, i.e., Group Technology and Numerical Control, had a far-reaching effect on manufacturing methods.

Group Technology served as the leading manufacturing technology until the mid-70s.

The Numerical Control **technical stage** remains one of the leading innovative technologies in our day. It helped introduce the computerized machines which dominate today's manufacturing resources. The CNC, DNC, Industrial Robots, the AGV, FMS, FMC, and the automated factory are some of the modern developments derived from the innovations of the '50s. However, the interface between the technical stages and production management leaves much to be desired.

Group Technology is quite different from Numerical Control; however, the introduction of an impressive, innovative support system developed by computer science experts did not contribute to solving the interface problem of NC, and actually caused the diminishment of GT as a leading manufacturing technology.

In truth, we are still searching for the perfectly integrated manufacturing system that can introduce flexibility and efficiency into management and support the above technologies.

Chapter 2
Group Technology

Remarkable and Destructive Innovations

Abstract This chapter describes Group Technology (GT) objectives and methods. The main goal of GT is toward reducing throughput time in manufacturing single or small quantity of items. The proposed method is by reducing the waiting time of items on shop floor (95%) which is achieved by organizing the factory into work cell that can manufacture a family of parts. GT users claims of 230% rise in labour productivity and 240% rise in shop output. The concepts of GT spread and was used in many tasks as: process planning; concept design; purchasing; cost estimating; etc. The broad meaning of GT now covers all areas of the manufacturing process. General definition of GT concept is: "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.

2.1 Introduction

Group Technology (GT) is a manufacturing philosophy aimed at increasing productivity in manufacturing of the job-shop type.

In job shop, because of the variety of jobs encountered, and the small number of parts in each run, set-up time often represents the most significant portion of throughput time. Conventional methods had tried to increase productivity by using capacity planning to attack the direct machining time. As already mentioned, it has been claimed that only 5% of throughput time in producing a part is taken up by direct working time, whereas the part spends the other 95% waiting in the shop.

GT directs its effort toward reducing throughput time by attacking that remaining 95%. This is achieved through organizing the plant layout according to work-cell rather than function. To reiterate, 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.

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Lecture Notes in Management and Industrial Engineering,
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2.1.1 The Evolution of Group Technology

Mitrofanov [1], the man credited as most likely having coined the term “Group Technology,” was impressed by the results that he saw at a machine-tool works in the Soviet Union during the Second World War, where a reduction in set-up time of over 80% was achieved. The managers of the plant had organized specialized component sections with flow lines for the machining of specific groups of components with similarities in design and machining sequences.

In the same era, Petrov [2] had given a touch of academic mathematical detail to the question of production planning and machine loading. He emphasized the need to design special machines that could manufacture a certain family of parts while stressing the importance of utilizing special chucks, such as universal prisms, for use in a milling machine, to save time.

In the subsequent years, between 1950 and 1957, several enterprises engaged in medium and small batch production improved the production structure of their main shops by adapting GT.

As the foremen and operators gained experience, the machining techniques and sequences were corrected and, to some extent, standardized. Those employed in the sections concerned became familiar with group production techniques and ended up taking a more responsible attitude towards the quality of their work and the delivery of scheduled batches (groups) of components on time. Finally, the system was integrally tied up with improvements to the system of operational planning, since it reduced the degree of dependence on the performances of other sections. As a result, a wide variety of other general improvements in technology, and in the organization of the shops and the works as a whole, was achieved.

2.1.1.1 Benefits of Group Technology

Apart from the advantages in respect to production organization and planning, the setting up of specialized sections was found to improve the shop and works’ cost figures quite significantly. One of the biggest cost advantages of GT is that it increases labor productivity, since each workplace can be specially designed for a definite operation on a specific component. This results in the reduction of labor and general production costs. Specialized sections can operate on a much shorter cycle time, because of the major reduction in what is known as ‘inter-operational delay’; in other words, the components take less time to pass through the production cycle. A shorter cycle time leads, in turn, to a smaller volume of work in progress and a more rapid release of tied-up capital. Sections organized to make specific components produce a better article, since narrow workplace specialization facilitates the adoption of rational techniques and the skill of the workers is improved.

A variety of enterprises have confirmed that, within 2–3 months of changing over to GT:

- labor productivity rises by 12–20%
- cost per unit value of finished products falls by 2–3%
- duration of machining cycle falls by 25–35%
- average value of work in progress falls by 15–25%.

In the years from 1957 to the mid-'70s, group technology was adapted as a universal manufacturing method. Its scope widened to cover all steps of manufacturing.

2.2 Definition of Group Technology[1]

There are many definitions of group technology, and they are always subject to change as the scope of GT changes. It has been realized that this technology can serve as a solution for additional activities.

One of the first definitions of GT was given by Ivanov [3], who stated,

> The main goal of GT is to produce a single or small quantity of items using mass production techniques.

Ivanov claims that GT has resulted in the achievement of a 270% rise in labor productivity and a 240% rise in shop output.

If we follow the literature on GT from the U.S.S.R. on its way west, we can sense the realization that the first goal of GT was probably something that could not be achieved. However, since the basic idea was a sound one, it was determined that this technique should not be altogether abandoned, but rather put into the proper perspective. Thus, we have V.R. Solaia's definition of GT:

> 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.

And in Journal "Engineering" (1968) we find the following definition:

> 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 methods.

The general manufacturing philosophy of GT has now been accepted; in truth, it had been practiced under different names, or without any label whatsoever, even before receiving formal recognition.

Thus, the goals and applications of GT have expanded beyond the original requirement, that of the work-cell manufacturing technique, and the broad meaning

[1]The material in this section has been adapted from 'The Role of Computers in Manufacturing Processes.' Author: Gideon Halevi. A Wiley-Interscience Publication. John Wiley & Sons, book ISBN 0-471-04383-4, 1980, pp. 76–78 with permission.

of Group Technology now covers all areas of the manufacturing process. The following is a list of such applications.

- Design. There have been improvements and savings in engineering design due to new methods of data retrieval, elimination of the duplication of drawings, and modification of older, similar drawings.
- Material management and purchasing. The use of groups of materials has led to greater purchasing efficiency, lower stock levels, and savings in procurement.
- Process planning. Savings in process planning have resulted from using the same process for a family of parts.
- Production control. Improved scheduling has resulted due to the similar setup of groups.
- Manufacturing. The use of flow-line systems, machine groups, and manufacturing cells has led to greater efficiency.
- Management. The grouping of parts for the evaluation of vendor quotations, cost, manufacturing load estimate and so on has led to improvements and savings.
- The main differences between GT and the conventional manufacturing system (including the IMS) lie in two areas:

1. *The engineering phase.* This phase was not treated systematically in the IMS. Modern GT offers systematic treatment. Although it merely involves a retrieval of parts according to similarity, the savings attributed to the use of GT are impressive. For example, one company reported that about 2500 new parts were released annually, while about 30,000 active parts were in its design files.

It has also been reported that between 5 and 10% of the annual output of new parts could be avoided through the proper use of classification and coding systems. Thus, a company could save anything from $237,500 to $475,000 just by reducing the duplicated design. This is without making anything; it simply involves preparing the part to go to the shop floor and be made.

2. *Target of attack.* The IMS tries to increase productivity by using capacity planning to attack the direct machining time. Group Technology, on the other hand, is concerned with the lead time. We return once again to the claim of 5% direct working time/95% waiting in the shop time. It is important to point out that the 5% can be further divided into 30% actual machining time and 70% for positioning, chucking, gauging, and so on. Hence, only 1.5% of the lead time is actual machining time, and GT directs its effort toward reducing lead time by attacking the remaining 98.5%. One way to achieve this is by organizing the plant layout according to work-cells, units that include all of the machines required to produce a family of parts, rather than functions.

2.3 Expectations of Group Technology

2.3.1 Group Technology as Leading Technology[2]

At this stage, Group Technology has become the leading technology in industry and academy. There can be no doubt that the problems of group technology and part families manufacturing are being widely studies and that companies all over the world are either in the process of trying to implement the resulting solutions or have already achieved a certain measure of success in doing so.

Koenigsherberger [4], in his paper, describes the use of Group Technology in the industries of various countries.

- In the Netherlands [5], the Organization for Applied Scientific Research (TNO) has investigated Group Technology and its applications.
- In Belgium, the research center for the nation's metal industry (CRIF) "concluded that through using the Opitz system, it was possible to reduce the variety of work-pieces studied in this case from 30 to 12."
- In Sweden, a number of companies have introduced group technology under the guidance of a firm of consultants. "There is, therefore, general consensus of opinion concerning the value of the group technology method."
- In West Germany, "group technology has been applied for the investment planning of a new factory in which part families are collected in families which appear not only to have similar shapes but also to need similar typical operational sequences."
- In Japan, in 1976, a "Group Technology Studying Committee" was established. "This was followed by systematically introducing flowlines of cells into three companies with production control by computers, and also installing special machine tools, including some N.C. machines. Some results indicated that lead time fell from 5 to 6 days to an average of 1 day, the amount of scrap was reduced by about 50% and the production efficiency increased by 30%." [6].
- In Great Britain, the introduction of the group technology method has been reported in the manufacturing of the Brake Linings Company. "A feature of their philosophy was the concept of a cell as a 'synthetic machine' consisting of a highly utilized 'key plant' and a less utilized 'supporting plant'." [7].

"In conclusion, there can be no doubt that the problems of group technology and part family manufacturing are being widely studied and that companies all over the world are either in the process of trying to implement the resulting solution or have already achieved a certain measure of success in doing so."

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[2]The material in this section has been adapted from the paper titled "The Use of Group Technology in the Industries of Various Countries" by F. Koenigsherberger, published at the CIRP Anaals 2, STC O, 21.2.1972, p. 209, with permission.

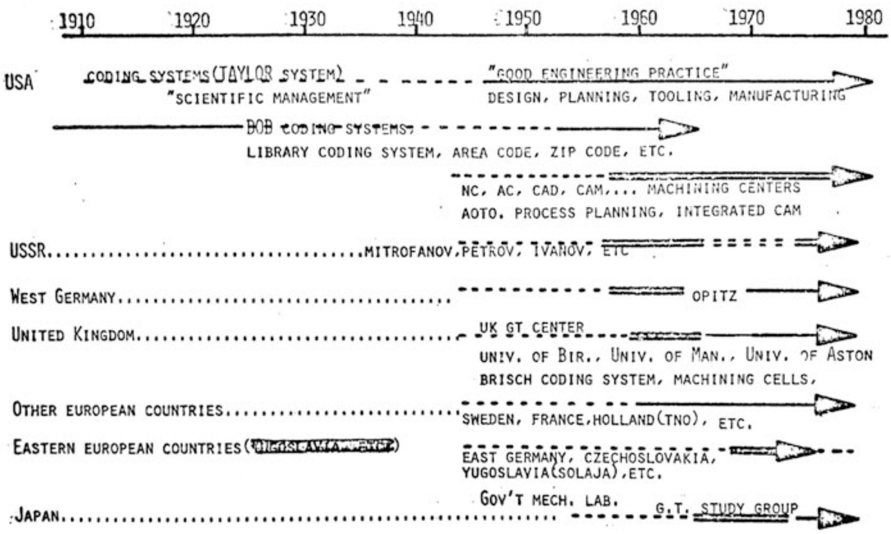

Fig. 2.1 Group technology applications in the US and other countries

A schematic diagram indicating the trend of group technology applications in the US and other countries was published by the CAM-I international seminar, held from April 21–23, 1976. The diagram, P-76-MM-02 on page 255, is shown in Fig. 2.1.

2.3.2 Predictions for Group Technology[3]

In his 1976 paper, 'State of group technology in the U.S.,' Inyong Ham made the following assessment of the potential for the use of Group Technology to spread.

One of the most important current problems in increasing manufacturing productivity is economic incentives. Manufacturing normally contributes approximately 30% of the gross national product of modern industrialized countries. It has been estimated that in the next decade, about 75% of all industrial parts produced in the U.S. will be on a small-lot basis, as opposed to about 25% at present. It is also reported that three-fourths of all U.S. metalworking production consists of lots numbering less than fifty pieces; furthermore, the metalworking industry employs almost 40% of the total employment in manufacturing in the U.S. The annual expenditure of the metalworking industry is estimated to be about fifty billion dollars. Thus, the potential for economic improvement of manufacturing by Group

[3]Material in this paragraph has been reprinted from the paper titled "State of group technology in the U.S." by Inyong Ham, Ph.D., Pennsylvania State University U.S.A., Published at the proceedings of CAM-I'S international seminar, Atlanta, Georgia U.S.A. April 21–23, 1976, pp. 250–260, with No copyright and claims. Public Domain permission.

Technology is indeed not only critical and tremendous in the present day, but will continue to grow with time.

Another area for potentially significant improvement is more efficient utilization of highly expensive machine tools and centers. This task is an essential requirement for achieving the goal of the implementation of computer-automated manufacturing. Again, Group Technology provides a key element in the furtherance of this effort. A forecast of the future of production technology advancement, carried out by both the University of Michigan and the International Institute for Production Engineering Research (CIRP), strongly indicated that the computer-automated factory would be a reality well before the end of this century.

It is especially interesting to note that the survey by the University of Michigan predicts that, by **1988, more than 50% of industry will use Group Technology** in manufacturing, while **the survey by CIRP indicates that by 1990, 70% of industry will use Group Technology** in manufacturing. It is evident that new technological innovations, such as NC, AC, machining centers, industrial robots, new mini-computers, etc., will be continuously introduced toward more automated computer integrated manufacturing systems involving CAD/CAM, and thus lead to more integrated applications of Group Technology for optimum manufacturing and higher productivity.

A more recent survey conducted by CAM-I (Computer Aided Manufacturing International, Inc.) in April 1975 also provides strong evidence of the importance of the priority status of Group Technology applications for batch-type manufacturing industries, not only in the USA, but also in Europe and Japan. Although there are many areas of concern and a real need for improved techniques in manufacturing, it can be concluded that Group Technology is one of our most important methods of solving contemporary problems and improving manufacturing in the future.

2.4 Disappointments in Group Technology

Part families are crucial for application GT. Wikipedia (https://en.wikipedia.org/wiki/Group_technology) defines families as “The group of similar **parts** is known as **part family** and the group of machineries used to process an individual **part family** is known as machine cell. It is not necessary for each **part** of a **part family** to be processed by every machine of corresponding machine cell.

A part family is a collection of related parts that are nearly identical or similar. They are related through geometric shapes and/or size and require similar machining operations. Alternatively, they may be dissimilar in shape, but still related by having all or some common machining operations. Parts are 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 shape elements 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 benefits of a good family forming method in connection with GT can be summarized as follows:

- Quick retrieval of design drawings and production plans.
- Design rationalization and reduction of design costs.
- Secure reliable work piece statistics.
- Accurate estimation of resource requirements.
- Reduction of set-up time and overall processing time.
- Improvement of tool design and reduction of tool design time, cost, and processing time.
- Rationalization of production planning procedures and scheduling.
- Accurate cost accounting and estimation.
- Better utilization of processing resources.

2.4.1 Form Families

There are three basic methods for the forming of a family of parts, namely:

1. Visual inspection—walking around the shop and looking.
2. Production flow analysis.
3. Classification and coding system.

2.4.1.1 Visual Inspection[4]

Many of the reports on successful group technology applications have come from studies in which the main work on the manufacturing concept was done with families of parts that had been organized manually. Engineers have tended towards taking a close look at each part produced by their company and making a human decision, relying on their memory and on the flexibility of the human mind. Therefore, this method is excellent for small companies for which the human mind might be capable of grasping all the parts produced by that company.

> Although this method is generally considered to be the least accurate of the three, one of the first major success stories of GT in the United States involved making the changeover using the visual inspection method.

The visual inspection method has proven very useful in the implementation of Group Technology at times, but overall, it suffers in regard to accuracy and is therefore the least widely used of the three methods.

[4]Material in this paragraph has been reprinted from the paper titled “State of group technology in the U.S.” by Inyong Ham, Ph.D., Pennsylvania State University U.S.A., Published at the proceedings of CAM-I’S international seminar, Atlanta, Georgia U.S.A. April 21–23 1976, pp. 250–260, Public Domain permission.

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2.4.1.2 Production Flow Analysis

Production flow analysis (PFA) is a technique for analyzing the operation sequence and routing of the components through the machines in the plant [8, 9]. Parts with common operations and routes are grouped together and identified as a manufacturing part family. Similarly, the machines that produce that family can be gathered together to form the machines group cell. It should be assumed that the majority of parts made by the company belong to clearly defined families and the company's machines to clearly defined groups. Several mathematics algorithms were developed to compute the family of parts, usually they are based on Boolean algebra and they are quite simple by nature [10].

A preliminary study of components with the aid of a PFA or an operations matrix established the optimal arrangement of work-cells. Example: families grouped by part and machine number. In Fig. 2.2, the columns represent the machines, whose names and numbers are at the top. The rows represent parts, whose names and numbers are on the left. An “X” in a cell indicates the proper pairing of part and machine.

While the first matrix (Fig. 2.2) is, perhaps, closer to what one might encounter in real life, the second matrix (Fig. 2.3) has been designed to make the process a bit less opaque, clearly indicating which machines are likely to be grouped together as a cell. Computer programs are available for manipulating large matrices but they cannot solve the problem of inconsistent routings that is often encountered in a PFA analysis. Inconsistent routing means that similar parts use different machines. This occurs for a variety of reasons such as:

Fig. 2.2 PFA original matrix

Item	R3	R4	R5	R8	R9	R11	R13
P#1							X
P#2	X		X				
P#3	X	X	X				
P#4						X	
P#5	X	X	X				
P#6	X	X	X				
P#7						X	
P#8				X			
P#9				X	X		
P#10				X			

Fig. 2.3 PDF organized work-cell

Item	R3	R4	R5	R8	R9	R13	R11
P#10						X	
P#4							X
P#7							X
P#8				X			
P#9				X	X		
P#10				X			
P#2	X		X				
P#3	X	X	X				
P#5	X	X	X				
P#6	X	X	X				

One of the most prevalent problems in PFA is the issue of inconsistent routing, which refers to situations in which parts that are similar enough to be made on the same machine are instead sent to different machines. This can be the result of something as simple as having more material than one machine can handle and thus sending it to another, but even more frequently, it is the byproduct of different process planners having their own ideas based on their own experiences about what should go where and why. When a product is made by the same company over a considerable period of time, during which personnel are likely to change, perhaps several times over, this sort of thing is bound to happen.

2.4.1.3 Classification and Coding System

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.

There are a number of approaches to the formation of a classification system. Each approach offers certain advantages and disadvantages over the other. The coding is done by collecting drawings and associated production data together on one hand and the classification system on the other.

Classification and coding systems can be categorized as:

- Design-oriented systems based on attributes of part design.
- Production-oriented systems based on attributes of part manufacturing.

Each system 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 in the hope that anone of the old drawings might fit its purpose. On the other hand the ***production oriented*** requires that a retrieving request will draw as many parts as possible.

2.4.2 Classification and Coding

A coding system establishes a code for each component in the company's data files. After coding, similarities between codes can be used to form families. The code, in general, represents information regarding the component size and data relevant to its machining requirements.

One of two different approaches is followed in constructing a coding system. The first approach is to establish a universal code that can be used for components of a given industry. Contrastingly, the second approach gives an outline of the procedure so as to establish a tailor-made code.

2.4.2.1 Coding Systems

A number of coding systems exists, each claiming to be superior in one aspect or another. However, general guidelines can be established for a good coding system for the purposes of GT. An appropriate classification system should have the following characteristics:

- Generally applicable to components or major classes of components designed and/or manufactured in different engineering firms of a certain industry.
- Easily definable and clearly unambiguous.
- Explicitly defined in all the factors which affect production methods and tools (e.g., configurational, dimensional, and accuracy parameters of components and production control data).
- Not subject to aging and designed to accommodate future developments.

The variations in codes resulting from the way the symbols are assigned can be grouped into three distinct types of code:

- Monocode or hierarchical code
- Polycode or attribute
- Hybrid or mixed code.

Monocode is a progressive, integrated coding system in which each digit qualifies and/or amplifies the information contained in the previous digit. Each digit may contain more than one descriptor or characteristic. The study of these similarities is ideal for combining similar parts.

The reference-like nature of monocode, which eschews the cataloging of strings of information such as work processes, makes it unsuited for the design side of manufacturing. But it does have the ability to store remarkable amounts of information using very little code, making it a very useful, if somewhat fragmented, reference indeed. On the other hand, it is often highly important to isolate and identify specific attributes of a part which may or may not be encompassed in the monocode. This isolation of attributes is performed by utilizing a polycode system.

Polycode is defined as a set of independent sequential codes, each digit or set of digits describing individual characteristic variations. Polycodes are often called "feature" codes. This means that each symbol always means the exact same thing (generally a facet of the product and its production process in this context), regardless of the other symbols with which it has been placed. The more complicated the manufacturing process, the longer the polycode (and some polycodes have been known to be quite long indeed).

The third type, **Hybrid Code** is the most widely used of the three, not surprisingly, as it represents the best aspects of both mono- and polycodes while avoiding their respective pitfalls. The mixture of monocode and polycode systems retains the advantages of both systems. Most coding systems use this code structure.

Forming a good classification system is quite a problem, and there are many specific companies that specialize in this field. Here is a list of some of the most prominent industrial coding systems:

- Opitz classification system (the University of Aachen in Germany [11, 12]
- The Brisch System (Brisch-Birn, Inc.) [13]
- CODE (Manufacturing Data System, Inc.) [14]
- SAGT (Systematic Approach to GT) [15]
- CUTPLAN (Metcut Associates)
- DCLASS (Brigham Young University, Provo, Utah)
- Miclass [16]
- MultiClass (OIR: Organization for Industrial Research)
- Part Analog System (Lovelace, Lawrence & Co., Inc.).

2.4.3 Creating Part Families[1]

In order to utilize the benefits of GT, a classification and coding system is required. Ham [17] defines the requirements of this type of system as follows:

> The system must be both design- or form-oriented and also production- or process-oriented. Care must be taken in formulating the process code so that the system can accommodate future changes in technology which may produce entirely new methods of processing the part family.

Many of the reports on successful GT applications have come from studies in which the main work on the manufacturing concept was done with families that had been organized by human effort. This is a byproduct of the standard approach taken by engineers, as mentioned in the section above on visual inspection.

The exhaustive research for selecting and determining the coding and classifications will need to meet the above specifications. Classification and coding systems can be categorized as design-oriented, production-oriented, or resource-oriented.

2.4.3.1 Design-Oriented Classification and Coding Systems

The first attempts to create classification and coding systems for components were specifically based on considerations of shape and size.

In my own previous paper, 'Adaptive Process-Production Planning' [18], I proved that the most economical process for producing components that have exactly the same shape and size will vary according to other considerations and requirements, such as quantity, raw material, and optimization criterion. Similar conclusions can be found in the paper by Hancock [19] from Group-Technology International, England, in which he writes:

> While they met with some measure of success, it was found that the systems available at that time (early ’60s), were design-oriented, and, projected into production-oriented systems, were not giving the results desired. Today, it is increasingly recognized that classification and coding of components by shape, etc., will not give the results desired.

Hancock goes further in developing his ideas and comes to a clear conclusion:

> From my own experience in this field, and that of my colleagues, my conclusion is that no one can devise a coding and classification structure as a sieve or riddle by which, with the appropriate number of shakes, rattles and rolls, component families will emerge, around which we can design Group Technology cells.

2.4.3.2 Production-Oriented Classification and Coding Systems

The inadequacy of the design-oriented approach thus leads to the use of a production-oriented classification and coding system. Naturally, as a result, the design utilization of the GT technique is neglected. However, this is permissible, since it constituted a secondary rather than a primary objective.

This type of classification and coding system should be based on process planning; however, the present situation in process planning, excluding my own work [20], is a strictly human-oriented activity, highly dependent on individual skills, human memory, reference manuals, and experience.

Due to the fact that more than one engineer (or process planner) will tend to be involved in the decision and specification as to how things should be made in the current process planning file, we find different plans, different machines and different sequences for the same or similar components. Thus, if we use the current process plans as a basis for a classification and coding system, we probably will not achieve the results desired. Furthermore, Hancock [19] has found and stated that:

> Many of the characteristics associated with production are either totally variable, or at best, semi-permanent. These include the production quantity, the manufacturing methods and the technological changes. To build these into a code structure would be very difficult.

The production-oriented approach to classification and coding has achieved some success in certain manufacturing industries, but has left many unsolved problems in others. Thus, even in those industries for which it may be a good approach, I am afraid it will only achieve short-term success, possibly proving disastrous in the long run. It is a rigid, baseless system that will not adapt itself to technological changes, and will, therefore, be a hindrance to technical development.

2.4.3.3 Resource-Oriented Classification and Coding Systems

The Resource-Oriented method calls for a machine layout according to a production flow analysis, in which a component will enter a work-cell and be terminated there. Hence, one work-cell or department might include sawing, milling, turning, drilling, slot milling, grinding, lapping, and deep drawing. Technological improvements can be made in each work-cell according to the specific components to be manufactured within it. The extreme example of this is the automated job-shop, where a transfer line and automatic chucking are installed.

The work-cell method represents the latest approach to GT and the reports on its use inform us that it is "immensely successful," showing "an average saving of 70% of machine time", "work in progress reduced by a ratio of 8–1," and so on. There is no reason to doubt the accuracy of these reports or that this is an excellent technique for certain types of industry.

A preliminary study of the components, with the aid of a PFA or an operations matrix, establishes the optimal arrangement of work-cells. Their classification and coding will be done through analysis of specifications so as to obtain the potential manufacturing work cell. Naturally, if the workpiece mix changes, a new study of the PFA should be made. Rearrangement of the work-cells and reclassification and recoding of the components should be carried out.

Before installing and using the work-cell concept, one should bear in mind the problems that will arise:

- *Reorganization*. The ability to reorganize the machine layout of the plant and, probably, to repeat the reorganization every so often.
- *Work-cell supervision*. In the functional layout, it is only required that the foreman be an expert in one type of manufacturing. In the work-cell concept, in order to supervise and instruct the workers, the foreman must be an expert in several fields, such as milling and turning.
- *Work distribution*. With the functional layout, there was no problem in transferring an operator from one machine to another, since they were of the same family and thus the operator had the training and skill to operate them both. In the work-cell environment, however, this cannot be done.

2.5 Summary

Group technology (GT) is a sound and widely accepted manufacturing philosophy. For practical applications of GT, the creation of part families is crucial. A part family is defined as a collection of related parts that are nearly identical or sufficiently similar. For several centuries, the traditional technique for forming such part families was through coding and classifications systems. The research on GT was sidetracked by research on classifications. Several methods were proposed, including: the Opitz system, which used 5 digit + 4 supplementary digits; the SAGT system, with 18 positions; and the TNO, with 31 digits completing a questionnaire of 75 lines.

Any classification and coding system will contain errors, owing either to the rigidity of the system or to human error in the classification and coding processes.

Houtzeel [21], in his paper describing the Miclass system [16], and based on his experience of seven years in development and testing, writes:

> Errors are a serious problem for all conventional classification systems. Classification may start off accurately but within a few months errors may run as high as 30–40%.

Still, despite these potential drawbacks, a classification and coding system is essential if the advantages of GT are to be fully realized. And, as per Ham [17], design, form, production and process must all be taken into account as necessary, as must the possibility, when developing the process code, of technological changes down the line that may affect the methods for processing part families.

To make these demands of a classification and coding system is practically asking for the impossible.

In my 1978 paper, 'GT, not coding and classification,' [22], I wrote that: "Group Technology" (GT) is a sound and widely accepted manufacturing philosophy, but not too many practitioners have succeeded in applying it. The main problem rests with the popular concept that the 'heart of GT' depends on classification and coding systems. A great deal of effort has gone into developing such systems; little success with GT has resulted.

"But, when you analyze the concepts of GT and attempts at its implementation, one conclusion becomes clear: group technology can be effectively used without any need for a classification system. Startling? Well, let's take a look at the aims and objectives of group technology…"

By the 1980s, due to the incapability of coding and classification to support group technology, both had begun fading, and by the mid-'80s, they had almost completely disappeared.

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Chapter 3
Numerical Control

Remarkable Innovation

Abstract The development and application of numerical control (NC) systems are described in this chapter. NC is an extraordinary technology, upon which most industrial resources are based. Starting from simple NC machines, the method evolved into Direct Numerical Control (DNC) and then into systems such as Industrial Robots, AS/RS, Machining centers, and, in a return of sorts, into Cellular Manufacturing. The incredible computerized machines has greatly contributed to flexibility in manufacturing, although this only applies to the hardware capabilities. Manufacturing, however, is sustained on two legs: hardware and software. The software is lagging behind in this respect and could practically be considered the missing link in system flexibility.

3.1 Numerical Control (NC)

The process of automating production, particularly in regard to the control of machine tools, has been a gradual one, not just in terms of taking place over a long period of time but also in determining the amount of human involvement that is necessary.

For example, one of the earliest innovations, the use of cams, which had become very effective by the first decade of the 20th century, necessitated precise manual work to achieve the precise shape required, a trial-and-error process that ate up a lot of time.

The innovation that really moved automation forward was the servomechanism, a device that, through feedback, automatically corrects any malfunctions in the mechanism to which it has been assigned, which is referred to as the control device. The control device sends out some sort of signal, which is picked up by the servomechanism's error detector. Meanwhile, the proper parameters of whatever facet is malfunctioning, which have already been programmed into another element of the servomechanism, called the command device, are also projected into the error detector so that the two pieces of information may be compared. The difference between the two pieces of information is sent from the error detector to an amplifier,

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which then sends the signal along to yet another element called the servomotor. The servomotor takes this information and uses it to correct whatever facet of the operation may be causing the error (e.g., acceleration, position, velocity).

This was also one of the first examples of numerical control, with data being used to effect operations for which humans would have at one point been responsible. Of course, the human factor was still present; someone had to program the information for the servomechanism to store so as to compare it when a malfunction occurred. The information would be coded into what was called punched tape, consisting of strips of paper carefully perforated so as to constitute a code that could then be interpreted by the machine into which it was fed. While this greatly reduced the capacity for human error in the actual correction process, as was pointed out in an evaluation of such programming released by MIT in 1958, the potential for mistakes and the time taken up by the labor of human workers had simply been moved from the correction phase to the programming phase.

In fact, programs had already begun to be developed that would merely require the human workers to enter the desired parameters into a computer that could then create the punched tapes itself, edging forward once again towards a process less subject to human error and significantly reducing the time it took to manufacture a part. One particular example of this sort of innovation developed at MIT in 1956 led to the spearheading of an Air Force program to create a standardized language that could be used to incorporate numerical control into any given situation. These efforts, in turn, led to the creation of the Automatically Programmed Tool (APT), which is actually exactly such a programming language. Full development of this language took some time, with various machine-builders tinkering with it along the way, until the finalized version was debuted in 1968.

3.1.1 CNC and DNC

As the size and cost of computers both began to fall, their use for correcting manufacturing errors began to eclipse that of servomechanisms. This trend only continued (as, indeed, it has in so many aspects of life) with the invention of the microprocessor in the 1970s. Additionally, it was found that Computerized Numerical Control machines (CNC) could produce results in ways previously unimagined.

Using a code that works as a sequence, employing letters signifying different aspects of the production process in combinations designed to specify the functions needed, CNC machines were found to be able to, for example, cut shapes that other machines had struggled to achieve, with remarkable consistency and with very little need for human oversight, both lowering the chance of human error and creating opportunities for the workers to spend time on other matters requiring their attention.

The language of a CNC machine is interpreted by a CNC control, which reads the sequence of letters and initiates the function signified by each command. CNC control is designed to be modified to fit the particular job, including accounting for errors that may be discovered along the way. The motion of a CNC machine is determined by the number of axes it has, which must be at least two, and by whether the axes move along a straight line or along a circle.

When the right program has been achieved, it is loaded into the CNC control as a text file, either manually or through use of a Direct Numerical Control System (DNC), known as a Distributive Numerical Control system. This is essentially a program storage system that can be connected to all the CNC machines in the factory, enabling it to send the proper program to each machine so that they may carry out their designated tasks.

3.2 Increased Processing Time

Incredible Innovation

Many industries have benefitted from the introduction of numerical control, perhaps none more so than the manufacture of metal parts.

A human process planner studies the drawing of the part and recommends a routing or roadmap of processing steps necessary to process the part, including which operations should be performed on which machine. The human process planner employs a programming language ("G-code") and his decisions are recorded on the company/machine's computer. The recorded data includes everything that an operator would be required to do with conventional machine tools. Data such as: reference points, selected tool, tool path, machine cutting speed and feed rate, all programmable with CNC machines.

CNC machines, as previously noted, have significantly reduced the amount of human labor that is required, because not only do these machines serve many of the same functions that humans would have previously, they also require very little oversight, meaning the worker in charge of the machine, once set-up has been achieved, can basically leave it to its own devices and is free to look for other places around the factory where their skills might be needed.

3.2.1 Automatic Tool Changer

One function of a CNC machine, as it follows the commands interpreted by the CNC control, is tool selection for a specific operation, thus transferring set-up from shop floor to tool room.

A comprehensive cutting tool management system is critical for the successful operation of a manufacturing system. Tool management can be defined as the capability of having the correct tools on the appropriate machines at the right location and time while maintaining acceptable utilization of manufacturing resources. One of the primary objectives of tool management is to ensure that tooling is never a cause for delay in the production schedule.

The need for and importance of cutting tool management becomes all the more evident when you consider what happens without it. Up to 80% of production time can be eaten up simply looking for the proper tool for the job, and with a significant amount of those tools being stored on the shop floor in boxes, even more searching becomes necessary, taking up even more time. The lack of proper tools subsequently leads to reduced achievement of production demand. And this does not even take into account the bloated percentage of the budget that most metal-working companies end up spending on tools, spare parts and related items.

The following statistics indicate the need and importance of cutting tool management:

- 30–60% of a shop's tooling inventory is somewhere on the shop floor, with most of it placed in the toolboxes.
- 16% of production demand cannot be met because the tooling is not available.
- 40–80% of production supervision time is spent to search the appropriate materials and cutting tools.
- In some plants, operators spend 20% of their time to search cutting tools.

A metalworking firm's annual budget for tooling, jigs, fixtures, consumable supplies, and spare parts is 7–12 times larger than its entire capital-equipment budget. The actual cutting that a cutting machine performs only takes up a comparatively small amount of the time for which it is used, capping around a mere 20%. Much of the rest of the time is taken up by such necessary but non-productive tasks as the setting and loading of tools and materials. An automatic tool changer can make all the difference by changing tools, whether because of wear or on account of appropriateness for the particular job, while the machine is still performing its other tasks, thereby saving all kinds of valuable production time.

3.2.2 Automatic Workpiece Loading/Unloading

Material removal process, can create a variety of features by cutting away the extra material. The process requires is: a machine (milling); workpiece; fixture; and cutter. The workpiece is a piece of pre-shaped material that is secured to the fixture, which itself is attached to a platform inside the machine. A cutting tool is also secured in the machine and rotates at high speeds. By feeding the workpiece into the rotating cutter, material is cut away from this workpiece in the form of small chips to create the desired shape.

Guaranteeing accuracy in machining a workpiece calls for bringing the coordinates of the drawing datum dimension points, the machine's coordinate point, the tool tip position, and the part to be machined all into line.

The securing of a workpiece described above was usually done by the machine operator, with the first piece subsequently being sent to quality control for inspection and approval to carry on machining the entire batch. While waiting for QC approval, the machine was kept idle, sometimes for as much as a day.

The notion of transferring non-production activities, such as setup, etc., from the shop floor to the office or tool room can apply to workpiece loading as well. The idea is to secure the workpiece in a tool room on a pallet. The pallet is placed on the machine's positioning base and is both situated and secured by a mechanism within the machine specifically built to do just that. The pallet coordinates match the machine coordinates, thus the workpiece coordinates also match those of the machine.

Aside from the mechanism that secures and releases the pallet, the other major mechanism in a pallet system is the automatic pallet changer. Its function is to transfer the entire pallet, complete with the workpiece on it, to the machine that will work on it next. This significantly reduces the transfer and set-up time required to continue the machining process.

3.2.3 Machining Center[1]

Machining center is a milling machine with extra features which will increase productivity. It incorporates the CNC/DNC control and advanced programming capabilities, which transfer part of the setup time from shop floor to the office.

It accumulate a large tool storage space to held as many tools that are required for processing of a part, it adds an automatic tool changer (ATC) that includes a tool magazine (carousel). Tools are inspected and adjust in a tool room and not on the machine, thus increase processing machine time.

Items loading and unload after processing is done by an automatic pallet changer (APC). Thus item changing time on the machine is significantly reduced.

A DNC computer control loads the part programming for the loaded item to the control and the machine start processing immediately.

In typical usage, all machining centers are mills, but not all mills are machining centers.

This field is keeping on developing and new features are added. Actually the machining centers will posses turning capabilities as well as measuring features. It might become (necessary or not) a sort of mini factory.

[1]This sections is based on the Wikipedia article on Milling (machining), the subsections Alternative terminology and Computer Numerical Control.

3.3 Auxiliary Manufacturing Hardware

REMARKABLE INNOVATION Expectations and accomplishments

3.3.1 Industrial Robots

The ongoing campaign to use automation to ramp up efficiency in manufacturing has led to the sub-discipline of robotics, an even more concentrated attempt to replace potentially error-prone human labor with that of increasingly autonomous machines.

The IRF (International Federation of Robotics) gives the official definition of an industrial robot as being an "automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes" (http://www.ifr.org/industrial-robots/). All robots are combinations of electronics and mechanics, in varying degrees of complexity, relying on pre-programmed information to know how to perform their functions (an obvious link to numerical control). Robots can, in fact, resemble actual lifeforms, if, perhaps, not generally to the extent imagined in our finest science fictions, although there is one consistent factor that they do share with their human counterparts: arms. Almost all robotic work is achieved through the placement of the proper tool for the individual job having been attached the one of the robot's (often multiple) arms. These arms and their tools can then be used to grasp, grind, weld, paint, relocate, package, etc., whatever product is being manufactured. Sensors installed within the robot help it to identify where the product is, how best to grasp it, and how best to put it down.

The simple fact is that robots are capable of things that human beings are not. A robot can perform the exact same task a thousand, ten thousand, a hundred thousand times without getting tired or altering the manner in which it performs it by the slightest degree. A robot can be lowered deep into the ocean to perform a task and then be brought right back up without fear of decompression sickness. This combination of consistency and utility is why robotics continues to be an expanding field in manufacturing. However, it must be remembered that robots are only as good as the human beings that design, program and utilize them, which is why good training in the handling of these machines is also an expanding field.

3.3.2 AGV—Automated Guided Vehicle

The type of robot most often used to transfer raw material, parts, finished products, etc., around a manufacturing environment is an automated guided vehicle (AGV; sometimes the 'A' stands for 'automatic'). This is a machine that runs along a path, or series of paths, designated through assorted means, sometimes literally following lines mapped out for it on the floor or, in more advanced cases, using some form of electronic sensor to navigate its surroundings.

Barrett Electronics of Illinois developed the first AGV, basically a tow truck, the innovation of it being that it followed a wire in the floor. This innovation was taken even further in 1976 when a company out of Michigan, Egemin Automation, developed its own automated, human-free control system, which ultimately resulted in a vehicle that followed marks laid down in ultra-violet that were undetectable in normal light.

Steering control is based on servomechanism- numerical control technology. To navigate three different steer control methods were developed:

AGVs can either be steered through a differential system, which uses two drive wheels, operating at either varied or identical speeds, depending on whether it needs to turn or simply move along a straight line, or a steered wheel system, which tends to be more suited to following pre-programmed routes, and which can be human-operated, much like a regular car, when necessary. There is also a hybrid system that incorporates the two, which, not surprisingly, is even more adaptable to the specificity of the situation.

3.3.3 AS/RS Automated Warehouse

In the 1960s, factories and warehouses began to use automated storage and retrieval systems (AS/RS). Their initial purpose was to move the heaviest loads that caused the most difficulty for the workers, but improvements in their technology inevitably moved them towards a more permanent position moving loads of all sizes.

The warehouse shelves are constructed in several aisles, each aisle has several floors, each floor has several storage area locations and each storage area might have a room location.

Numerical control enters the picture in the information that is programmed into them, using codes that instruct them as to what materials are needed, where those materials are and where those materials are supposed to go. The materials' actual transfer may be effected through the use of some sort of conveyance system that runs throughout the space (e.g., belts, rollers) or they may be transferred by the afore-mentioned AGVs. Regardless of the mode of transfer, the common factor in AS/RS is the storage and retrieval machine, which is the actual device that loads and unloads the materials. There are two primary models for this type of machine: fixed aisle and vertical lift/carousel. The former is a large unit that is, of course, fixed, usually on some sort of track, and is attended to by individual shuttles that are capable of traveling through the shelves, both up to their respective levels, but also to deep within the shelves themselves, in order to load or unload the needed material. The vertical lift/carousel types are smaller units that either work individually or in tandem with other such units. Vertical lift is sort of like a smaller version of fixed aisle, with two single deep columns of shelves that are attended to by a retrieval shuttle in the middle. Carousel types, on the other hand, are essentially collections of smaller individual storage bins designed to rotate so that the appropriate bin can be accessed when necessary (there are three different styles of carousel: horizontal, vertical and rotary).

In each case, the machine acts according the information it is fed, regarding the proper storage area, the proper space within the area and the nature of the material, all of which the central computer then uses to update its inventory listing for more efficient accounting and future retrieval.

3.4 Remarkable Successes and Disappointments

3.4.1 Flexible Manufacturing System—FMS[2]

The basic objective of FMS is to produce a great variety of parts in low and medium volume while retaining the efficiency level of mass production systems. This is done through a configuration of semi-independent work stations and material handling systems.

Generally, an FMS comprises a system of hardware, consisting of a group of NC machine tools, a device for automatic loading/unloading, a transfer mechanism (conveyor system and/or industrial robots) to move workpieces automatically from one machining station to the next, and a controlling computer equipped with a system of software for managing the overall material flow and execution of processing operations.

The environment of an FMS System is therefore completely different from that of a conventional job shop. This new environment provides new capabilities but also imposes new constraints on the scheduling function, which should be adapted accordingly.

In an FMS, the hardware and layout provide flexibility in manufacturing by allowing parts to be transferred, automatically, rapidly and without delay, from one machine to another. The machines do not require set-up time, and thus can switch from one part to another with a minimum loss of time. The utilization of the hardware's flexibility, however, depends heavily on the flexibility of the software used. Improper software might (as has happened in some FMS installations) cause overload on some underemployed machines lacking the proper tooling to carry out the job and handle high in-process inventory. Thus, machine utilization is low, the automatic transfer system is overcrowded, and overall efficiency suffers. Currently, the development of a multipurpose software module for FMS is lagging behind the

[2]The material in this section has been adapted from CIRP—The International Academy for Production Engineering, "On Line Scheduling for Flexible Manufacturing Systems" Author: Gideon Halevi, Roland Weill, Technion, Haifa. Published in Annals of the CIRP Vol. 33/1/1984, pp. 331–334. Used with permission.

development of hardware. Difficulties arising from the development of suitable software are not to be underestimated.

The hardware components of an FMS are:

- Independent numerical control (NC) machines. Usually machining centers.
- A conveyance network (possibly robotic) for moving parts and sometimes tools between machines and fixture stations.
- An overall control network that coordinates the machines, the part-moving elements and the work pieces.

In most FMS installations, incoming raw work pieces are fixed onto pallets at a station or group of stations set apart from the machines. They then move, via the material handling system to queues at the production machines where they will be processed. In properly designed system, the holding queues are seldom empty, i.e., there is usually a work piece waiting to be processed when machine becomes idle. When pallet exchange times are short, and machine idle times are quit small.

The number of machines in a system typically ranges from 2 to 20. There are several method of FMS transfer mechanism layout. One is constricted as a loop layout and one as a rectangular layout. Others are using industrial robots, or AGV —automated guided vehicle and AS/RS. The conveyance system may consist of carousels, conveyors, carts, robots, or a combination of these. But the important aspect of these systems is that the machine, conveyance elements combine to achieve enhanced productivity without sacrificing flexibility.

Perhaps the easiest approach to understand an FMS is to flow of parts through the system. Part flow begins at the load/unload stations, where the raw material and fixtures are kept. The FMS controlled computer keeps track of the status of every part and machine in the system. It continually tries to achieve the production targets for each part type and in doing so tries to keep all the machines busy. In selecting parts to be sent into the system, it chooses part types which are the most behind in their production goals, and for which there are currently empty fixture/pallets or load stations. If an appropriate pallet/fixture combination and a work piece are available at the load station, the loader will get a message at his computer terminal to load that part on its pallet. He will then enter the part number and pallet code into the terminal, and the computer will send a transporter to move the pallet. The transporter is then sent to the appropriate machine.

Once at the queue in front of the machine, the computer actuates the transfer mechanism in the queue and the pallet is shifted from the transporter onto the shuttle. The transporter is then free and will leave when a new move request is assigned. The part and pallet wait until the part currently being machined is completed, and then the two parts and their pallets exchange position. As the new part is moved onto the machine, the proper NC part program is downloaded to the machine controller from the FMS control computer. After completing the download, machining begins.

The finished part, now on the shuttle, waits for the computer to send a free transporter to collect it and carry it to its next destination. If, for some reason, the part cannot go to that destination, the computer checks its files for an alternate destination. If one exists, the computer decides whether conditions in the FMS warrant sending the part to that destination. If they do not, then the part either circulates around the system on the transporter until the destination is available, or the transporter unloads it at some intermediate or storage queue, and retrieves it when the destination is available. The final destination is usually the loading station, now functioning as an unloading station where the part is removed from the pallet and replaced by a new part, or the pallet is stored until needed.

3.4.1.1 FMS Control Planning[3]

A new methodology for performance analysis of a flexible manufacturing system with priority scheduling is presented. This analytic approach is based on Mean Value Analysis of closed network queues with multiple product types, various non pre-emptive priority service disciplines, and with parallel machine stations. The performance measures derived include the expected throughput per product and per station, machine and transporter utilization, queuing times and queue length statistics for various systems.

Extensive comparative evaluations with simulations *have* shown that the accuracy of this methodology is satisfactory for any given practical situation. The paper also illustrates the application of *the* model of a system with a mixture of FCFS and HOL disciplines, giving insight into various priority assignment policies in an FMS. Special attention was given to the problem of scheduling the robot carriers.

The mathematical model developed here is also being implemented in the analysis of other queuing network systems, such as computer networks and transportation systems.

FMS are designed to combine the efficiency of a mass-production line with the flexibility of a job shop for the batch production of a mid-volume and mid-variety of products. The control of an FMS is more complex than the transfer of lines or job shops, because of the flexibility of machines and operations. In general, FMS operation decisions can be divided into two phases: planning and scheduling. The planning phase considers the pre-arrangement of parts and tools before the FMS begins to process, and the scheduling phase deals with routing parts while the system is in operation. The scheduling phase involves a set of tasks to be performed. There are trade-offs between early and late completion of a task, and between holding inventory and frequent production changeover. Scheduling has

[3]The material in this section has been adapted from the paper titled "Analysis of Flexible Manufacturing Systems with priority scheduling" by Sarit Shalev-Oren, Abraham Seidmnan of Tel-Aviv University, and Paul Scheitzer of University of Ben-Gurion. Published at the International Conference and Exhibition on the "Factory of the Future", Tel-Aviv Convention Center, November 4–7, 1984, pp. 293–298. No copyright or claims. Public Domain permission.

been proven to belong to the family of NP-complete problems that are very difficult to solve.

An FMS system must control the CNC equipment, the material handling equipment, the movement of a part within the system, and information on the system's performance. The tasks of the software control system are:

- System data acquisition
- System data storage and retrieval
- System data interpretation
- System status determination and interpretation
- Decision making
- Decision implementation.

There are three levels of control. The first level communicates directly with the process and involves most process control tasks. The second level supervises the first level, makes tactical decisions, communicates with the first level, acquires and manages system data using a local database, determines the status of system decisions and makes and implements those decisions. The third level of control exercises indirect control, makes strategic decisions and maintains a complete database.

An FMS increases the flexibility and productivity of discrete part manufacturing. This technology is not only becoming more complex to control, but also presents a number of decision problems. The environment of a FMS is completely different from that of a conventional job shop. This new environment provides new capabilities but imposes new constraints on the scheduling function, which should be adapted accordingly. In FMS the hardware and the layout provides flexibility in manufacturing by allowing parts to be transferred automatically, rapidly and without delay, from one machine to another. The machines do not require setup time and thus one can switch from one part to another with minimum loss of time. The utilization of the hardware flexibility, however, depends on the software used and its flexibility. Improper software might cause (and it happened in some FMS installations) overload on some machines, underemployment of machines not having the proper tooling to carry out the job and high in-process inventory, thus machine utilization is low, the automatic transfer system is overcrowded and overall efficiency is low.

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3.4.2 Flexible Manufacturing Cell—FMC

The drawbacks of an FMS system, as previously listed, and the high investment required to construct the system, have led to the proposal of a simpler and less sophisticated system.

The objective of a flexible manufacturing cell (FMC) is the same as that of an FMS, i.e., to produce medium to low quantities of items with the efficiency of mass production. An FMC may also be defined as a computer-controlled configuration of cells into a single ***machining center*** with added transfer mechanisms and buffers to move items, unload the processed item, load a new item and insert the routing commands for the purpose of processing.

Production planning andscheduling for an FMC is done externally. In most FMC installations, the planned items to be processed in the coming shift are fixed onto pallets at a station set apart from the machines. The pallets are set on a loop layout conveyor (or the material handling system) according to the planned schedule. Whenever the machine finishes processing an item, the item is driven out of the machine onto the automatic workpiece loading/unloading station, and from there onto the finished items tray (or conveyor), whereupon it is eventually removed from the pallet. The loop layout conveyor advances until it brings the next pallet (item) in front of the automatic workpiece loading/unloading station. The pallet (item) is set in the machine and its processing instructions are loaded into the machine's control computer.

It is assumed that the loop layout conveyor will be long enough to hold the number of pallets required to serve the machine with work for an entire night's shift. Thus, a workman would be able to set sufficient pallets during his workday, and then start the FMC to work unattended, close the plant and go home.

Next morning, the workman will collect the finished items, prepare jobs for the next shift and perform his regular duties.

3.4.3 Unmanned Factory—The Factory of the Future

The 1980s were an innovative decade: machining centers; industrial robots; automatic warehouses; automated guided vehicles; all were introduced in this period, capturing the imagination of engineers. The idea was that, if a flexible manufacturing cell could be constructed comprised of one machine or one cell, why not multiply it and have an automatic factory, or whatever one moght chose to call it: an unmanned factory, the factory of the future, manufacturing excellence, etc.

In 1980, Mikell P. Groover wrote a paper for the Journal of Industrial Engineering entitled ‘Automated Factories in the Year 2000,’ in which he speculated as to where the innovation might take industry in the years to come. I thought it would be interesting and thought-provoking to revisit his speculation, given what we know now.

3.4.3.1 Automated Factories in the Year 2000[4]

If you attempt to analyze the current technological trends in manufacturing, and to forecast the future social, economic and political environment in which manufacturing will take place, it is possible to construct a vision of the modern automated factory of the year 2000.

There is no doubt that some plants in the year 2000 will have changed very little during the preceding two decades, just as there are plants today in 1980 which have changed little since 1960. The most highly automated factories at the beginning of the next century are likely to be owned by large, financially resourceful corporations. The smaller companies will find it more difficult to achieve the same level of automation because of the high investment cost of this technology.

The level of automation in the factory of the future will also depend on the type of production performed. There are four types of production which we can distinguish for our purposes:

- Continuous flow process-continuous chemical process plants, oil refineries, etc., where the same product is produced continuously.
- Mass production of discrete products-automobiles, appliances and engine blocks. Large volume means the production facilities are dedicated to one product (with perhaps limited model variations).

[4]The material in this section has been adapted from the paper “Automated Factories in the Year 2000” by Mikell P. Groover, in the Journal of Industrial Engineering, November 1980, Volume 12, Number 11, pp. 34, 40, 42–43.

- Batch production—the manufacture of medium lot sizes of the same product. The lots may be produced only once or repeated periodically.
- Job shop production-this is characterized by its low volume. Lot sizes are small. Sometimes only one of a kind is produced.

In the case of the continuous flow processes of today, the automated plant is more the rule than the exception. As we move down the list, it becomes increasingly difficult to economically justify and technologically achieve the fully automated factory.

Difficulty in Forecasting

The most difficult area in which to forecast the future is the social, economic and political environment. Yet this environment may have an important influence on the future factory. If current trends are projected into the future, the following conditions will be manifest at the turn of the next century. (We have limited the conditions to those that are likely to have an influence on manufacturing plants.)

- Gasoline will be in shorter supply than today. That which is available will cost more. Energy in all its forms (electricity, heating, etc.) will be more costly.
- The scarcity of natural resources and raw materials will be an ever increasing problem.
- A decreasing number of people will be entering the labor force in manufacturing. Those who do will demand more challenging and interesting work.
- Computers, telecommunications and associated technologies will have a growing impact on society and the economy.
- The need to increase productivity in manufacturing will continue to be important.

These factors will no doubt have an effect on the design and operation of the future factory.

Future Automated Factory

Now that we have reviewed the current status and future trends in manufacturing technology and computer applications, let us attempt to synthesize a verbal sketch of the automated factory in the year 2000. This description will apply mostly to mass production and batch production plants, but some aspects will also apply to job shop operations as well.

The future automated factory will be comparable in many ways to the highly integrated and computer-controlled plant currently used for continuous flow processes (chemicals, petroleum refineries, etc.).

A relatively small crew will manage and maintain the plant, but will not participate directly in the manufacturing operations. The same functions of processing, assembly, inspection, material handling and storage will have to be accomplished. The performance of these functions with little or no human intervention will be made possible by the data handling, decision-making and control capabilities of integrated computer systems. These computers will coordinate and control the activities of factories in which automated machine tools will be interconnected by automatic material handling systems, delivering parts to and from automated storage and retrieval systems.

In the future factory, the specifications for components and products will be contained in digital coded form within the memory banks of the company's central computer system. It will be possible either to view the geometry of the product by means of graphical CRT displays, or to obtain a hard copy reproduction of the design if needed. However, this will be unnecessary in most cases, because the departments which traditionally use these drawings (process planning, purchasing, production shop scheduling, expediting, etc.) will have been largely computer automated to speed the information flow.

In the case of batch production and job shops which receive job orders from outside customers, the orders and job specifications (part geometries, material specifications, etc.) will be transmitted via low cost telecommunications systems to the company's computer system. In the case of the plant's proprietary products, the designs for these products and their components will be developed by means of highly sophisticated interactive graphics CAD systems. The results of the CAD work will become part of the plant's computerized design/manufacturing data base.

Automatic Assembly

By the year 2000, assembly technology will have advanced, perhaps significantly. Automatic assembly machines will be much more prevalent than today. These machines will tend to be modular in construction and programmable, and the upper size limit on the machines will have increased to accommodate larger work parts and assemblies. Industrial robots will be used as components in these automated assembly systems. Product design practices will have developed and been standardized to promote and facilitate assembly by automatic means.

On completion of assembly, the product will be transferred either back to the AS/RS or to the shipping department, depending on the scheduled delivery date. During the processing and assembly of the products, inspection and testing will be performed by computer directed

inspection stations integrated with the workstations. These inspection stations will use sophisticated technologies to accomplish their tasks. Visual sensors, lasers, tactile sensing probes and other techniques will be used to 100% inspect the products accurately and quickly. When workpiece deviations are discovered, feedback data will be used to adjust the process and correct the defects.

The future factory in the year 2000 will still require human workers. However, the nature and distribution of factory work will have changed. Manual tasks such as parts handling, inspection and machine tending will be eliminated or reduced for mass and batch production shops. For job shops, humans will still perform these types of functions in 2000, but the individual workstations will be more fully automated. The use of NC (CNC and DNC) will be greater in the job shop than it is today.

The general level of human work will be upgraded from tedious manual tasks to duties requiring more skill, training and intellect. These duties will include production supervision, maintenance and repair, and programming and operating the computer systems. The content of these jobs will have changed by the year 2000. Production management will not involve the same level or type of personnel supervision as required today. The technical level of this supervision will be greater.

Maintenance will have become significantly more important in the future automated factory than it is today. In order for the automated plant to be economically feasible, it is essential that the equipment be kept running as much as possible. Data files on equipment breakdowns and repairs will help to guide preventive maintenance schedules.

Computerized diagnostic routines will be used to help identify the problem when a machine breaks down. Some machines will be equipped with their own diagnostic packages. It is likely that machines of the future will be equipped with more redundant features than today so that their reliability will be increased. Data on minor machine malfunctions will be automatically collected by the computer, so that optimal preventive maintenance schedules can be determined. In many cases, it will be possible to anticipate future failures of the machine tool from the malfunction data, so that machine components can be replaced before actual break down occurs.

The procedures used to program and operate the computer will have changed by the year 2000. Voice programming, optical scanning for data input and/or other advanced technologies will be employed.

IE Practices

The practice of industrial and manufacturing engineering may be somewhat different in the automated factory of the future. Work measurement practices will change. With the shift of human labor a way from direct participation in manufacturing operations, time study and other work measurement techniques for cyclical tasks will be used less frequently. Work measurement and performance evaluation will tend to emphasize indirect labor.

The need for manufacturing engineers to plan the production process will be reduced with the widespread use of CAPP systems. The future jobs of industrial engineers and manufacturing engineers will probably involve more automated methods studies and associated economic analyses, more development of computer systems and more microprocessor design applications. [This section speaks of the year 2000 as if it were still in the future.]

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3.4.3.2 CIM as a Basis for the Factory of the Future[5]

Today, throughout the world, manufacturing is being subjected to major economic and social pressures which can only be satisfied through major advances in manufacturing productivity and quality. Fortunately, there are also strong technological resources emerging today which have the potential to provide such major advances. These resources derive from the emerging technology known as computer-integrated manufacturing (CIM). This technology, taken together with today's long-term economic and social pressures, is clearly shaping the factory of the future. In this section, we first define the nature and potential of CIM. We then evaluate it by combining the results of a survey of the members of the CIRP Scientific Technical Committee on Optimization with information derived both from recent literature and from the author's personal observations of the development of CIM throughout the world. The resulting appraisal reveals that, although implementation of CIM is still in its infancy, even at this early stage, tremendous economic benefits are being reaped from implementation of this technology. In addition, its potential for further benefit, both economic and social, is quite considerable indeed.

[5]The material in this section has been adapted from the paper "CIM as a basis for the Factory of the future" by M. Eugene Merchent, published at the International Conference on the Factory of the Future, at the Tel-Aviv Convention Center, November 4–7, 1984, pp. 193–212, No copyright and claims. Public Domain permission.

Future Prospects

What lies ahead in the development and implementation of CIM and the factory of the future? The members of CIRP expect growth of the different elements of the CIM system, and its integration, over the next five to ten years. Moreover, they expect the ultimate potential of CIM to improve the performance of manufacturing in the future. These expectations, however, do not specifically treat the question of the impact of emerging technologies on CIM, or the question of the likely overall characteristics of the future factory. Let us therefore make a few observations on each of these two topics.

Robotics and Artificial Intelligence

Of the various emerging technologies evident today, it appears that at least two are destined to have further significant impact on the system of computer-integrated manufacturing. These are robotics and artificial intelligence (AI).

Robotics is, of course, the more mature of these two emerging technologies and has already had a salient impact on manufacturing. Although, in the broadest sense of the term, robotics is already becoming a feature of such shop-floor systems as unattended manufacturing cells, as yet, the emphasis has still been primarily on dealing with robotic devices, and particularly with industrial robots as such, as stand-alone units. While such application of this emerging technology has already made important contributions to improving productivity and quality in manufacturing, it does little more than scratch the surface of its potential. Instead, robotic devices must be dealt with as yet another useful component of the CIM system, and emphasis shifted toward integrating them fully into that system. Only as that is done will the full potential of robotics for improving the performance of manufacturing be realized.

While the future impact of robotics on manufacturing will still be significant, the emerging technology which promises by far to have the greatest impact on it in the long term is artificial intelligence. This is because the system of manufacturing (despite the best efforts of the engineering profession to arrive at fully deterministic methodologies) can never be a completely deterministic system. Included in the reasons for this is the fact that the system must always interface with nondeterministic elements of the real world. These include human beings, who are often far from logical or free of error in their performance, and the economic, social, and political systems of the world, with all their vagaries. Furthermore, even within a given manufacturing company, the process will involve such an overwhelming welter of variables, parameters, interactions, activities, flows of material and information, etc., that unless a detailed, explicit algorithm is made available for each solution to the problems of each procedure, all the facts, mathematical relations, and models available in perfect arrangement and complete form for a deterministic (and unique) answer can never be found.

What realization of the full potential of CIM requires is intelligent manufacturing systems "capable of solving, within certain limits, unprecedented, unforeseen problems on the basis even of incomplete and imprecise information." Before that potential can be significantly realized, the technology of artificial intelligence must advance considerably in terms of capability in order to be able to carry out the kinds of inference and even intuition which persons now use to overcome the problems that arise from the nondeterministic nature of the overall manufacturing system. As AI technology advances, however, the manufacturing engineer must be quick to integrate that capability into the computer-integrated manufacturing system to reap the exciting possibilities for further dramatic improvement of manufacturing productivity and quality which that technology holds.

Technological Vignette of the Future Factory

What, then, might the CIM factory of the future ultimately be like? Even though it is surely not possible to give a definitive answer to this question, the potential power of the technology is already sufficiently clear to permit a glimpse into the future factory. This technological vignette might play out somewhat as follows.

The process of designing a product will be carried out by iterative communication between the designer and a computer. The designer will supply the design concepts and requirements and do the creative work. The computer will supply standardized and other stored information and perform the design calculations. During this design process, the computer will constantly retrieve and evaluate information on the manufacturing costs and capabilities of the equipment and processes required to produce each of the alternative features conceived by the designer. The computer will then use that information to find a design which not only satisfies the product requirements but can also be produced at optimum cost and reducibility.

Almost simultaneously, the production planning part of the system will use this information to set up an optimized production plan by choosing the proper equipment and processes, sequence of operations, operating conditions, etc., for producing the product. This numerical information will, in turn, be used to control the array of automatic machines and equipment which will actually produce the parts and assemble the product. These machines and equipment will be capable of setting themselves up automatically, handling parts, selecting their own tooling, and carrying out a variety of fabrication processes (removal, forming, and consolidative), including assembly of the product. These machines will be self-optimizing, because they will feed information back to the control system. This system, as it constantly receives information about the actual performance of the equipment and processes, will compare this with the "ideal" performance planned in the earlier phase. When it finds performance beginning to depart from the planned optimum, it will override the original plan, perform dynamic scheduling, and adjust operating conditions of the machines and processes, etc., as necessary to maintain optimum performance at minimum cost.

Meanwhile, the machines and equipment will carry on self-diagnosis of their condition. Where an impending malfunction is detected, they will carry out appropriate corrective action, including automatic replacement of defective modules in the system. Furthermore, the machines will also carry out automatic real-time, in-process inspection of the product throughout each stage of its production so that any impending deviations from the original specifications are automatically corrected and held within prescribed tolerances. Thus, the final assembled product will be completed with full inspection and in full conformity with the original design concepts and requirements.[18-24]

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3.4.3.3 Conclusions

As stated at the beginning of this chapter, the remarkable contributions to manufacturing flexibility that the technology of computerized machines has made to the area of hardware has been regrettably undercut by its lack of contribution to the area of software. This is the primary obstacle to the achievement of complete system flexibility,

The vision of the automatic factory consists of FMS machines, controlled transfer lines, or industrial robots. Direct control over any device in the plant is possible through a hierarchical computer network. The network links the main central processor to the individual microprocessor controlling a single device. Process and load optimization are carried out by the central computer. 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 the machining center (transfer time table), the same chucking and gripping as the production line (handling time table), and the same increased flexibility as the work cell. Thus, by assigning the appropriate values to the relevant table, the system can be used in decision-making concerning the automatic factory.

The automatic factory, the abiding technological forecast for the future, would be a computer-integratedmanufacturing system that controls all phases of the industrial enterprise: process planning, flow of materials, production planning, positioning of materials, automatic production, assembly and testing, automatic warehousing, and shipping.

Technology predicts that the unmanned factory, functioning, as it would, without humans, would not need light, air conditioning, or even windows.

Unfortunately, this forecast has yet to occur; the cynic says that "the factory of the future is always in the future". Is this really so?

In the 1990s, the idea became revitalized and then faded away again. The cynic's maxim prevailed.

However, in 2014, it resurfaced as a hot topic. And thus, the question remains open.

Chapter 4
Integrated Manufacturing Systems

Abstract This chapter describes the development of the manufacturing process since the mid-1960s when management turned to a more scientific approach. The introduction of computers found ready ground for their implementation. Computers enabled the use of complex algorithms to regulate and control the manufacturing process, and thereby introduced better planning and control. These manufacturing control systems dominated the industry up until the early 80s. The dominant methods and concepts were: Management Information System (MIS); Production and Inventory Control Systems (PICS); Material Requirement Planning (MRP); and Computer Integrated Manufacturing (CIM). The fact that these systems could not deliver the required control and benefits created a need for a new paradigm for manufacturing methods. In addition, the competitive market of the late 1980s and early 1990s imposed new demands and objectives on the manufacturing process that required a similar paradigm. More than 140 proposals were presented, none of which became "the" manufacturing method. Most of them made use of "routine," which makes the system complex and does not satisfy the cost control needs of the system.

4.1 Introduction

The manufacturing process is a chain of activities aimed at meeting a set of objectives defined by management. These objectives, which are set, in tandem with management, by such non-engineering functions of the organization as sales, marketing and finance, could be:

- To develop and produce products
- To produce parts or products designed by the customer
- To reproduce items that have been manufactured in the past.

G. Halevi, *Expectations and Disappointments of Industrial Innovations*,
Lecture Notes in Management and Industrial Engineering,
DOI 10.1007/978-3-319-50702-6_4

The manufacturing environment can differ with respect to:

- Size of plant
- Type of industry
- Type of production (mass production, job shop, etc.)

However, the fundamental principles of the manufacturing process are the same for all manufacturing concerns, and thus, a general cycle can be formulated. Since each type of production is subject to different specific problems, the emphasis on any particular phase of the cycle will vary accordingly. For example, in mass production (in which products are manufactured in very large quantities, usually on automatic lines) or continuous-type production (in which production is conducted on flow lines), emphasis should be placed on process planning methods. Auxiliary production aids, such as special tools and machinery, jigs and fixtures, and automatic inspection devices, should be designed and used. On the other hand, material requirement planning and scheduling usually need not be very sophisticated, since the rate of production is limited or fixed by the initial design.

In production of the large-scale job-shop type, in which many orders are produced in small quantities, sharing the same resources, emphasis should be placed on scheduling: as a rule, there is not much sense in developing auxiliary production aids or in devoting too much time to methods. Furthermore, in a small-size job-shop specializing in the production of parts designed by customers, the engineering design phase may not be required at all, while in a goods-type industry, the engineering design phase must be emphasized.

Modern production and operation management are relying on science more and more. This trend started with the publication of Taylor's book "Principles of Scientific Management" (1919). At that time, the owner-manager of the business remained separated from the manner in which the production process was carried out. The workers themselves did whatever production planning seemed minimally necessary and determined how to produce based on their skills and experience. In the true spirit of Taylor's scientific management philosophy, there were early formulations of models of operational problems: F.W. Harris formulated the classic EOQ inventory model. W. Shewhart introduced statistical quality control, which not only impacted the field of quality control, but paved the way for the acceptance of probability and statistical concepts in forecasting, inventory control, and many other fields.

The extraordinary impact of computers on operations management has been felt everywhere, including within product-process technology, information systems, decision-making, and control technology; they have even become machine members themselves. For example, linear programming without computers would have had a limited field of application. The program evaluation and review technique/critical path method, simulation, CNC machine, and CAD\CAM systems are all computer-dependent systems. In the future, an "automatic factory" could logically be expected to come about. The technology for product processing is already fairly well in place. What remains is to develop the algorithms and computer programs that integrate decision-making with controls, the merging of managerial technology with product processing technology in a practical operational system.

In order to achieve good performance, the manufacturing process must consider the points of view of many disciplines, including:

- Marketing and Sales
- Customer relations
- Product definition and specifications
- Product design
- Process planning and routing
- Production management: MRP, capacity planning, scheduling, dispatching, etc.
- Shop floor control
- Economics
- Purchasing
- Inventory management and control
- Costs and bookkeeping
- Storage, packing and shipping
- Material handling
- Human resource planning.

Each discipline considers a problem at hand from a different angle. For example:

- Marketing will evaluate the product's appeal to customers
- The product designer will evaluate methods of achieving product functions
- The process will evaluate the required resources
- Finance will evaluate the required investment
- Manpower will consider the work force demands
- The manufacturing engineer will consider floor space and material handling
- Purchasing and shipping will consider how to store the product.

4.1.1 Manufacturing Concepts and Objectives

Manufacturing is but one discipline in the organization of an industrial enterprise, albeit a dominant one, as it controls the daily activities of other disciplines. Management must consider all of the activities in the enterprise. The objects of management are:

- Implementation of the policy adopted by the owners or the board of directors
- Optimum return on investment
- Efficient utilization of manpower, machines, and money.

In other words, industry must make a profit. Therefore, the optimization criteria for management decisions must be cost, capital tied up in production, and profit, which are collectively referred to as the finance criterion.

Scientific management calls for specialization in performing each task of the manufacturing process. Manufacturing and engineering are divided into stages according to the expertise required to perform each function of the manufacturing process. These stages are shown in Fig. 4.1.

The major stages of PICS—a Production Inventory Control System—are described below, with their function and criteria of optimization indicated.

Engineering Design. The purpose of this stage is to transform the objective into a detailed set of engineering ideas, concepts and specifications.

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. 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.

Process planning. This task should be carried out separately for each part, assembly, and subassembly of the product. Process planning's prime **optimization** criterion is to meet the specifications given in the engineering drawings. The secondary criteria are cost and time.

Master production schedule. The master production schedule makes real the manufacturing objectives of quantity and delivery dates for the final product. The decisions in this stage depend either on the forecast or on confirmed orders, and the **optimization** criteria are meeting delivery dates, a minimum level of work-in-process, and plant load balance. These criteria are subject to the constraints of plant capacity and those set in the routing stage.

Material requirement planning (MRP). The purpose of this stage is to plan the manufacturing and purchasing activities necessary to meet the targets set forth by the master production schedule. The decisions are confined to the demand of the master production schedule, and the **optimization** criteria are meeting due dates, a minimum level of inventory and work-in-process, and department load balance.

Capacity planning. The goal here is to transform the manufacturing requirements, as set forth in the MRP stage, into a detailed machine loading plan. This 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 balancing, meeting due dates, a minimum level of work-in-process and manufacturing lead time

However, in the PICS methodology, no stage of the manufacturing process considers finance, economics, and cost as its primary objective. Each stage optimizes its task to the best of its ability. Each stage in the manufacturing cycle, according to its function, has its own objectives and criteria of optimization. Even if each stage functions optimally, this does not necessarily guarantee overall optimum success with respect to management's prime objectives.

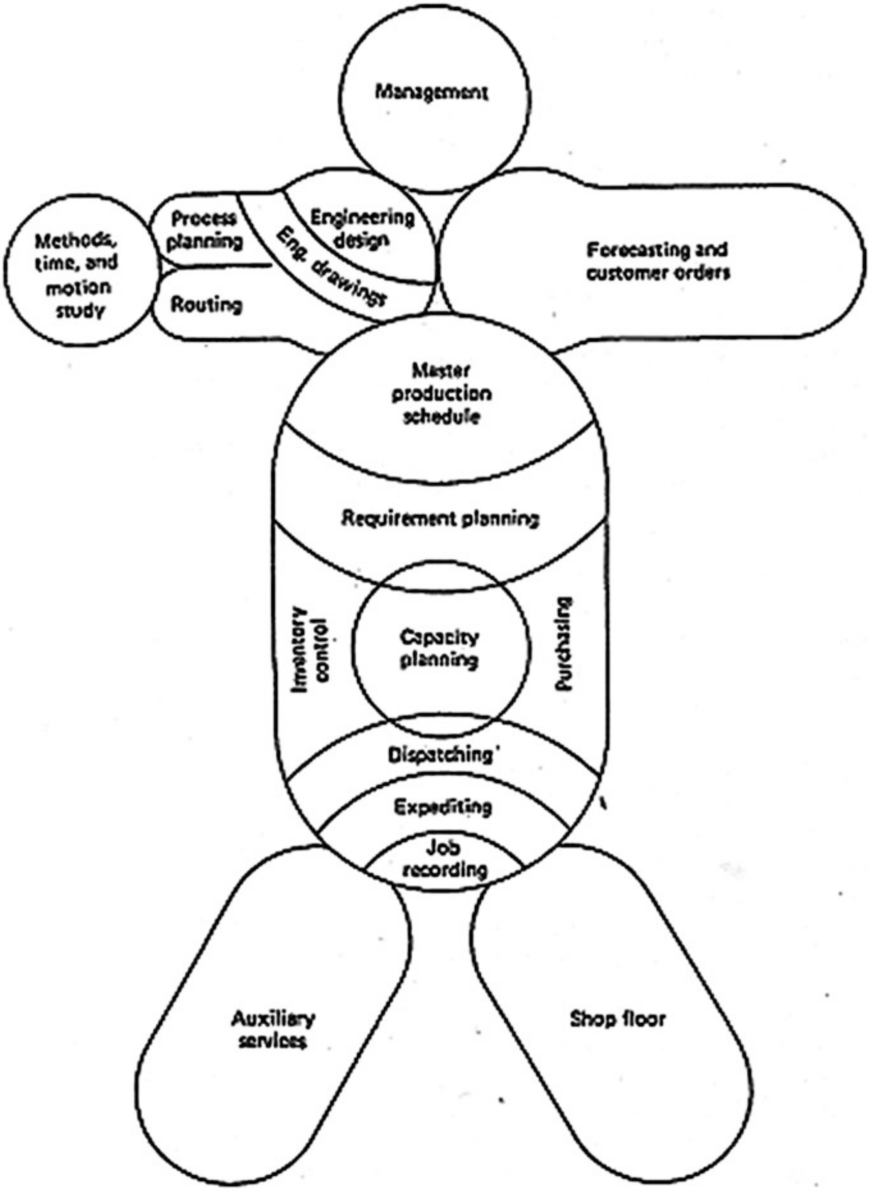

Fig. 4.1 The manufacturing cycle

4.2 Traditional Manufacturing Approach[1]

The PICS approach to the design of manufacturing systems is a hierarchical approach. The design is top-down and strictly defines the system modules and their functionality. Communication between modules is carefully controlled and limited in such a way that modules communicate solely with their parent and child modules. In a hierarchical architecture, modules cannot take initiative; therefore, the system is sensitive to perturbations, and its autonomy and reactivity to disturbances are weak.

The objective of each module is clearly defined and optimized by the system. However, the criteria for optimization are not always synchronized with the overall objective. Local optimization of a single operation does not necessary lead to optimization of the item. Likewise, item optimization does not necessary lead to optimization of the product. Product optimization does not necessary lead to optimization of the product mix, and product mix does not necessary lead to optimization of the business.

Hence, each method solves secondary objectives while ignoring the real task of production scheduling, i.e., to make sure that the orders will be ready on time. Moreover, the planning and execution regards the routing as static and unalterable; as a result, it robs the shop of production flexibility and efficiency with its use of questionable routing in its optimization.

4.2.1 Basic Notions of a Hierarchical Approach

The basic notions of hierarchical approach techniques are:

- The "best" routing for the job should be the one used.
- The "best" routing for maximum production optimization, resulting in the shortest throughput, should be the one used.
- The larger the batch quantity, the better the productivity. Therefore, all orders are considered and divided into their product trees, the quantity of individual items being combined, when possible.
- Job release to the shop floor will assure maximum efficiency and the meeting of delivery dates.

There are, however, arguments that lead one to the conclusion that these notions are, in many cases, incorrect. Let us now look at these arguments.

[1]Based and republished data from:
Halevi G. All Embracing Manufacturing—Roadmap System Springer Nature 2012
Halevi G. International Journal of Innovation and Technology Management, 2004.

4.2.1.1 The "Best" Routing for the Job

Recent research in the field of process planning (CAPP) highlights the fact that routing is an obscure term. There is no such thing as the "best" process. For any given task, there might be many different routings, which differ from one other in processing time and processing cost and objective. Usually, the shorter the processing time, the higher the processing cost.

The term "optimized routing" is somewhat misleading. Routing based on criteria of optimization of maximum production actually means that the time to produce the item, as a standalone, is at a minimum. However, this does not refer to the time elapsed in producing a product or product mix. In many cases, the maximum production routine will result in the longest possible processing time for a product mix. In process planning, there are several levels of optimization:

- Optimization of a single operation
- Optimization of an individual item
- Optimization in producing a product
- Optimization in producing a product mix
- Optimization of factory business.

Each one has different requirements and must consider the elements of production differently, most likely resulting in a different recommended routine.

4.2.1.2 Maximum Production Optimization

Use of the "best" routing for maximum production optimization has been theorized as resulting in the shortest throughput time. But doing so creates an overload on these efficient resources, and thus, in fact, increases the throughput time. Minimum cost routing generally uses old, low-cost, inaccurate resources for rough operations, and accurate, efficient resources for finishing operations. Thus, the processing time increases, but is spread out over several resources, and thus reduces the throughput time and probably the cost.

4.2.1.3 The Larger the Quantity, the Better the Productivity

This notion has the appearance of being logical and reasonable. The larger the batch sizes, the lower the set-up cost and time consumed per single item.

Increasing the quantity increases the processing time, and thus affects the throughput. The logical conclusion might recommend avoiding the increase in quantity by combining items from different orders. However, this conclusion lacks firmness, steadiness and any academic backing. In order to check this hypothesis, simulation techniques were employed by a specially written computer program. The program was composed of three stages:

- Stock allocation (MRP). Considers all orders, the product structure of each order, the order delivery date, and the available inventory.
- Capacity planning (CPS). Considering the working product structure, the delivery date, and flexible routings, the program loads the materials into the available resources, considering the available capacity of each resource. Several options are available in order to evaluate different loading algorithms.
- Release the job to shop floor control (SFC). The early loading periods are transferred to the shop for execution. The algorithm has many scheduling options, in order to evaluate different algorithms.

In this simulation, three orders, each for a quantity of 40 units, are considered; each order is composed of 10 items, in 4 bills of material levels. The number of operations per item ranges from 1 to 7; overall there are 60 operations. There are 15 resources that cover all processes required, made up of the following: milling machines, lathes, drill presses, saws, robots, and mechanical assembly.

The simulation uses five modes of scheduling. In one, all orders are combined to be produced as one batch of 120 units. Another uses two batches of 60 units each, and a third combination produces each order separately. Another simulation examines the case in which the batch sizes are divided into two batches, one of 80 units and the other of 40 units. In this case, the object is to see whether the sequence of loading the asymmetrical batches has an effect on the processing time.

The results are shown in Table 4.1 and refers to the number of periods (1 period = 2 h) that it takes to process the orders.

The simulation as shown in Table 4.1 clearly demonstrates that, regardless of the criteria of optimization used, the number of periods necessary to produce the batch quantity size is reduced.

The results in Table 4.1 also show that scheduling with limited flexibility, using the Cost/Production algorithm, improves throughput time. Furthermore, it shows that the use of the Cost/Production method is superior (in this simulation) to the Production/Cost scheduling method, and that treating each order as a separate unit also reduces throughput time.

The indication that limited flexibility improves the throughput time of producing a product mix led to investigation into the effect of flexible dynamic scheduling.

4.3 Computer Integrated Manufacturing[2]

The integration of computers into three fields of industry—computers as data processors; computers as machine members; and computers as engineering aids—was accepted in short order. However, these integrations were developed as islands

[2]Republished with permission of CRC press LLC from ‘Restructuring the manufacturing process: applying the matrix method'; author, G. Halevi, published in 1999, ISBN 1-57444-121-3 Chapter 1, pages 19–23, permission converted through Copyright Clearance Center, Inc.

Table 4.1 Processing number of periods

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

of automation. The transfer of data and information between one and another was through manual means.

The next step in the development of computer applications in industry was to combine the three separate application fields into one integrated system. This system, and subsequently the era in which it was used, was called computer-integrated manufacturing (CIM), a decision for which there was unanimous agreement. Beyond the name, however, several interpretations exist concerning the meaning and scope of integration. Some examples of these are as follows:

- The goal of integration is not to tie computers together, but rather to tie organizations and their customers together.
- The basic engineering and manufacturing functions must all be encompassed in one operative system.
- CIM integrates all data-processing functions within the company.
- An important role of computer integration is to move functions closer together, not so much in terms of physical distance but rather in the completeness and timeliness of information flow.
- The goal of CIM is to improve product flow.
- Effort is made to focus on executing rather than revising the plan.
- CIM is a technology that combines all advanced manufacturing technologies into one manufacturing system that is capable of:
  - Rapid response to manufacturing and market demands
  - Batch processing with the efficiency of mass production
  - Mass production with the flexibility of batch production
  - Reducing manufacturing costs.

The change from the integrated manufacturing system (IMS) era (which was the leading technology from the 1960s to the early 1970s) to the CIM era can be appreciated by comparing the architecture of the system, represented here as a wheel.

Figure 4.2 shows an example of CIM architecture as proposed by the U.S. Air Force ICAM program (circa 1970s). As indicated, one circle incorporates group technology and simulation models, and design application is added to the outside circle. Yet, the central circle is the database.

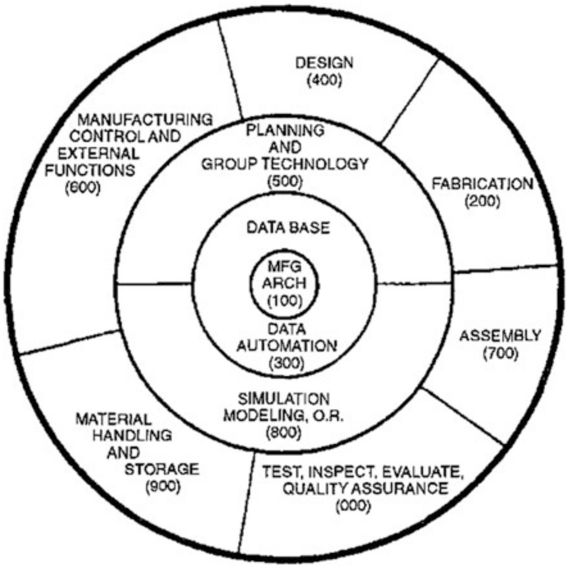

Fig. 4.2 ICAM proposal for CIM architecture

Figure 4.3 shows the Computer and Automated Systems Association of the Society of Manufacturing Engineers (CASA/SME) architecture, also in the form of a wheel (circa 1980s): "The wheel expresses our belief that Computer Integrated Manufacturing encompasses the total manufacturing enterprise. Therefore, the outer ring of the wheel includes marketing, finance, strategic planning and human resource management."

Figure 4.4 shows an example of CIM architecture from the IPA (Institute of Manufacturing Engineering and Automation), Stuttgart, Germany (circa 1980s): "The plurality of goal conflicts which come up in the production field shows that the competitiveness of an enterprise cannot be fully guaranteed if solutions are used which cover only part of the whole production system. All sections of an enterprise which are directly or indirectly involved in the production process have to be optimized all the time."

Figure 4.5 shows an example of CASA/SME architecture in the form of a wheel (1993). In this wheel, technology is replaced at the centre by the customer, people, organization, and teamwork. Besides manufacturing, disciplines such as customer service, suppliers, and ethical, environmental, and life cycle considerations are added.

Implementation of ClM requires knowledge, research and development in several disciplines:

- Communication between computers, terminals, and machines
- Computer science for solving data storage and processing problems
- Computer-operated resources, such as CNC, robots, automatic guided vehicles, etc.

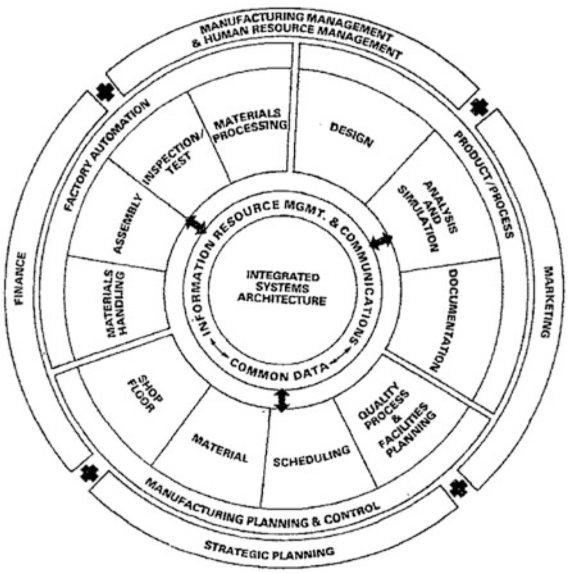

Fig. 4.3 CIM wheel developed by the Technical Council of the Computer and Automated Systems Association of SME (CASE/SME)

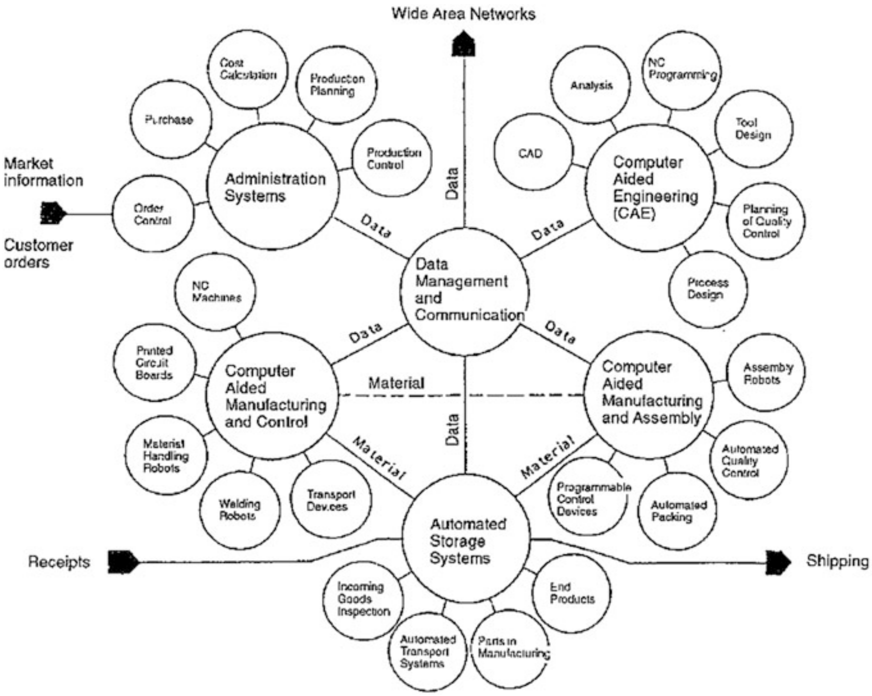

Fig. 4.4 CIM IPA architecture

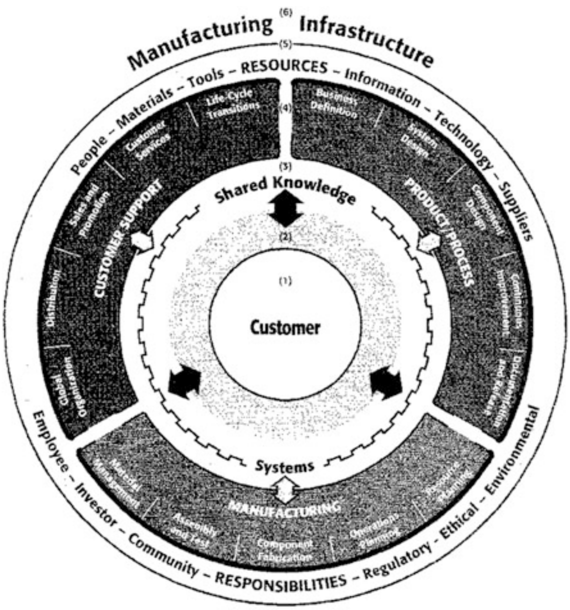

Fig. 4.5 1993 CASA wheel (CASA/SME)

- Algorithms and methodology in the field of basic engineering and production management.

The need for advanced technologies in these disciplines brought many researchers to concentrate on these topics, and significant progress was made.

4.4 Overview of Manufacturing Proposal Methods

The fact that CIM could not deliver the required control and benefits created a need for a new paradigm for manufacturing methods. In addition, the competitive market of the late 1980s and early 1990s imposed new demands and objectives on the manufacturing process that also called for a new paradigm. The new demands were:

- Short time to market
- Product diversity and options
- Quality products
- Customer satisfaction and customer appeal
- Naturally competitive price.

The addition of the above market demands resulted in substantial rethinking of the initial CIM system concept. This lead to the realization that the initial CIM system concept needed to be broadened beyond one which primarily encompasses the technological operation of an enterprise. It should be extended to one that encompasses both the technological and managerial operations of an enterprise as an integrated manufacturing operation.

From the late 80s up to the late 90s, there was tremendous advancement in the field of computer science. The technological problems that inhibited the success of CIM were solved. Communication between computers, terminals and machines became common practice. Database capacity grew tremendously, while storage and retrieval time shortened. Using computers as machine members is now taken for granted and most processing resources are computerized.

However, there has been no corresponding breakthrough in the development of algorithms and methodology in the field of basic engineering and production management. Developing algorithms for management methods, as well as for processing in different fields, will take much time and large-scale effort to accomplish. Research and development in this area, despite the considerable need, have been irksome. Industry needs solutions and methods without the long wait required for algorithms to be developed. Unfortunately, serious research has been neglected under the excuse that manufacturing and processing do not represent a completely deterministic system. The effective operation of such a system therefore requires use of logic, but also inference, intuition and experience. Hence, developing management and processing methods has become a topic for the disciplines of artificial intelligence, expert systems and computer science.

As a result of the need for a new management method, a new competitive arena emerged, a competition to create new manufacturing methods, and get recognition for having done so.

This competition brought over 130 proposals for manufacturing methods. Some of the most famous ones were: ERP, Concurrent Engineering, Total Quality Management (TQM), Business Process Modeling, World Class Manufacturing, Agile manufacturing, Lean manufacturing, Bionic manufacturing, virtual manufacturing, Mission statements, etc.

Some of the proposed methods were of a technological nature, while others were organizational and architectural, and yet others focused on information technology. Some were aimed at lead-time reduction, others at inventory reduction, and yet others on customer satisfaction or organizational and architectural needs. In some methods, environmental issues are becoming dominant, (environmentally conscious manufacturing), while others focus on respect for people (workers) as the vehicle that will promote a journey of continual improvement (indeed, many of the proposed methods are based on human task groups).

Some of the proposed management methods are computerized versions of the previous manual methods, for example, flexible manufacturing systems (FMS) are a computerized version of the work cell of the group technology method. Enterprise resource planning reminds us very much of the CIM version. The difference between the new computerized methods and the previous methods is that the technology and engineering which were the basis of the previous methods have disappeared and been replaced by expert system know-how. The new methods are based on teamwork and computer programs that provide services for storing, retrieving, computation, and simulation. Human beings were made the centerpiece of the architecture of the system because of the fact that they must be the overall driving force, as well as controllers, of the functions to be performed in the plant, representing, therefore, a human, and not automatic, algorithm, i.e., leaving the basic technology and engineering data to be supplied by the human user, as well as letting the user make logical decisions. Most of the proposed methods emphasize the need for each discipline of the manufacturing process to consider the objectives and problems of other disciplines. However, each method is mainly directed to respond to the needs of a specific discipline.

The flood of proposals, in which each one is directed toward the needs of a different discipline, makes it difficult to decide which method is the best for the specific manufacturing enterprise. Moreover, in the 60s and 70s, there were only a few methods to select from. The life cycle of a manufacturing method tended to span several years, with the shortest life cycles being seen in the 90s. For example, Total Quality Management (TQM) was a hit in 1994, with billions of dollars being spent for its installation. Toward 1997, a new paradigm took its place: enterprise resource planning (ERP) became the new fashion. And again, billions of dollars were spent to install it. By 1998, enterprise resource management (ERM) had either replaced or enhanced ERP. And by 1999, a competition between customer relation management (CRM) and supply chain management had broken out.

In the next section, a list of proposed methods will be introduced, mapped according to the activities they aimed to improve, such as: reducing inventory; reducing lead time and time to market, improving communications, etc. Through this categorization, managers will be able to select the method that is most suited to their organizations.

4.4.1 List of Manufacturing Methods

This list includes 126 manufacturing methods, set out in alphabetical order. A detailed description of certain methods is given in Sect. 4.1.1, including an extended bibliography:

1. Activity-based costing (ABC)
2. Advanced material requirements planning
3. Advanced technologies for scheduling
4. Agent-driven approach
5. Agile Manufacturing
6. All Embracing Technology
7. Artificial Intelligence (AI)
8. Autonomous Enterprise
9. Autonomous production cells (APE)
10. Autonomous Scheduling and Planning
11. Benchmarking

12. Bionic manufacturing system
13. Borderless Corporation
14. Business intelligence and data warehousing
15. Business Process Re-engineering (BPR)
16. CAD/CAM
17. Cellular manufacturing
18. Client/Server Architecture
19. CNC
20. Collaborative Manufacturing in Virtual Enterprises
21. Common-sense manufacturing (CSM)
22. Competitive edge
23. Competitive intelligence (CI)
24. Computer Aided Process Planning (CAPP)
25. Computer Integrated Manufacturing (CIM)
26. Concurrent Engineering (CE)
27. Constant work in process (CONWIP)
28. Cooperative manufacturing
29. Computer Oriented PICS (COPICS)
30. Core competence
31. Cost Estimation
32. Cross-functional leadership
33. Customer relationship management (CRM)
34. Customer retention
35. Cycle Time Management (CTM)
36. Demand chain management
37. Customer Retention
38. Digital factory
39. Drum Buffer Rope (DBR)
40. E-Business
41. E-Manufacturing (F2B2C)
42. Ecological Manufacturing
43. Electronic commerce
44. Electronic data interchange (EDI)
45. Electronic document management (EDM)
46. Enterprise Resource Planning (ERP)
47. Environmentally Conscious Manufacturing (ECM)
48. Executive Excellence
49. Expert Systems
50. Extended enterprise
51. Factory of the future
52. Factory Simulation
53. Flat organization
54. Flexible manufacturing system (FMS)

55. Fractal manufacturing system
56. Fuzzy logic
57. Genetic manufacturing system
58. Global manufacturing network (GMN)
59. Global manufacturing system
60. Group Technology
61. Holonic manufacturing systems (HMS)
62. Horizontal organization
63. House of Quality (HOQ)
64. Human resource management (HRM)
65. Intelligent CIM
66. Intelligent Manufacturing System (IMS)
67. Just in Time manufacturing (JIT)
68. Kaizen Blitz
69. Kanban system
70. Knowledge management
71. Lean manufacturing
72. Life cycle assessment (LCA)
73. Life cycle management
74. Life cycle product design
75. Management of Autonomous Distributed Production
76. Manufacturing enterprise wheel
77. Manufacturing excellence
78. Manufacturing execution system (MES)
79. Master product design
80. Master Production Scheduling
81. Material requirements planning (MRP)
82. Material resource planning (MRPII)
83. Matrix shop floor control
84. Mission statement
85. Mobile agent system
86. Multi-agent manufacturing system
87. One-of-a-Kind Manufacturing (OKM)
88. Optimized production technology (OPT)
89. Outsourcing
90. Partnerships
91. Performance measurement system
92. Product data management (PDM and PDMII)
93. Product life-cycle management
94. Production-information and control system (PICS)
95. Quality Function Deployment (QFD)
96. Quality Information Systems
97. Random manufacturing system

98. Reactive scheduling
99. Re-Engineering
100. Robotic Manufacturing
101. Scenario models
102. Scientific methods for Managing Complexity
103. Self-organizing manufacturing methods
104. Seven paths to growth
105. Simultaneous Engineering (SE)
106. Single-Minute Exchange of Dies (SMED)
107. Statistical Process Control (SPC)
108. Strategic Sourcing
109. System dynamics
110. Supply chain management
111. Taguchi method
112. Team performance measuring and managing
113. Theory of Constraint (TOC)
114. Time-based competition (TBS)
115. Total Quality Management (TQM)
116. Value chain analysis
117. Value Engineering
118. Virtual Company
119. Virtual enterprises
120. Virtual Manufacturing
121. Virtual product development management (VPDM)
122. Virtual reality for design and manufacturing
123. Virtual reality
124. Waste management and recycling
125. Workflow management
126. World Class Manufacturing

4.4.2 Detailed Descriptions of Certain Methods

4.4.2.1 JIT—Just in Time Manufacturing[3]

Just-in-Time is a system approach to developing and operating manufacturing systems. Many companies have the opportunity to significantly improve their overall manufacturing performance by taking a total system viewpoint and integrating optimization procedures and processes for the purpose of preventing waste

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and inefficiency. The positive results of this effort are a reduction in overall cost of manufacturing and an improvement in company profits through reduction or elimination of specific types of overhead, the area most affected by following a total system integration approach. The reduction of overhead will improve profitability in a minimum amount of time and at the lowest cost. The areas of overhead that will be most affected by following a total system integration approach involve functions and processes that have developed to address system-related manufacturing problems. Many of these functions and processes do not add value to the product; they exist only to compensate for inadequacies in certain parts of the manufacturing system. Eliminating unproductive overhead can be achieved by identifying and removing the system inadequacies that necessitate overall expense.

The term JIT is meant to convey the idea that the three major elements of manufacturing—Capital, Equipment and Labor—will be made available only in the amount required and at the time required to do the job.

JIT management achieves the goal of having a competitive edge through the use of three simple management tools:

1. Integration and optimization. Reducing the need for unnecessary functions and systems such as: inspection reworks loops and inventory.
2. Continuous improvement. Developing internal systems that encourage constant improvement in processes and procedures.
3. Understanding the customer. Meeting the customer's needs and reducing the customer's overall cost of purchasing and use of a product.

The philosophy of JIT manufacturing is centered on the operation of a simple and efficient manufacturing system capable of optimizing the use of manufacturing resources such as capital, equipment and labor. This results in the development of a production system capable of meeting a customer's quality and delivery demands at the lowest manufacturing price.

The goal of JIT is to eliminate any function in the manufacturing system that burdens the company with overhead, impedes productivity, or adds unnecessary expense to the customer's operating system.

The five basic principles in developing a JIT system are:

1. Each worker or work unit is both a customer and a supplier.
2. Customers and suppliers are an extension of the manufacturing process.
3. The path of simplicity must be sought continuously.
4. It is more important to prevent problems than to solve them.
5. Items must only be obtained or produced when they are specifically needed (just in time).

Simply put, JIT is about having only that which is needed only when it is needed.

The five basic goals associated with a JIT manufacturingsystem are:

1. Designing for optimum quality/cost and ease of manufacturing.
2. Minimizing the amount of resources expanded in designing and manufacturing a product.
3. Understanding and being responsive to the customer's needs.
4. Developing trust and opening relationships with suppliers and customers.
5. Developing a commitment to improving the total manufacturing system.

The biggest misconception about JIT is that it is an inventory control system. Although structuring a system for JIT will control inventory, it is not its major function.

The direct cost savings from a JIT materials system are significant in terms of reducing purchasing, receiving, inspection and stockroom cost. The savings from these functions alone could be in the range of 30–50% of aggregate operational costs. Material-related costs are reduced in a JIT system through several means:

1. Reducing the number of suppliers with which the company deals.
2. Developing long-term contracts.
3. Eliminating expediting.
4. Reducing order scheduling.
5. Obtaining better unit pricing.
6. Eliminating the need to count individual parts.
7. Simplifying the receiving system.
8. Eliminating receiving inspection.
9. Eliminating most unpacking.
10. Eliminating the breaking down of large material lots.
11. Eliminating the stocking of inventory.
12. Eliminating excess material spoilage.

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4.4.2.2 TQM—Total Quality Management[4]

The main goal of total quality management (TQM) is to satisfy the customer. Total quality management is not only concerned with the final customer who wants to buy a product without defects. The product and the customer are understood in a wider sense than is normally the case in manufacturing:

- Products include goods and services.
- Customers can be internal or external. No part of a company's operation is omitted from this definition.

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- A customer does more than simply take delivery of the goods purchased; the added experience of services offered, such as telephone calls, presentation, and invoices, also influences customer satisfaction.

Customer satisfaction leads to sales and cash flow. To turn cash flow into profit, quality costs have to be minimized. Inspection is not the way to improve quality while cutting quality costs. Control and monitoring of the manufacturing process can save extra costs in regard to inspection, rework, and scrap. TQM is an approach to business whereby a company is determined to achieve a level of quality that is more than simply acceptable and which is subject to continuous improvement, no matter how good it already is.

Sophisticated JIT focuses on manufacturing problems that are within the scope of the work group or cell; however, variability can also be improved outside the work group and exported by the work group. TQM begins with a focus on the customer and meeting the customer's needs. This results in an emphasis on links between work groups, in particular, on the impact that the variability originating in one group has on other groups. Improved communication and feedback between work groups speeds the path to the immediate customer or supplier of the work group without going through the organizational hierarchy. Within the work group, the major activity associated with TQM is the process of continuous improvement. In particular, this means searching for non-value-added activities that can be eliminated. Because the search for improvement opportunities has to involve all members of the work group, it is essential that they be trained in team skills and problem-solving skills, many of which involve approaches similar to those used in other methods.

One of the outstanding gurus of TQM is Dr. W. Edwards Deming. His method consists of 14 points:

1. Create constancy of purpose.
2. Adopt the new philosophy.
3. Cease dependence on inspection.
4. End "lowest tender" contracts.
5. Improve every process.
6. Institute training on the job.
7. Institute leadership.
8. Drive out fear.
9. Break down barriers.
10. Eliminate exhortations.
11. Eliminate arbitrary numerical targets.
12. Permit pride of workmanship.
13. Encourage education.
14. Ensure top management's commitment.

Another guru is Richard J. Schonberger, who lists an "action agenda for manufacturing excellence":

1. Get to know the customer.
2. Cut work in process.
3. Cut flow times.
4. Cut set-up and changeover times.
5. Cut flow distance and space.
6. Increase make/deliver frequency for each required item.
7. Cut the number of suppliers down to a few good ones.
8. Cut the number of parts.
9. Make it easy to manufacture parts without error.
10. Arrange the workplace to eliminate search time.
11. Cross-train workers for mastery of more than one job.
12. Record and retain production, quality, and problem data at the work place.
13. Assure that line people get first crack at problem solving—before the experts.
14. Maintain and improve existing equipment and human workforce before thinking about new equipment.
15. Look for simple, cheap, and movable equipment.
16. Seek to have plural instead of singular workstations, machines, cells, and lines for each product.
17. Automate incrementally, when process variability cannot otherwise be reduced.

Joseph Juran, another guru, identified ten steps for quality improvement:

1. Build awareness of the need and opportunity for improvement.
2. Set goals for improvement.
3. Organize towards achieving goals by establishing a quality council to identify problems, select projects, appoint teams, and designate facilitators.
4. Provide training.
5. Carry out projects to solve problems.
6. Report progress.
7. Give recognition.
8. Communicate results.
9. Keep score.
10. Maintain momentum by making annual improvement part of the regular systems and processes of the company.

Another guru is Philip B. Crosby, who recommends using the following 14 steps:

1. Management commitment
2. Quality improvement team
3. Quality measurement
4. Cost of quality evaluation
5. Quality awareness
6. Corrective action
7. Zero defects planning

8. Supervisor training
9. Zero defects day
10. Goal setting
11. Error-cause removal
12. Recognition
13. Quality councils
14. Do it over again.

Many other gurus have practiced TQM and have proposed methods for its implementation. However, in examining the gurus' recommended methods, one finds agreement among all of them on the following points:

- Change must start with top management.
- The change to TQM is a cultural one.
- Quality is achieved through people.
- Quality involves everyone.
- Quality is not a separate function.
- The change to TQM requires more than simply motivation.
- Education and training are essential for lasting improvements.
- Continuous improvement requires steadfast management.

The culture of a company is the integrating factor for all the behavioral and attitudinal patterns which prevail within it. That culture also determines the quality of its products and services. Therefore, quality improvements demand cultural changes.

The Key requirements of the TQM process are:

- There must be a common understanding of quality and of the need to change.
- Management must develop operating principles and values which create an environment for continuous improvement,
- Management must create organization and provide the resources to support the improvement process.
- Everyone must contribute to the end product or service used by the customer.

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4.4.2.3 Lean Manufacturing[5]

The lean production system, pioneered by Toyota, evolved from the Ford production system. The lean system, however, is based on a strong and inseparable relationship between JIT and TQM, leading to a virtual circle in which quality is a prerequisite of JIT and JIT allows quality to be improved through enhanced control and increased visibility of all productive activities. The lean system is also based on jidoka, which has the dual meaning of automation and autonomous defect control. The underlying concept is automation with “a human mind.” Automation goes hand in hand not only with worker ability, but also with product and process design. The process capability of the lean system is built around and evolves with limited resources. Capabilities are built around work organization and employee skills, external relationships with suppliers, etc.

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Different philosophies and approaches to automation raise questions, such as: What kind of relationship exists between such automation approaches and the lean system? Are the lean system and the automation approaches convergent?

There are four approaches to automation:

1. Low-cost automation.
2. Human-fitting automation.
3. Human-motivating automation.
4. High-technology automation.

An analysis of the different approaches to the lean system must highlight both the problems raised by its adoption and other innovative approaches to using problems as learning tools. In many cases, such analysis must take into account the embedded organizational knowledge and capabilities that influence the evolutionary pattern.

As an example, Fiat adopted lean manufacturing principles at the end of the 1980s after a period in which the company had been following the strategy of the highly automated factory with a strong emphasis on automation of assembly operations. Their adoption process highlights some specific features, in particular:

1. A conceptual priority of TQM over JIT; TQM is a key to adoption of the new lean system.
2. The slow acquisition of JIT and an unwillingness to accept the stress imposed by the full-scale adoption of it; JIT is seen as counterproductive in terms of good working conditions.
3. A focus on involvement of the workforce rather than on performance alone; focus on performance is seen as creating conflict rather than resolving it.
4. Bargaining and resolving conflict require a continuous search for consensus.
5. The inadvisability of automating simply "for the sake of automation."
6. A preference for "slow Japanization," with technological solutions that positively impact both production flow and work organization.

In practice, lean manufacturing and TQM use the same tools:

- Process organization
- Customer satisfaction
- Teamwork
- Continuous improvement

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4.5 Summary

It is not easy to define the overall expectations of manufacturing as each stage have dissimilar objectives;

Management objectives are:

1. Meeting delivery dates.
2. Keeping the capital tied down in production to a minimum.
3. Reducing manufacturing lead time.
4. Minimizing idle time on the available resources.
5. Providing management with up-to-date information.

Management's initial attempt to coordinate and control enterprise operations involved building an organizational structure that mainly encompassed the technological departments and tasks. The philosophy and assumption was that if the technology disciplines (producing tasks) were able to accomplish the above objectives, management's objective would also be accomplished. The above assumption did not prove to be correct.

Manufacturing planning stage objectives are:

1. Meeting delivery dates—production planning and control.
2. Reducing production costs.
3. Rapid response to market demands—product design.
4. Reducing lead time—production.
5. Progress towards zero defects—quality control.
6. Progress towards zero inventory—increasing inventory turns.
7. Improving management knowledge and information—Enterprise communication.
8. Improving and increasing teamwork/collaboration.
9. Improving customer/supplier relationships.
10. Improving procurement management and control.
11. Management of strategic planning—Competitiveness—Globalization.
12. Improving management of human resources.
13. Improving enterprise integration—improving supply chain globally.
14. Continuous improvement.
15. Environmental production.
16. Marketing—market share.

Manufacturing shop floor stage objectives are:

1. Minimum level of work-in-process.
2. Maximum number of processes completed.
3. Maximum number of jobs sent out of the shop.
4. Minimum number of processes completed late.
5. Minimum average lateness (tardiness) of all jobs in the shop per period.
6. Minimum queue wait time of jobs in shop.
7. Minimum number of jobs waiting in shop.
8. Maximum shop capacity utilization.
9. Minimum number of jobs waiting in queue for more than one period.
10. Minimum size of jobs waiting in queue for more than one period.

What, actually, are we trying to accomplish? As there is no chance of building a system to meet all manufacturing expectations, let computers be limited to supplying data and let humans make the decisions.

Chapter 5
Analysis and Restoration

Abstract The first four chapters of this book described the expectations and disappointments of four incredible industrial innovations. Despite their monumental potential, they all took a conceptual turn somewhere along the line of their development which caused them to fail to achieve the solutions which they sought, and thus each of these incredible industrial innovations faded away. This section attempts to clarify what went wrong and how the originality and contribution of those innovations might be rectified and restored. Group Technology could be revived by a CAD system able to "see" and compare items, thus solving the problem of classifications. Process planning could stop running after the "routine" that blocked several systems of progress systems, replacing it with a ROADMAP. Numerical control could be rectified through the cessation of the practice of developing modules simply because they can be developed, shifting focus to developing what the other modules need instead. Manufacturing itself can be revitalized by using a roadmap, instead of routing, to realize a vision of flexibility and the option to meet due dates and minimize cost, lead time and idle resources.

5.1 Introduction

The remarkable industrial innovations, such as Group Technology, Numerical Control and manufacturing, that, despite being so different in their methods, rose to become the leaders of industrial technology starting in the 1940s, were all discarded at about the same time, in the mid-1970s.

Group Technology (GT) was aimed at assisting the engineering and manufacturing phases. However, it depends heavily on classification and coding systems, on past performance, and on human effort, skill, and experience. It is basically a manual technology. Even with the use of computers, it calls for interactive dialogs, but does not lead to a fully automatic system. This is probably the reason why GT and IMS have not merged into one complementary system that introduces engineering into the manufacturing stages; GT is a good philosophy, but very difficult to

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implement. It seems that the main developmental barrier was the obsessive search for “**how to generate a routine**”. This threw the research objective off course and several decades of research were spent in vain, causing this remarkable industrial innovation to fade away. With questionable routing, no process-oriented classification can be created.

Flexible manufacturing that only utilizes one routine cannot provide the flexibility needed, thus causing bottlenecks on the FMS transfer line. Eventually, this is what caused the incredible technology of FMS, which is possible from the hardware point of view, to fade away as well, taking the dream of the factory of the future with it.

The production information and control system (PICS), as well as the integrated manufacturing system (IMS), regard the engineering phases of manufacturing, that is, product design (bill of material), process planning, and methods (**routing**), as constraints. These constraints are artificial and exist only because the product designer, the process planner, and the production engineer do not (and practically cannot) communicate continuously and work as a team. The engineering problems in manufacturing are being transformed into mathematical problems at too early a stage, so that, in spite of the impressive mathematical techniques and a true optimum, from a mathematical standpoint, a real optimum solution cannot always be obtained. The inherent logic of the IMS results in inefficiency, long lead times, and high levels of work-in-process.

Routing is the process of selecting the best paths in a network. The routine indicates the one best method for producing a specific item. A single routine (which is all most of the available commercial manufacturing systems can handle) blocks the required flexibility, as well as robbing the manufacturing system of its natural flexibility, thus making manufacturing very complex. Routing specifies how to transform raw material into the form specified, as defined by the engineering drawing. This task should be carried out once for the total assembly and separately for each sub-assembly and individual part of the product.

The conclusion reached, after researching manufacturing and production planning over several decades, is that the approach of giving extreme importance to “routing” was misleading and adverse to the objectives. Routing restricts flexibility and results in a very complex system. Routing is actually an edited version of the output gained from **process planning**.

Process planning is a decision-making task for which the prime optimization criterion is to meet the design specifications and intentions as given by the designer and expressed by 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 resource load balancing. The designer’s intentions should be transferred to the process planner. The transfer method should convey the designer’s ideas and intentions precisely. Otherwise, manufacturing might not interpret the designer’s decisions as intended. The most widely used transfer method is the engineering drawing.

The engineering drawing is the language used to describe a component. This language has been particularly developed over the past several decades (although it was in use for quite a long time before that), has proved reliable and unique (no ambiguity), and is universally recognized and accepted. In other words, thanks to the establishment of accepted standards, anyone in any part of the world who speak different languages should be able to interpret an engineering drawing to produce the item it describes in exactly the same way almost purely by virtue of the geometry, dimensions and tolerances presented in it. To that end, drawings should be as free of notes and abbreviations as possible so that the meaning is conveyed graphically.

Technical drawing is essential for communicating ideas in industry and engineering. Drawings convey the following critical information:

- Geometry—the shape of the object; represented as views; how the object will look when it is viewed from various angles, such as front, top, side, etc.
- Dimensions—the size of the object is captured in accepted units.
- Tolerances—the allowable variations for each dimension.
- Material—represents what the item is made of.
- Finish—specifies the surface quality of the item, functional or cosmetic. For example, a mass marketed product usually requires a much higher surface quality than, say, a component that goes inside industrial machinery.

A technical drawing must be considered a contract, to be honored in all its details.

A part is defined by an engineering drawing, which gives complete information on its geometry and associated data. It is the fundamental means of communication between the designer, the process planner and all other functions within the enterprise; it is the medium through which the designer's intentions and wishes are expressed in an unambiguous manner.

Attempts made to use aCAD system to transfer that data from engineering to process planning failed. One may wonder why CAD's success in the design stage could not be translated into manufacturing. It seems that the design stage made possible the explicit definition of specific needs, the requests for which computer personnel could then set programs to address; introduction of the astonishing development of Additive Technology subsequently proved that much more could also be done. In manufacturing, however, the only request that could be computerized was simulation of the data of engineering drawing. The data itself did not generate a process plan. It was the process planner who decided what the required process plan was.

There has been effort to transfer some of the manual burden to an automated process through Computer-Aided Process Planning. In this method, a computer uses data and algorithms to determine the parameters for production. This approach still has its limits, of course, being best suited to very specific tasks.

In addition to the massive amount of prep work required to form a production plan, IMS expects the process planner to edit his process alternatives and recommend a **routine** to be used by the other stages of manufacturing. The editing calls for selecting the “best” process for the job. The term “best” is a bit ambiguous and it may be understood through optimization one of the following: single operation; single item; single product; product mix. Each one has a different objective, as well as being subject to the question as to whether to optimize through maximum production or minimum cost. Such a decision, if one can define the objective, calls for knowledge of cost accounting, business management, mathematics, or all of the above. The idea that your average process planner, one of the least appreciated positions in a company, will possess all of this required expertise is a ridiculous expectation, yet the process planner is still the one shaping the process plan on the way to routing. No wonder that manufacturing has become such a complicated, complex task, not to mention inefficient.

This chapter will show how sensibility in manufacturing, after too much time spent on destructive ideas, namely the misguided use of CAD for manufacturing and several decades of running after the perfect generating routine, can be restored.

5.2 Process Planner Activities

Process planning is a most difficult, complex and time-consuming activity. Traditionally, the process plan is designed through the so-called manual method. Under use of this method, a process planner is forced to evaluate the sequence of manufacturing operations in the process plan’s structure, as well as analyzing alternative processes. In this case, the quality of the process plan depends exclusively on the process planner’sknowledge and skills.

The process plan we will now analyze relates mainly to a metal-cutting process for the following reasons: about 75% of all items in the United States are produced through metal cutting, in batches of 50 or less at a cost of over 80 billion dollars each year. It is clear that many of the logical steps taken in metal-cutting can be easily transferred to other processes, such as assembly, disassembly, molding, sheet metal and electronics. Thus, the value of the analysis applies to general manufacturing methods.

The process planner’s first step in recommending a process operation is to examine the drawing (assembly and items) in order to determine the type of process best suited to the item described by the engineering drawing, i.e., assembly, electronics, metal-cutting, etc. To determine the type of process, the process planner has to visualize the shape as described by the engineering drawing, including all of its details and the intention of the designer on one hand and the raw material shape and size on the other hand.

5.2.1 Metal-Cutting Process Planning[1]

Process planning is a decision-making process. The objective is to devise an economic process plan.

The parameters to consider are:

- geometry of the part
- raw material for the part
- dimensional accuracy of the part
- surface finish of the part
- geometric tolerances of the part
- heat treatment of the part
- quantity required.

The constraints are:

- specification and strength of the part
- the available machines
- the available tools
- the available fixtures, chucks, clamping devices, etc.
- the available technology.

The criteria of optimization are economic, and might be:

- maximum production of parts
- minimum cost of parts
- maximum profit rate during a given period of time.

The decisions to make are:

- select type of metal removal process
- select chucking type and location
- select machine for the job
- select detail operations
- select tooling for each operation
- select path for each operation
- select cutting conditions for each operation.

A faulty 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 primary decision of selecting a chucking location and

[1]The material in this section has been adapted from the book Process and Operation Planning—Revised Edition of "The Principles of Process Planning: A Logical Approach" Gideon Halevi, Published by Kluwer Academic Publishers 2003.

type imposes constraints on the permitted cutting forces, and thus on the 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 the surface finish of the produced hole.
- There is a relationship between the force exerted on a part and its deflection.
- The allowed deflection of the part during metal-cutting is a function of the dimension tolerance.
- The permitted cutting forces in a metal-cutting operation are a function of the permitted part deflection.
- Cutting forces are a function of cutting conditions.
- There is a minimum depth of cut, below which there will be no 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.

To eliminate artificial constraints and deal only with technological constraints, it is proposed that the process planner **assume an imaginary resource and tools**, i.e., a resource that poses only technological constraints, thus overcoming dependence on the sequence ofdecisions. This process can be generated by a computer program or by manual effort.

The proposed algorithm concept divides the process planning task into two stages:

Technology stage: Generates Basic Process. This is the “best” possible process from a technological stand point. It does not violate any physical law. It is theoretical from the specific viewpoint of the shop.

Theprocess planner has to build two tables, one including the technological data which is used for defining the required setup data, i.e., tools, materials, etc. (not presented), and a table to be used for the manufacturing stages, i.e.,process operation and their process time, including sequence constraints. Notice that the table does not specify resource data, but rather the required specifications alone. This table contains the general data and the computational data. The general data hold the following:

- Sequence number (the same as that to be used by the set-up table)
- Operation number
- Priority connections
- Relationship constraints.

And the computational data contain the parameters necessary to compute the operation’s processing time.

The general data contain:

- Sequence Number (The same as that to be used by the set-up table)
- Operation (Operation process type, i.e., milling, drilling, turning, etc.)
- Priority (A priority value indicates the operation sequence number that must precede the present operation. Priority 0 means that an operation can be the first resource operation or can be performed at any time)
- Relation (This operation must be done with the indicated operation without removing the part from the resource or fixture)
- As a side note, due to technological constraints, such as geometric tolerances, some operations must be processed without removing the part from the resource or fixture.

The Computational data contain: Parameters and their values necessary to compute each operation's processing time. This time is theoretical, since we are using an imaginary resource and ignoring resource constraints. Its purpose is to enable us to transform this theoretical time into real time, considering real enterprise resources or evaluating any other resources (see next section).

5.2.2 Process Planning Method

The process planning decision employs two visual shapes: that of the designer's specifications and that of the raw material. The process planner compares these two shapes in the search for aprocess operation that will bring the raw material's shape closer to that of the designer's specifications and ensure tool access. The planner scans ("sees") the design specification's shape from all directions (X, Y, Z) to differentiate between the basic shape and special features (slots, chamfers, threads, pockets, holes, etc.) and determines the length and depth of cuts, datum points, and other parameters to define a process operation. This operation is recorded on the table that contains both the general data and computational data, with the shape of the raw material being changed in parallel as if the presumed operation had been carried out.

This procedure continues until the two shapes are identical.

The computational operation of the details process is based on the following steps done by a computer algorithm, which can be found in books such as "Principles of Process Planning—A Logical Approach," and by scanning CAD from all directions (X, Y, Z) to retrieve relevant information and establish a free tool approach:

- Compute the location-free chucking type with minimum overhang.
- Assign the depth of the cut limits based on the surface finish.
- Define the type of cut required for each segment. Attempt to combine as many segments as possible to be machined in one rough cut operation. Use the depth of cut limits to achieve this goal.

- Ensure tool access to each specified operation. Change the sequence of operations if required.
- Establish the feed rate limits based on the surface finish and depth of cut.
- Compute the allowable forces as a function of the chucking type and location, surface finish, and tolerances. Use the force of least magnitude as the controlling one (bend, torsion, or chuck).
- Compute the feed rate based on the allowable forces.
- Try to reach the maximum feed rate through:

  (a) Division of depth of cut between rough and finished cuts.
  (b) Change in rough depth of cut and in combination of segments.
  (c) Change in chucking location.
  (d) Change in chucking type.

- Check the effect of step 8 on previous operations and change them, if necessary.
- Compute the economical cutting speed. Check against speed limits.
- Compute the forces, power, and time for each operation.

The above sequence of computations ensures an economical process by specifying:

- Minimum number of chucking.
- Minimum handling time.
- Minimum number of operations. Economic cutting conditions.

Transformation stage: Transforms the processing time of each operation to consider a specific resource's constraint, and builds a table signifying the time needed to process each operation, on any resource of the specific enterprise.

To consider individual machine capabilities and constraints, the operation time of the theoretical process (technical stage) is translated and adjusted to comply with each individual machine feature. It is obvious that the machining time cannot be decreased; it may only be increased. The adjustment considers the following factors: physical size of the machine, machine accuracy, special features, available power and torque, available speeds and feeds, number of tools, type of controls, handling time, etc.

If machine accuracy, type, and size do not comply with the operational requirements, this particular operation on this particular machine is marked as 99 in the processing time column. Otherwise, the operation can be adjusted to specific resource constraints and specifications. Some adjustment rules are:

- When machining power is less than that required, the cutting speed, feed rate or depth of cut has to be reduced.
- Cutting speed reduction will proportionally reduce power and increase cutting time.
- It is more profitable to reduce the cutting speed than to reduce the feed rate. Reducing cutting speed will also result in an increase in tool life.

A practical conclusion is that power adjustment should be made according to the following priorities:

If the power has to be reduced by less than 50%, reduce the cutting speed down to its lower value, or reduce the feed rate down to its lower limit value, and reduce the depth of cut, i.e., split the cut into more than one pass and adjust the cutting speed and feed rate.

If the power has to be reduced by more than 50%, split the depth of cut to more than one pass and then use the priorities mentioned above.

A machine file containing the machine specifications is used for the conversion. The indirect times, such as set-up, which is for a whole batch, will not be added at this stage, but rather as a transfer time (penalty) for changing a machine. The direct time, such as tool change, adjustment speed, inspection, etc., are added to the operation time by using a handling time table.

The handling time is a function of machine type, size, etc. Therefore, for each machine or machine group, a separate operation handling time is represented by a column in the table. When adjusting the TP operation time to a specific machine, the appropriate handling column is employed. This feature enables one to evaluate the economics of using conventional machines versus CNC machines, manual operations versus tool-assisted operations, old machines versus new machines, etc. The cost is computed by multiplying the time by the hourly rate.

5.2.3 Example of the Concept[2]

This section demonstrates how the method works. The part or product to be produced is defined by engineering drawings. The drawings can be done on a drawing board or a computer-aided design system. The process planner interprets the specifications in the definition drawing for the part and, based upon his or her skill, recommends a process. Alternatively, the drawing is introduced to a CAPP system to generate a process.

As an example, a sample part "plate" is shown in Fig. 5.1. The theoretical part process calls for nine operations. Their cutting conditions, required power, and machining time are shown in Table 5.1.

A manual process may be generated if it follows the TP rules (i.e., considers only technological constraints and ignores the effects of order quantity and handling time). The priority column indicates the constraints on the actual sequence of machining operations.

Priority 0 means that this operation can be the first machining operation or can be performed at any point. The constraint is usually due to tool access or sometimes to burrs. As can be seen in Table 5.2, operation 010 must be the first operation. Operation 020 can be done only after operation 010. The finish pocket milling

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[2]Republished with permission of CRC press LLC from Restructuring the manufacturing process: applying the matrix method, author G. Halevi, published in 1999, ISBN 1-57444-121-3 Chapter 4, pages 103–108, permission converted through Copyright Clearance Center, Inc.

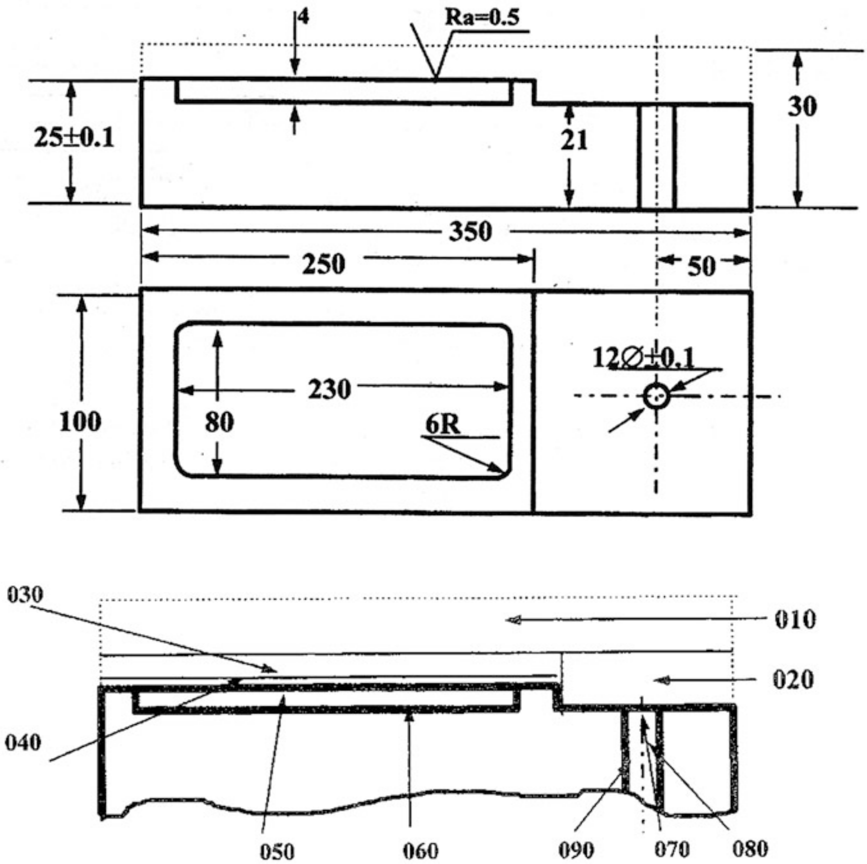

Fig. 5.1 Sample part "plate"

(operation 060) can be done only after the rough pocket milling operation (050). The number in this column indicates that the relevant operation can be machined only after the indicated operation number in the priority column has been carried out. It does not have to follow this operation immediately. This means that the sequence of operations can be 010; 020; 030; 040; 050; 060; 070; 080; 090; or 010; 020; 030; 070; 080; 090; 040; 050; 60; or 010; 050; 020; 070; 030; 080; 040; 090; 060; or many other combinations.

Now, reconsider what we said above in regard to the theoretical process and individual machine capabilities and constraints (second paragraph in the section on the Transformation Stage). TP plan operations time is translated and adjusted to comply with the capabilities and constraints of each individual machine.

Assume that six machines are being considered. A short list of specifications of these machines is given in Table 5.2. The direct handling time (such as change tool, adjust speed, etc.) is added to the operation time. If a machine cannot perform a

Table 5.1 Process plan for a part "plate"

No.	Operation	Priority	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	472	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 5.2 Specifications of available machines

Resource number	Machine specifications	Power (KW)	Speed (RPM)	Handling time (min)	Relative cost
1	Machining center	35	1500	0.10	4
2	Manual milling	15	1500	0.66	1.4
3	Small drill press	1	1200	0.66	1
4	Old milling	15	2400	1.0	1
5	Small CNC milling	10	3000	0.25	2

specific operation, due to accuracy (or for any other reason), it remains in the table, and its machining time or cost is set to a high value (99). This will prevent the selection of this machine for that specific operation, while leaving open the possibility of selecting it for other operations. Old, inaccurate, low-cost machines can be used for rough operations, but are not suitable for finish operations.

Construction of the table also enables evaluation of the economics of assorted choices.

The TP operation time translated to the individual machine as specified in Table 5.2 is itself presented in table format in Table 5.3. Thus, the table contains *Ti, j* values, where *Ti,j* represents the time to machine operation *i* on machine *j*. The time table can easily be converted to a cost table. This is done by multiplying the time by an hourly rate. The hourly rate for each machine is represented by a relative number, as specified in the relative cost column in Table 5.3. Thus, the value *Ti,j* is converted into *Ci,j* in which *Ci,j* represents the cost of performing operation *i* on machine *j*. The time values converted to cost values are shown in Table 5.4.

Table 5.3 Machine–Operation time table

Operation	Time (min)	Priority	Rel	M #1	M #2	N #3	M #4	M #5	M #6
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 5.4 Machine–Operation cost table

Operation	Time (min)	Priority	Rel	R	E	S	OU	C	CE	Minimum cost
				#1	#2	#3	#4	#5	#6	
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

5.2.4 *Routine*

The goal of a manufacturing routine is to prescribe the flow of work in the plant. It derives its information from process planning and presents it to the production phases. The manufacturing routine describes how items are processed and assemblies produced.

Traditional techniques take for granted that the routine should be established by the process planner, as routine is an editing tool for the process plan. The process planning stages require a technological background, however, the routine stage requires knowledge in mathematics, combinatory, business economics,

Table 5.5 Alternatives for routine as a function of quantity

Quantity						
	High		Medium		Low	
Machine No. Used	Total time	Total cost	Total time	Total cost	Total time	Total cost
1	8.59	34.36			8.59	34.36
2	9.04	27.12			9.04	27.12
3	13.92	19.50			13.92	19
1…2	9.19	26.55			12.19	29.55
3…5	16.11	19.50			19.11	22.50
5 2 6 3 1 4…	15.29	17.45			24.14	47.45
		and	so	on		

management, etc., which are not know to be included in the technical training of a process planner (if they receive any at all).

A criterion of optimization might be maximum production or minimum cost, but such a decision should be made by management and not by the process planner. The optimum of maximum production or minimum cost depends on the order quantity. The process plan shown in Tables 5.3 and 5.4 includes handling time but not set-up time. All orders must have set-up time for the first operation. If the process uses more than one machine, set-up for each machine should be added to the processing time and cost. This time is for the order, and must be divided by the quantity in order to compute the total time and cost.

The routine options are shown in Table 5.5. For high quantities and instances in which the set-up time per item is negligible, the figures are shown under “High”. For very low quantities, the options are shown under “Low”. For other quantities, the figures must be computed for each quantity.

Note that the best machine for maximum production is the worst for minimum cost. The small CNC milling machine with 10 KW competes with the machining center with 35 KW, both in terms of machining time and cost. This makes sense, as rough cuts require high power for short processing times, while finished cuts require low power and longer processing times. The rough cut is divided into several cuts to adjust the required power to the availability of the machine.

Selecting a routine from the process planning alternatives is a very complicated and crucial step, one that affects an enterprise’s efficiency and its ability to compete. Moreover, at this point in time, there are no data in regard to such considerations as batch quantity, or optimization criteria, which might assist in making this decision. It was established that having one routine (or at least a limited number) makes production planning a very complex task. Therefore, it is proposed that Tables 5.3 and 5.4 be used as data for a production planning (**variable routine**) system. Such a system restores the Integrated Manufacturing System and is discussed in Sect. 5.6.

5.2.5 Universal Process Planning Method

The process planning approach, as presented for a metal-cutting operation, was developed to overcome dependence on asequence of decisions and the problem of artificial constraints. Using this concept, a process is generated using only the real constraints (technological ones) by assuming an imaginary machine and tools. The difference between conventional process planning and the process planning being presented is that the process planner generates a process using an imaginary machine, i.e., a machine that poses only the technological constraints. This process can be generated through a computer program or by manual means.

At the second stage, the process operations are translated (through a computer program or manually) into practical process operations by using the available resources. These practical operations are arranged in a table format. This is practical, as it considers only the available resources in a specific shop. The third stage will transform it into a practical process plan.

This table establishes a network of all possible routings, while deferring the decision, of which routing to take, to a later stage.

This table method is a universal process planning method. Some of the processes that might be handled by it are demonstrated in Table 5.6. The left side shows the operations and the theoretical time needed to perform them, as well as some constraints marked as priority (PR.) and Relationship (Rel). These are for the sequence of operational constraints. On the top right side of the table, all the candidate resources for each operation are listed (R1, Rn). The content of the table is Ti,j—which is the time needed to perform operation i on resource j. For costing considerations, the content of the table is Ci,j, which is the cost of performing operation i on resource j. The table does not provide a solution or a process plan, but rather lists all of the alternatives. Cleaning, for example, can be done by hand, with a rag, brush, vacuum cleaner, etc. The decision as to which alternative to use is made at the processing stage and is not affected by intuition or rules of thumb, but rather by consideration of the order quantity and the optimization option selected.

Assembly process planning has at least four stages: moving, locating, laying, and fastening. They may be entered into the operation column.

Assembly is a collective term for a large number of very different technological steps. Assembly planning might use manual, automated, robotic, or conveyor methods; they might be entered into the table as Resources.

There are a number of reasons for considering assembly planning, but the most common one is seeking a reduction in operation cost. It is clearly shown that, for small batch size, the simple manual size is the most economic, while for high quantities, assembly with an automatic machine is the best option.

Table 5.6 Universal process planning table

Operation	PR	Rel	Time	R1	R2			Rn
Welding								
Riveting							Ti,j	
Forging								Ci,j
Casting								
Cleaning								
Assembly								
Electronics								

5.3 CAD for Manufacturing Support[3]

The manufacturing cycle is composed of several stages, each one of which requires data and knowhow of a different discipline.

CAD systems were developed to comply with design needs. This resulted in incredibly innovative developments benefitting many design applications. However, it was found that, for other manufacturing disciplines requiring engineering data, such as process planning, inventory control, scheduling, master production planning, etc., the most relevant data needed for them to perform their tasks was not available. The needs of those manufacturing stages and disciplines were not specified as objectives for the CAD for a manufacturing system. Therefore, the systems supply neither the data, nor the system requirements.

A lengthy research was made and surveys were conducted, one for the CIRP's (The International Academy for Production Engineering) CAPP working group[4] (Computer Aided Process Planning) and one for the IFIP's[5] (International Federation for Information Processing) CATE Task Force (Computer Aided Time Efficiency), in order to understand what the needs of manufacturing are. Based upon these studies, specifications for the CAD requirement of the manufacturing process were compiled.

[3]The material in this section has been adapted from the paper titled "CAD for manufacturing support" by Halevi, G. Published at the proceedings of the IFIP International Conference, FEATURE MODELING AND RECOGNITION IN ADVANVED CAD/CAM SYSTEMEN, Valenciennes, FRANCE, Mai 1994, pages 374–390, with no copyright and claims. Public Domain permission.

[4]Workshop on Computer Aided Process Planning, Paris, January 21–22, 2002, held at ENSAM (Ecole des Arts et Metiers). There is no registration fee for attending the workshop.

[5]IFIP TC5 Task force CATE (Computer Aided Time Effectiveness) was active from October 1988 till June 1993.

The functions that were considered in our study were:

(A) **Obvious functions**:

- Concept design
- Detail design
- Auxiliary computational functions (stress, flow, etc.)
- Design review (design suggestions)
- Design simulation and recommendation
- Automatic tools and jig and fixture design
- Automatic feature for changing a design
- Process planning
- Preparing cost estimates and quotations
- Forced process planning
- Generating NC programming
- Inventory management and control
- Stock utilization (by shape)
- Quality assurance
- Statistical process control
- Technology transfer feature and literature search
- Value engineering

(B) **Indirect functions:**

- Master production scheduling (MPS)
- Material requirement planning (MRP)
- Material resource planning (MRPII)
- Order release
- Capacity planning system (CPS)
- Shop floor control
- Job recording

(C) **Desired functions**:

- Dynamic production planning
- Work cell design and control
- Automatic design of part families (by objective)
- Manufacturing productivity
- Production cost reduction
- Combining technical operations (reliable data)

(D) **Auxiliary functions**:

- Facility planning
- Personal management
- Plant layout

- FMS and CIM design (flexibility)
- Translating the needs of the above functions to CAD specifications resulting in the following list of additional objectives:
- Searching for concepts that meet product functionality
- Assisting in translating a concept into an engineering design
- Retrieving existing drawings and design by: Concepts, Key, Attributes
- Automatic change in design
- Automatic design of sub-systems and tooling
- Checking and enforcing company standards
- Checking and recommending design for ease of manufacturing and assembly
- Checking and recommending material selection (by inventory)
- Checking and recommending tolerances
- Tolerance for distribution module
- Tolerance for function module
- Automatic dimensioning
- Analysis of strength and stress and kinematics
- Technology transfer and update (old drawings)
- Automated process planning capability
- Automated NC program preparation
- Automated bill of material preparation
- Automated design feature checking (completeness…)

To meet the above CAD specifications, the following features have to be available:

- Comparing workpiece drawings in computer memory
- Manipulating workpiece drawings in computer memory
- Updating workpiece drawings
- Having access to auxiliary files, such as:
  - Feature library
  - Machine members library
  - Computerized product catalog
  - Computerized material databank
- Displaying workplace drawing on a monitor
- Improving user friendliness and seductiveness
- Fast design presentation in: solid, isometric, picture

The most important feature of the proposed CAD is that the computer will possess the ability to "see" the part and contain all relevant data. Therefore, it enables us to manipulate, compare, and change parts, and also (if needed) display the part on the monitor.

Some may be discouraged by the long list of desired specifications, and wrongly estimate and predict that it would be almost impossible to develop such a CAD system.

5.3.1 Available CAD Technologies

The object of this section is to reveal that the available CAD technologies may be used to meet almost all CAD manufacturing functions, as listed in the previous section. The following technologies were gathered from catalogues of CAD suppliers.

5.3.1.1 Solid Modeling

One of the most persistent stumbling blocks in engineering design over time has been the attempt to address certain issues that can arise in regard to a three-dimensional object using a two-dimensional format, viz. the engineering drawing. The advent of computers has certainly played a role in alleviating this problem, particularly in the form of what has become known as solid modeling. Solid modeling is exactly what it sounds like. The computer program creates a "three-dimensional" image of the item in question, often in the form of a "wire" frame that represents the item's assorted shapes, which can then be rotated so as to view it from any angle in an incredibly realistic fashion, allowing the designer to get a very genuine idea of what the item will look like and how its various parts will relate to one another, in a truly physical sense.

5.3.1.2 Parametric and Feature-Based Modeling

An item's features are everything that defines it and distinguishes it from other items, from its length to how the material out of which it is made behaves when it moves to how it sits when positioned in a certain way. Feature-based parametric modeling is especially useful for determining the ramifications of design choices before the item is actual built. Using a CAD program, often in conjunction with a constructive binary solid geometry program (CSG), the designer can establish an initial "intent" which serves as the basis for any number of variations. Adjusting the parameters from that point allows the designer to see how different ideas about that particular item might play out. As you can imagine, this is particularly useful in creating part families, because the computer maintains the initial base intent as it considers the different iterations of the item. These programs tend to be infused with very detailed knowledge about physicality, allowing them to create simulations with remarkably faithful depictions of how an item's, e.g., weight might factor into its use.

5.3.1.3 Parameterized Primitive Instancing

Object families are groups of objects (screws, nuts, etc.) that all stem from a base design, each individualized iteration defined by the particular parameters by which it deviates from that base. These families are also known as generic primitives and the iterations as primitive instances. The limitation of this format in regard to design is that, owing to the definition by way of rigid parameters, including those set by the base parameters that define the object family, experimenting with new forms is not a viable option, even with the use of computer algorithms.

5.3.1.4 Identifying Related Objects in a Computer Database

Systems, methods and techniques for identifying related objects can be kept in a computer database. In one representative implementation: (1) a feature vector that describes an existing object is obtained; (2) comparison scores are generated between the feature vector and various sample vectors; (3) a set that includes at least one designated vector is identified from among the sample vectors by evaluating the generated comparison scores; (4) a computer database is searched for matches between labels for the designated vector(s) and labels for representative vectors for other objects represented in the computer database; and (5) at least one related object is identified based on the identified match(es).

These technologies and other innovative methods can be used, if given precise specifications, to determine what the particular manufacturing requires.

5.3.1.5 Examining the Desired Features

Examining the desired features indicates that the main deficiency of the present day CAD manufacturing systems is in their file management and not in their display. To perform the above specifications, memory manipulation is needed. The required features call for scanning the part from all sides while searching: basic shapes, special features, relationships between features, datum points, similar accuracies, etc.

5.3.2 Notions for CAD Part Description[6]

As already mentioned, the engineering drawing is the recognized language of engineering. It has served all manufacturing activities well. So far, there has been no inclination to change it. We are working in an engineering environment; therefore, let us adopt its language and teach the computer to read engineering drawings. The proposed CAD part description methodis based on the rules of classical technical drawing and adapted to computer capabilities. Its basic concern is with the method of part definition and the method by which part descriptions, that is, the information needed for "working" with and on the part, are stored in computer files. The display routine may be special or use an existing CAD system with an interface to the proposed file management.

The system's notion is bounded geometry, bounded by coordinate systems or lines of symmetry for bodies of rotation. Each coordinate initially has two fixed reference lines. These lines are for orientation and dimensioning. Additional reference lines at any distance can be used. They can be fixed or temporary reference lines. Any temporary reference line can be changed into a fixed reference line if required. Any given dimension will be identified by the direction in which it points and by the datum from which it is given. It may be from a fixed or temporary reference line. A reference line can be shifted, defined and placed at any required location. Establishing additional coordinate systems or center lines is allowed. This feature is used to show a cross-sectional view as an alternative to the three regular views, or a cross-section of an assembly of mixed mode shapes (that is, concentric, flat, sheet metal or three-dimensional elements). The center line can be straight, curved, or circular.

The part description methoddivides the part into basic shapes and special features. This division serves the part retrieval and part manipulation modes, as well as the needs of process planning. Basically, the special features are processed after the basic shape has been machined.

The basic shape is divided into segments. A segment is defined as a portion of the part for which the basic shape remains unchanged. The division into segments is done separately for each view. A segment is initially described by its basic body shape, that is, the overall dimensions of the contour envelope. Body shapes are defined by lines or curves in a coordinate system. A code defines whether the description is of a body of rotation, a flat body, a three-dimensional body or an assembly.

For bodies of rotation, it is assumed that a defined line or curve rotates around the line of symmetry (polar coordinate system) and creates the area of an envelope. This envelope, when marked as "M", becomes a solid body; when marked as "V",

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[6]The material in this section has been adapted from Sect. 15.3 of the book 'The Role of Computers in Manufacturing Processes', published in 1980, ISBN 0-471-04383-4. With permission.

it becomes a hole in a body; and when marked as “S”, the envelope line is widened by the thickness of the material and becomes a tube (solid with a hole in it).

Three dimensional bodies might be defined, as in classical engineering drawing, by three views. Each view will have its own reference lines to serve as datum. It is assumed that the line represents the diagonal of a cube. The part is constructed by connecting the edges of this line with the neighboring lines. If the other lines are not specified, it is assumed that they are straight lines perpendicular to the coordinate system presently in effect or lines of the adjoining segments.

It is assumed that, with three-dimensional sheet metal, a defined line is a diagonal of a rectangle surface. The thickness of the material is added perpendicular to the defined surface, thus creating a body. The other views will define the shape of the body. The defined surface or volume, when marked as “M”, becomes a solid body; when marked as “V”, it becomes a void on the surface.

The initial defined body shape is then transformed into or exchanged for the real shape. Such shapes can be tapers, radii, triangles, spline, or any special shape.

The designer may define segments in any order he/she wishes. However, knowing the basic coordinate system, the individual segments will be stored in the computer memory in the proper order to create the shape of the parts and the voids in it.

The accuracy (tolerances, surface roughness, etc.) can be defined as default values or specific to each dimension. The tolerances are from the datum point to the defined point, in which the datum may be either fixed or variable, depending on the designer’s wishes.

Special features can be defined as being imposed on the basic segment or independent. In order to facilitate the description of such common features as slots, burrs, chamfers and key ways, an index (table) of special features has been compiled. There are rules and options by which to define them and assign their dimensions and accuracy.

Threads and gears are regarded as special features. They can be either standard, and thus defined by their nominal dimensions according to the engineering standards, or nonstandard, and thus have their dimensions given. The special features are an integral part of the system and can be used generally. Any shape or feature that is used repeatedly can be inserted into the system during customization and become part of the system. The concept of coordinates, center line, datum and reference line is applied for the special feature as well. The data of each special feature generate a temporary center line, or temporary origin of coordinates, upon which a fixed reference line is defined.

Temporary special features or curves may be defined, and be in effect only for the single part within whose entry data they were defined. Within that part, they can be used as many times as required. Such special features and curves are described point to point, with sections as straight lines, arcs, radii, angles and splines.

There are many possible shortcuts for reducing the work of definition. Whenever data have to be duplicated, for example, a mirror image feature can be used. Any group of basic segments can be looked upon as a temporary special feature. Any mixture of basic segments and standard and temporary special features can be defined as a subpart by looking at it as a temporary special feature. A part can be seen as an assembly of several parts. As in engineering drawing, dimensions that can be computed may be omitted in order to prevent over-dimensioning.

The importance of dividing the part into a basic shape and special features and storing them separately in the computer memory is essential for process planning and comparing parts in memory. There might be some confusion in this respect, when one designer refers to a feature as a basic segment while another designer might regard it as a special feature. For example, a very wide slot might be regarded as a basic segment. Users must have the freedom to define parts according to their convenience. Therefore, for storage and memory management purposes, a computer program will examine the definition and bring it to a common method.

File management: the system should allow the user to store the part description data in both an intermediate mode and a working mode. The intermediate mode stores the data as is. The working mode checks the data for completeness and consistency before storing it.

Auxiliary files of standards are available, allowing the user to specify the standard. The system checks the design against company standards, and draws the attention of the user to cases of deviation. It checks for engineering feasibility and notifies the user when the rules are violated. Some of the simple checks are to make sure that the voids (holes) do not create discontinuity in material (breaking the part), or that the wall thickness is not below a minimum value (defined by the user).

The user may request to review or edit the data of each segment separately. When editing a part shape, the system checks for any violation of the rules of classical drawing. For example, if one of the sides of a segment was used as a reference line, this side cannot be erased. The system will notify the user, and ask for definition of a new reference line before the initial reference line is allowed to be destroyed. Tolerance and special features are not automatically carried to a changed segment. This is not a violation, and therefore the user will be notified and asked if he/she really wishes to carry on the modification.

5.3.2.1 CAD Search

A fixed format might be seen as old-fashioned in the era of free formats and sophisticated databank file management. However, this old-fashioned method can, within 1 s, scan a file of 30,000 part drawings in search for a part/parts defined by any search parameter, including name, catalog number, raw material, raw material dimension, part geometry, any special feature, location relationship of features, and, indeed, any desired request made of the part data. The request may be for a precise dimension or one of limits greater than or smaller than a particular amount.

A CAD part description method that may meet almost all specifications was proposed. The technologies and other innovative methods presented earlier are likely to come up with an even more superior solution. It should be evaluated according to its response to the manufacturing objectives.

The most important feature of the proposed method is the computer's ability to "see" the part. As a result, it can manipulate, compare, change and retrieve drawings of any detail of the total drawing, and also, if needed, display the part on the monitor. Moreover, it provides a fast response and requires moderate memory and storage space to store the part data.

5.4 Group Technology

Group Technology (GT) is a manufacturing philosophy aimed at increasing productivity in manufacturing of the job-shop type. The method involves alleviating problems associated with short run, low batch sizes 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 throughput time. The initial objective was reducing throughput 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 resources required to produce a particular family of parts. GT benefits and predictions were detailed in Chap. 2.

GT philosophy is remarkable and can, as predicted, increase productivity in manufacturing. For practical applications of GT, it is crucial to create "Groups", i.e., part families. A part family is defined as a collection of related parts that are nearly identical or at least very similar. They are related by geometric shapes and/or size and require similar machining operations. Several years of research were dedicated to the search for a method of creating such a family of parts. Several systems were proposed, but none was accepted. The disappointment that no system was able to create "Groups" caused the fading away of GT.

Lately, remarkable advancement in the fields of CAD and process planning has been made, as was discussed in the previous sections. **These new technologies can restore and revive GT by overcoming the deficiencies that caused its decline**. Utilizing the remarkable functions of today's CAD, such as the "see" function, there is no need for any classification methods to be able to apply the remarkable philosophy of GT. Each user may create families just by specifying the objective. The following sections demonstrate such capabilities, as well as additional ones.

5.4.1 Drawings Management

The data storage should be constructed to capture shapes, rather than points and lines. Its purpose is to serve the following functions:

- Enable data comparison techniques.
- Retrieve data by key and function.

- Selective retrieval according to attributes and parameters. Retrieval is to be fast to suit the interactive mode and with no limitation on permissible inquiries.
- Manipulation of data. Transformation of the product design drawing into inspection, processing, assembly drawings, and so on.
- Change. A part drawing changed as per the designer's request, or a specific attribute change on all part drawings in the file. For example, scan the file and change all hole sizes within the 9–12 mm range to 10 mm.
- Supply data to process planning.
- Display. The ability to display any item on the terminal.

Notice that only the last purpose requires graphic capabilities. It is the both last and least important function of the system. The database construction method is of critical importance. Part data are not kept in the same form as that entered by the designer. The details, however, are preserved. In describing a part, designers have the freedom to choose any coordinate system they prefer, to use any dimensioning option they wish, to look at and describe the part from any side they want, to use and define any special feature, to divide the part into segments in any way they like, to use any unit of measure they favor, and so on.

This freedom is desirable for the user, but hinders the function of comparing parts. User entry data have to be arranged in such a manner that the precise intentions expressed in the description will be maintained, while allowing the functions of comparison and retrieval by attribute to operate. The part description method proposed is just a tool facilitating the required data bank organization. Any company may devise another part description as long as it meets the above provisions.

5.4.1.1 Retrieval by Key

Any drawing available in the system file can be retrieved by drawing, part number, or function key. The first is used when designers know exactly which part drawing number they need. This is applicable mainly in assembly design, revisions, and inquiries. A function key can be attached to each item, stating its normal purpose, such as brackets, springs, bearings, screws, cups, lids, or shafts. Each company can create its own function key. However, it is recommended that the next feature, retrieval by parameters, be carefully examined before using the function key, which reminds one of a classification and coding system. Function keys can be used for a limited number of purposes. A general purpose key might retrieve too many drawings, thus defeating the purpose.

The designer might create standard subassemblies, such as lids, bearing housings, and hydraulic sealing units, and assign them a purpose name (function key) or a part number. In such cases, the data are kept only by pointers to the separate parts, thus saving storage space.

5.4.1.2 Retrieval by Parameters

This feature is used to eliminate the redesign of existing parts and the need to design a new part if minor modifications to an existing drawing can create a new part drawing. This feature can also create group families of parts, to be used for any desirable purpose.

Parts can be retrieved through a search argument that describes the desired features and the search limits. The inquiry request is not limited to any prearranged keys, but is presented in a method similar to the part description system, with two exceptions: (1) Dimensions are not defined as a unique number, but rather within a range, stating the lower and upper limits, and (2) the part must not be uniquely defined, and portions of it can be omitted. This will indicate that the designer does not care about the shape in that particular section of the part.

The search argument can be defined in rough terms, such as: a part whose external dimensions are 100–150 by 70–90 by 40–60. In such a case, all parts, regardless of material, holes, threads, steps, and so on, will be retrieved.

The definition can restrict the search to only those parts made out of a specific material and possessing any special feature, such as a hole or taper or a combination of and/or/nor features. The search argument can be defined in fine terms, such as: a bracket of 80–90 by 20–25 by 5–7 that has a hole of 6–9 mm in the middle and a 90° bend at 10–15 mm from the edge; or a shaft that has two bearings of known size 250–280 mm apart, and between them a pulley with inner diameter of 1 in. is mounted and secured by a key. Find an existing drawing that can be used. The search argument can also be defined in exact form, giving a sketch of the desired part.

An inquiry is a free format; two letters designate the feature request, followed by the lower and upper limits. The following example shows an inquiry in four steps, starting with a rough definition of only two parameters; 250 parts satisfy this request. A third parameter reduces the selected group to 50 parts. When a fourth parameter is defined, the number of parts complying with the inquiry is reduced to 5, and drops to only 1 part when a sixth parameter is added. This example was prepared using a file of 25,000 part drawings. It takes 1–2 s in elapsed time.

5.4.2 New Design

When a new part/product is required, do not rush to design. Remember the good old Group Technology rule that "***many problems are similar and a single solution can be found to a set of problems, thus saving time and effort.***" Introducing a new part can affect several activities, costing thousands of dollars. These are:

- Engineering activities:
  - Design and detail draft Prototype building
  - Testing and experimentation

- Auditing and cost
- Records and documentation

- Manufacturing and finance activities:
  - Advance manufacturing engineering (central)
  - Manufacturing engineering (plant)
  - Tool design and tools and gauges
  - Time study and standards
  - Production control and scheduling
  - Cost accounting
  - Data processing
  - Purchasing and inventory
  - Quality control

Therefore, before rushing to design, compare the available parts to decide if any of them can be used. Research shows that at least 5% of new required parts can be avoided by using available parts.

For example, a company reported that about 2500 new parts were released annually, while about 30,000 active parts were in its design files. It has also been reported that from 5 to 10% of the annual output of new parts could be avoided. Thus, a company can save anything from $400,000 to $800,000 just by reducing the duplicated design. This is without making anything; it simply involves preparing the part to go to the shop floor and be made.

One thing that needs to be kept in mind is that manufacturing is bound by the decisions that design makes, including in regard to budget. The amount of a particular product's budget that is taken up by the design phase is dwarfed by the amount that design ends up determining for the remainder of production (popular estimate is one to ten). Please check and recheck your decisions. **Do not rush**. Do not search for shortcuts in the job of designing.

5.4.2.1 Conceptual Design

In this stage, designers employ their creativity. They can give free rein to their imaginations and come up with any wild idea. The more extravagant the ideas, the better designers they are. A computer is a machine and has no imagination at all. For this task, a human is far superior to a computer, and thus humans should perform this task. It is possible to devise intelligent software with automatic design capabilities; however, using it in the conceptual design stage will limit and hinder technological progress. If they wish, designers can employ computers for the following purposes:

- To remind the designer of secondary objectives.
- To help facilitate decisions. This might serve as a checklist and, more importantly, can be the method by which documentation of this stage is preserved.

- To assist in generating ideas. A data bank contains many modules for the automatic design of elements or subsystems. Scanning and/or retrieving these modules according to purpose might trigger ideas and supply data required for the decision matrix. A request for a power source, for example, might retrieve electric motors of different types, hydraulic motors, hydraulic cylinders, pneumatic cylinders, internal combustion engines, solid or liquid propulsion rocket motors, springs, turbines, solar cells, solenoids, propellers, and so on.

5.4.2.2 Detailed Design

Detailed design is of a more technical nature; therefore, a computer can be employed to perform this task. In some fields, automatic design programs have been constructed and successfully used. The most advanced field in this area is electronics, in which products are being designed, board layouts prepared, processes established, and, in some cases, productions carried out under computer control. Hydraulics can calculate and check the stationary and dynamic behavior of circuits. The circuits can be composed of standard elements, special elements, or function groups.

In the mechanical field, automatic gear train design programs are available. Engineers input their special design requirements into the computer and, in minutes, get back all of the data that they and the shop floor need in easily readable, abbreviated English. I am sure that many more programs of this nature exist.

Today's CAD systems (design) are remarkably innovative and provide most of what GT may propose. However, from a manufacturing point of view, there are several design features that might be of benefit to their users. Such features are listed hereafter.

5.4.2.3 Automatic Change of Design

Whenever a company decides to adopt a new technology or design standard, it can make an automatic change in all company drawings that will be affected. This feature is carried out for design standards (such as hole sizes, threads, slots, and keys) by introducing a table listing all new standards and a change command. The above list will act as an inquiry for retrieving parts that have the standard features. The retrieved part drawing will be changed automatically to correspond with the new standards. A report of all changes made will be prepared. The designer might ask to see any or all such drawings on the screen.

This mode of change can handle most of the mating parts automatically, since the part description system regards a feature as a neutral that becomes a male or female according to its location.

For new technology changes, the user must specify what to alter (and how) in a given design. This definition is in general terms and not for a specific part. The above definition is the search argument by which the drawing file is to be searched. Such a definition can refer to an individual part or to an assembly. The retrieved parts and assemblies will be automatically changed as instructed.

5.4.2.4 Automatic Drawing Preparation

The drawings in the system file are part drawings. In many companies, additional sets of drawings are prepared for inspection and production. These drawings deviate from the part drawings by tolerances and dimensions. The deviation is usually carried out by a set of rules. Such rules can be incorporated into the system, and the required additional set of drawings will be prepared upon request.

5.4.2.5 Stock Utilization Feature

For many justified reasons, stock usually builds up to include dead stock, slow moving and rejected items, and used and leftover pieces. Although information about such items carried by the inventory system is available, they are usually not utilized by such production systems as MRP (material requirement planning). Due to system logic, such items cannot be treated automatically by a system and are thus treated manually (if treated at all).

The main difficulty in applying an automatic system approach is the rigidity of the systems. Items are classified and named by catalog or inventory number. These names are carried through and are the connecting link between the separate manufacturing stages. Bill of material, inventory, purchasing, and production all use the name of the items and disregard the item itself. They operate in a purely clerical way. Rejected items, for example, do not have a name in the system. Many tricks and immediate solutions are employed, but they mainly serve inventory accounting and not inventory management.

By using the GT technique and CAD capabilities, it is possible to treat the items as such and not as names or catalog numbers; that is, the items can be treated in the manner of an automatic system. The following sections will describe these options.

5.4.2.6 Dead Stock and Slow-Moving Items

The output of the material requirement system is a list of materials which should be purchased and a list of the unused materials in inventory. Both lists refer to the inventory catalog number. It is possible to arrive at the source of the requirement (parts) for the materials to be purchased by using single-level in which data are used in the bill of material file. It is recommended that, before proceeding with the purchase, an additional phase be added in an attempt to utilize dead stock.

The additional phase uses the part description system. It retrieves a part by name and transforms its drawing into a minimum raw material part drawing. The new drawing is scanned for maximum values, and a circumference shape representing a minimum raw material dimension for the part is established. A rough estimation based on the volume of material removal and an economical algorithm is used to determine the maximum raw material dimensions.

The dead stock material is retrieved, unit by unit, and checked to see whether its dimensions fall within the minimum and maximum raw material dimension range of the parts required. If it falls within the range, an accurate cost computation is made, taking into account extra machining cost, material cost, and the time the material has been in stock. The material resulting in the most favorable cost ratio is selected.

If no material falls within the established range, a second pass with enlarged maximum limits can be made. The decision as to whether to use such material or not is based on accurate cost computations.

5.4.2.7 Stock in Cut Pieces

The sizes by which stock is purchased are not equal to those issued for production. Cut pieces are left over in inventory. They are recorded in inventory accounting and must be distinguished from the uncut material. This solves the inventory accounting problem, but at the same time, it prevents these pieces from being considered for use by the production system.

The method used to utilize dead stock, as previously described, can also be used to handle this group of materials. Gripping allowances should be added to the minimum raw material dimensions.

5.4.2.8 Rejected and Leftover Items

In production planning, an anticipated rejection factor is used to increase the required quantity. If the actual rejection rate is not as anticipated, leftovers will be accumulated from assembly. The rejected parts are not considered for use by any of the automatic systems. The leftovers are considered by the requirement planning system. If no assembly requires these parts, they become dead stock. From a cost standpoint, the rejected parts and most of the leftovers are covered and have no registered value. If such items can be used, it is practically all savings. In order to consider the use of such items in the manner of an automatic system, their geometric shape must be captured. Capturing these data is done as follows. The operation in which the rejection took place is known. Inspection reports specifying the dimensions that caused rejection are available.

Process planning keeps track of part geometry from raw material to the last operation. A machining drawing for each operation is easily prepared. Thus, the geometrical shape of the part before and after the operation that caused the rejection is available. Superimposing inspection reports onto the original geometrical shape results in the geometrical shape of the rejected item.

The output of the requirement planning system is a list of orders to be released to the shop and a list of the unused items in inventory. It is recommended that an attempt be made to utilize the unused and rejected items through remachining prior to the issuing of shop orders. This is done through the use of the part description system. Each of the required items is matched against the surplus items.

In the first stage, a test is made of the geometrical equality and inclusion of the required item within the surplus item. Required items that do not pass the test are released to the shop and are excluded from further consideration. The remaining required items are compared not for inclusion, but according to the required special features and their locations, thereby reducing the number of alternatives. All alternatives are examined with respect to the conversion cost from the surplus item to the required item. This is done by defining the surplus items as **shaped raw material**. The output is an optimum process, including time and cost. An economic algorithm analysis decides which of the alternatives to choose, that is, which surplus item is to be remachined in order to obtain a required item.

More than one alternative can be chosen if the quantity of the surplus items is insufficient. Special shop orders are issued for such machining operations. If the economic module decides that it is not economical to transform items, a normal shop open order is issued for such items.

5.5 Numerical Control

The incredible technology of computerized numerical control introduced a number of smart machines (most industrial resources today are likely computer-controlled) and auxiliary deceives, such as Industrial Robots,—the Automated Guided Vehicle (AGV)and Automated Storage and Retrieval (AS/AR). All contributed to an increase in manufacturing flexibility. Set-up can be prepared in the office and not on the shop floor, thus increasing real processing time in machining centers that have their own tool storage and tool changing. ***These capabilities exceed expectations***.

These capabilities also introduced expectations for the Flexible Manufacturing System (FMS) and the Flexible Manufacturing Cell (FMC), which allow a machine to work unattended and produce a set of items and products scheduled for that date. Such work centers that actually are currently in service create a vision for the automated factory.

The vision of the automated factory consists of FMS machines, 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 hierarchical computer network. The network links the main central processor to the individual microprocessors controlling single devices.

The automatic factory utilizes the benefits of all of the previously mentioned facilities. It has the same reduced operation handling time as the DNC machine, the same interoperation transfer time as the machining center, the same chucking and gripping as the production line, and the same increased flexibility as the work cell.

Unfortunately, these expectations led to disappointment. The hardware performed perfectly, but the scheduling software, in several cases, caused items to crowd the transfer line. If a robot was used, it was too slow to serve all of the machines; if several robots were used, they collided with one another (there was, at that time, no good software that could maneuver and control the traveling path).

When the manufacturing system becomes more flexible and dynamic, expectations will be revived, and will probably deliver this time.

5.5.1 Machine Capabilities Upgrade

Machining is greatly improved through the combination of a numerical control program and a controller that acts upon the information the program feeds it, resulting in a system that can store both processes and the information that may be needed to correct them as they are being used. Starting with the design drawing, the process is mapped out and the commands for the various machines are determined. These are then transferred to the computer by the programmer or operator.

The machine control unit decides cutting speed, feed rate, depth of cut, number of cuts, tool selection, coolant on/off, and tool paths. The machine control unit issues commands in the form of numeric data to motors that position the slides and tools accordingly. Direct numerical control is a tool that has gained popularity in recent years. It is comprised of a CNC connected to a computer by a serial line.

Such a machine is perfect for a small job shop with only one machine that receives orders to produce relatively simple items. However, for a larger job shop, it presents several obstructions to efficiency.

1. A machine must be selected for processing without knowing whether it is the one preferred for the job or its processing time, thus making it impossible to prepare a capacity planning program or select the appropriate machine for each operation.
2. The machine control unit determines the cutting conditions, without the user knowing anything about its effectiveness, the computation method or the parameters. The machine must work with statistical averages and ignore the specific requirements of a specific item. Several experiments were carried out to compare the cutting conditions decided by the control unit to those computed (determined) by expert process planners, or through the logical approach of process planning, and demonstrated the benefit of using cutting conditions designated by experts.
3. Usually, processing an item calls for several cutting passes: a rough cut and a finished cut. The rough cut requires a machine with high power, and the processing time is relatively short, while the finished cut requires a machine with low power, and the processing time is relatively long. No single machine can provide these contradictory requirements efficiently.

Using a single machine, no matter how smart it is, will result in longer throughput time and a higher cost than multiple machines. Therefore, it is preferable to use several machines, whose power has been graded evenly, and run them from the main computer as part of the manufacturing system.

5.6 Manufacturing

The dominant manufacturing methods and concepts have been: the Management Information System (MIS); Production and Inventory Control Systems (PICS); Material Requirement Planning (MRP); and Computer Integrated Manufacturing (CIM). More than 140 different methods proposed to improve the manufacturing cycle had been counted by the end of 2014, and they keep on coming at an ever-increasing pace. Any one of the proposed methods may improve a certain aspect or several aspects of the manufacturing cycle. However, none of them improves all of the cycle's disciplines, aspects, and areas of activity. One method common to almost all of them is that production planning repeats itself at least four times, each time for a different purpose. To supply data to management concerning the status of resources and their capacity level in regard to already-placed or anticipated orders, a capacity plan is created without considering resource load or available materials. Also, the material requirement system needs due dates, which is a function of timely resource scheduling; as it is concerned with the material for all orders, it combines orders. Then, capacity planning is done in order to sequence the release of items to shop floor control. And finally, an accurate capacity plan is created for the shop floor for processing.

The proposed method is to engage in manufacturing planning only once, and accurately at that, thus making one able to supply the data both for each individual order and in regard to any of the company's functions.

The task of manufacturing planning is to make sure that management can create a plan to produce products in a certain quantity, at a certain quality and by the date at which they are scheduled to be delivered, all at minimum cost and maximum machine utilization. **That is all**. However, the commonly accepted notion is that manufacturing planning and control is a very complex task. This notion was correct in the past when manufacturing methods were developed according to the available tools of their time.

Today, however, computer capabilities can change the situation. This section demonstrates how new approaches, methods and technologies can introduce flexibility and simplicity into meeting management's manufacturing objectives. It proposes an innovative method that utilizes the present capabilities of computers.

When computer technology became common, there was a lot of talk about how it would change the scope of mathematics; how it would make it possible to compute the values of an equation to find the maximum or minimum values, without the need to find the first and second derivatives of the equation to establish these values. Since computers could do calculations very fast, we would only need to write a program to run the variables from the extreme values so as to indicate the maximum and minimum values.

Today, computer speed is several times faster than it was in the early days. It is amazing how, in almost no time, one can obtain a response to any inquiry, for example, what is the population of Philadelphia? Google can respond to any inquiry in a mere second. When you dial a friend with a smartphone, the recipient sees your name immediately. “WAYS” can direct you to any location you desire, show you a map of the location and your proximity to it in no time, and if you don’t care to follow the particular instructions it gives you, it will immediately present an alternate route. It is astonishing that when you listen to a song on radio, you can use an application that will tell you the name of the song, the name of the band, the names of its members, the year in which it was recorded, etc., all instantaneously. Do you know how many songs there are all over the world and how to select the one just by listening to it while you’re driving? [AU: The gist of this previous sentence is a bit confusing.] An automatic warehouse storing several hundred items can retrieve a particular required item faster than anyone ever imagined.

In short, today’s computers operate at truly astonishing speed. (The throughput capacity for Ethernet is *one million characters per second*.) They are smart, and possess both vast storage capacity and the ability to present shapes on a screen. They can retrieve any data that are stored in their memory and on disks of any type, solve mathematical equations, and solve and map out several dimensional matrixes at once in no time at all. Thus, they can convert a manufacturing system from one that is complex to one that is simple and flexible.

Human nature is very flexible: we set objectives and decide the methods through which we might accomplish them, however, when disruptions occur, we may alter the original decision in order to remedy the situation. For example: If one plans to go from point A to point B, than one studies the map and plans the optimal route to take. This is a present time decision. However, at another time when you have to move between the same two locations, say, at night, you might change the route. In winter, you probably will look for a route with maximum shelter from the rain and snow. 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 the original routing decision, if you run into disruptions, such as a blocked road (bottleneck), a traffic light or a major traffic jam, you might decide that instead of waiting, it is better to consult the road map and change the route in order to find a path with no obstacles. Such change is done at each junction. It might be a longer route, but it will be faster in regards to time. The original decision must not prevent one from adapting to the new route.

Such a method may also be beneficial for manufacturing planning and scheduling. But why was it not even considered? Because there is no roadmap to consult for an alternative route, there is no GPS to guide. A good process planner probably considers several processing steps, but his/her task calls for selecting one routing to be recorded in the company's databank, which is where the flexibility stops. However, if all of the steps considered for the process plan are kept on record, it can become the roadmap needed to introduce manufacturing flexibility. One detailed process plan may generate over 100 process steps, which may be tripled or more by a computer's process planning algorithms, and serve as a roadmap for production management. The proposed process planning method described in Sect. 2.3 of this chapter generates a computerized manufacturing roadmap.

5.6.1 Notions for a Simple, Flexible Production Planning System

The notions and tools listed here are in random order of importance:

- Production planning treats each order independently.
- The task of a process planner is to create a roadmap, and not to create routing.
- The system creates a **working product structure**, based on the level product structure, order quantity and due date, and then a roadmap for the items. A critical order m**ust be set and given** priority in production planning.
- The system eliminates or rectifies bottlenecks in production planning.
- Shop floor control is maintained through free resource searches for free operations.
- This enables alterations in the production plan at any point in the process.

The basic tools for production management are orders, product structure, and the data in the table of the process plan.

5.6.1.1 Shop Floor Control

Shop floor control (SFC) in a batch type manufacturing environment is regarded by the current research community as a very complex task.

The purported complexity is a result of the systemic approach in which inflexible decisions are being made at too early a stage in the manufacturing process. It 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 a production management system, proposes that in order to introduce flexibility, routings should be regarded as a variable.

5.6.1.2 Concept and Terminology[7]

The proposed 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 just finished an operation, the part having been removed, or one that 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 the auxiliary jobs are available, and which is within reach of the resource. An intermittent operation is one for which the previous operation has been completed and the part has been unloaded from the resource that performed the previous operation, and which is within reach of the required resource.

The term ***operation*** has a different meaning for production management and scheduling than it does for technology. A ***production management operation*** considers an operation to be a set of all of the activities done on one resource, from the loading to the unloading. It does not give any indication as to what these operations are. Production management operations (routing) are used for production planning and scheduling, while technological operations are used for the setting up of resources 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.

5.6.2 Job Released for Execution

The objective of this stage is to set the release of jobs for shop floor control. The strategy is to set priorities to the critical order, in which critical is defined as being the order the lowest level item of which has to start at the earliest time. The earliest time might be in the past, or in the future, or on the exact day of the planning date. To effect this strategy, the first step is to build a product tree on a time-based scale (Fig. 5.3), instead of on a product level-based scale (Fig. 5.2).

The time-based product tree is constructed backwards from the order delivery date. The name of the order is retrieved from the level-based product tree (level 0) and the cost process planning tables (Tables 5.3 and 5.4) are called to compute the processing time. The processing time of such an operation is given for a single item. The total processing time is computed by multiplying the order quantity by the processing time of a single product.

Next, each item of level 1 of the same order is treated individually, using the finish time of level 0 as the delivery date. The finish time of the level 1 items is the

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[7]The material in this section has been adapted from the book Gideon Halevi All-Embracing Manufacturing—Roadmap System, Springer 2012.

And Gideon Halevi book Industrial Management-Control and Profit—A Technical Approach, Springer—Lecture Notes in Management and Industrial Engineering 2014.

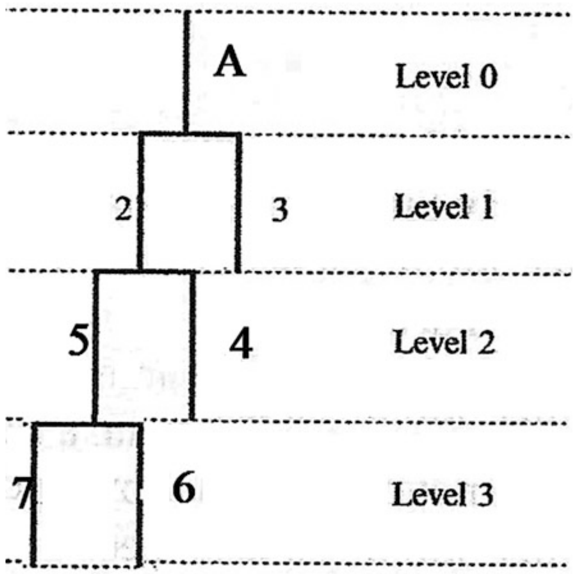

Fig. 5.2 Level-based product tree

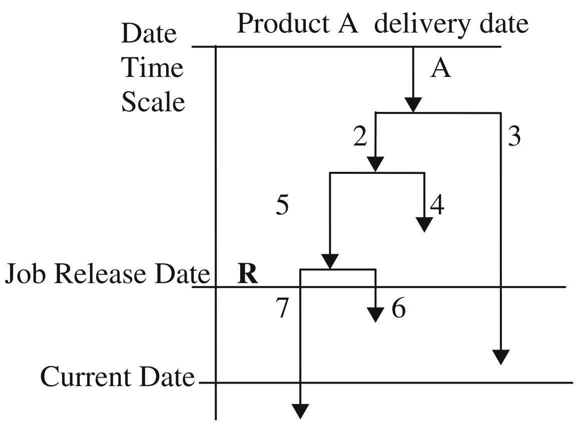

Fig. 5.3 Time-based product tree

due date for the level 2 items, and so forth. This process is repeated for all levels of the order and for all the orders in the file.

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 working product structure represents the activities that should be engaged in order to fill the customer orders.

Table 5.7 3D Resources–Operations–Items

Op	PR	R1	R2	R3	R4	R5	R6	BEST
	I	T	E	M		#3		
10	00	12.5	9.51	5.15	99	4.02	6.54	5
20	10	5.04	3.93	2.55	99	99	2.82	3
30	20	6.28	4.86	2.98	2.53	2.47	3.44	5
40	*10*	*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	*00*	*3.12*	*3.17*	*4.02*	*3.27*	*99*	*99*	*1*
20	*10*	*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	00	3.12	3.17	4.02	3.27	99	99	1
20	10	6.15	4.2	8.05	9.3	99	99	2
30	*20*	*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	00	4.6	3.60	2.39	99	2.05	2.60	5
20	10	5.96	4.59	2.87	99	99	3.28	3
30	*10*	*11.5*	*12.8*	*11.9*	*11.2*	*13.1*	*99*	*4*
40	30	99	99	99	99	1.45	1.72	5

5.6.2.1 Construct Resources–Operations–Items Table

The system scans the time-based product tree (Fig. 5.3) of all orders to determine which jobs should be released to shop floor control for execution. It is up to management's strategy to determine the time frame period for release. An example in Fig. 5.3, the line marked by "R", indicates that items 7, 6 and 3 are ready to be released. The two-dimensional process plan table of all the selected items is used to construct a 3-D Resources–Operations–Items process plan table, as shown in Table 5.7. Such a table is constructed once for the time base and once for cost. These two tables are reversible and supplement each other.

5.6.2.2 Scheduling Concept

The scheduling cycle starts by scanning (see Table 5.7) all resources in search of one that is free. The free resource scans all free operations, as indicated by the "00" value in the PR column, and lists them. The best operation for a resource can be based on a 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 on another resource. This is done by scanning the operation row across the resources column.

If the list is empty, this means that there is no free operation available for processing that particular resource. Hence, the resource becomes idle, waiting for an appropriate operation. Idleness is a waste of time, such time that could be used to process a free operation, which, despite an increase in processing time, might be economical. Therefore, the system searches for a free operation that the idle resource, despite not being the best resource for the job, can perform more economically. One method for computing the economics of using an alternate resource 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[8].

As an example: suppose that the quantity is 100 units, and the best processing time is 5 min. The processing time of the alternate resource is 6 min and the time that machine would otherwise spend waiting is 150 min. Thus, the economic consideration is as follows.

To produce the operation with the best resource, it will take $5 \times 100 = 500$ min; to produce the operation with the alternate resource, it will take $6 \times 100 = 600$ min, 150 of which it would otherwise spend waiting. 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 the subsequent operation is more economical or better in terms of performance for this resource, then the subsequent operation is allocated to that resource. More economical or a better performance means that this resource is the best one for this operation, or that its processing time (or cost) minus a transfer penalty is equivalent to or lower than the best time of that operation. A *transfer penalty* is defined as the time/cost needed to transfer a job from one resource to another. It includes set-up time, inspection, storage, material handling, etc.[8]

In the case of a resource breakdown, no special treatment is needed. It will be marked as busy, and hence it will not be regarded as a free resource in the scanning cycle.

In the case of an item being rejected, the product structure is consulted to determine if it will hold up assembly. If so, all items required for that assembly are no longer needed and will be removed from the list of released jobs for the period.

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[8]This material was published in "Self Organization Shop Floor Control", Digital Enterprise Technology, G. Halevi. 2007.

5.6.3 Algorithm and Terminology[9]

Shop floor control starts with a list of the jobs that should be processed during the relevant period. Such a list may be compiled from the production planning module, or from any other source. The list is:

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 commence, some auxiliary jobs have to be performed. The auxiliary jobs are:

- Fixture design and build
- Tool preparation
- NC program generation
- Material preparation (inventory management and control)
- Material handling (transport)
- Quality control (preparation of method and tools)
- Set-up instructions
- Set-up job instruction

Each of the free jobs retrieves the two-dimensional process plan matrix (as shown in Table 5.4) from the company database and constructs a 3-D matrix process plan (as shown in Table 5.8, 3-D: 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*** indicates the time remaining for the item to be processed. When loaded, it is set by multiplying the quantity by the processing time, as indicated by the 3-D matrix, and it is updated at each scan cycle by the time elapsed since the last scan cycle.

[9]The material in this section has been adapted from the Springer book, 'Intelligent Systems, Control and Automation: Science and Engineering All-Embracing Manufacturing Roadmap System', Authors: Gideon Halevi.
DOI 10.1007/978-94-007-4180-5, **Volume 59, Chapter 3, Figures 3.5 and 3.6, Excerpts (pages 66–71) 2012. With permission of Springer.**

Table 5.8 3-D matrix status when R4 is idle

Op	PR	R1	R2	R3	**R4 IDLE**	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 stores 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 with actual performance, so as to determine 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 those resources that are free, and updates the resource counter. The sequence cycle loop starts whenever the processing of an operation is finished. At this point, the resource becomes idle and a decision has to be made as to its next assignment.

Sequence cycle time is the time elapsed between the 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.

Shop floor control[10] is based on the concept that whenever a resource is free, it should search for a free operation to process. A free operation is identified by scanning the "PR" column in the 3-D process plan matrix (Table 5.8). 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 the resource 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 equals 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 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 of 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 of that operation. The operation is allocated to that resource, the resource status file of which is updated and its counter set to the new operating time.

As an example: Table 5.8 represents the shop floor status at a certain time. Operation 20 of item #7 was just finished, having been processed on R2, and operation 30 became free. The best resource for this operation is R4, at 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 time to process on R2 is 8.92. The increase in time is $8.92 - 7.23 = 1.79$. Assume a transfer penalty of 25 min and a quantity of 40 units, making the increase in time $40 * 1.79 = 71.6$. Therefore, only 25 min will be saved, and thus it not economical.

Another case: Operation 20 of item #9 was just finished, having been processed on R3, and operation 30 became free. The best resource for this operation is R4, at 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 time to process 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, making the increase in time $40 * 0.4 = 16$ min. Therefore, the saving will be 25 min, a clearly economical amount, and R3 will process operation 30.

If it is not economical to process the next 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

[10] Adapted from Gideon Halevi book Industrial Management-Control and Profit—A Technical Approach, Springer—Lecture Notes in Management and Industrial Engineering 2014.

operations, marking them as to which are best. This list includes all free operations that the specific resource is best suited to handling.

If the list contains only one entry, then this entry (operation) is allocated to the resource, the status file of which is updated and its counter 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 matrix and computing the difference in processing time between the best resource and the other available resources. Each free operation will be tagged by this difference value. The free operation with the highest tag value will be the one allocated to the idle resource for this sequence cycle.

Table 5.9 demonstrates this algorithm: R4 is the idle resource, and there are four free operations for which it is best choice. The system scans these operations across all resources and computes the difference between the minimum time (BEST) and

Table 5.9 Status when R5 is idle

Op	PR	R1	R2	R3	R4	R5 IDLE	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**

the time it would spend 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 (meaning it is not the best choice for that resource), the BEST field in this row indicates which resource is the best one 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 shown in Table 5.9, which displays the status of the 3-D matrix at this stage. R5 is idle and searching for a free operation (PR = 00). A scan of the "BEST" column of the table finds that none of the free operations calls for resource R5. The BEST choice for the free item #3, operation 40 is resource R4. Calling up the *resource status file* for resource R4 raw indicates that operation 40 is in process and will take another 25 min to be completed, which means that waiting time for operation 40 is 25 min.

The system checks if 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 alternate operations, 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 use that resource. The computation is as follows:

Processing the free operation, item #3, operation 40 with 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; thus, by working "inefficiently" and increasing the processing time by $(5.93 - 5.78) * 100 = 15$ min, a savings of $(25 - 15) = 10$ min in throughput time is attained.

Checking the other three open operations indicates that this is the best alternative. Therefore, item #3, operation 40 is loaded onto R5.

If the finished operation was the last one in the processing of an item, the data of that item is removed from the 3-D matrix, summoning the bill of material for another item. The data for the new item (item name and quantity) are recorded and its process plan from the two-dimensional matrix master file is introduced into the 3-D matrix.

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 once again in working condition. 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.

5.6.4 Summary

The task of the production module is to plan and produce products according to management orders and policy. The major conventional objectives of the task are:

- Meeting delivery dates.
- Keeping the capital tied up in production to a minimum.
- Minimizingmanufacturing lead time.
- Minimizing idle time of resources.

Traditional systems usually meet only some of these objectives. Their system is based on using several stages, such as Master production planning, Material requirement planning, Capacity planning, and, finally, Shop floor control.

The proposed system recommends moving from orders to shop floor control. The flexibility that is built into that system can meet all of the above management objectives.

The minimum cost is inherent in the system through the use of a process cost table.

Meeting the due date is achieved through the flexibility method of assigning jobs to resources.

Minimizing lead time and idle resources is achieved through the concept of a free resource search for open operations.

Traditionally, the job release stage was done 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 into the shop floor control.

The proposed system recommends a shop floor control method that does not plan the routine for each released job in advance, thereby avoiding bottlenecks and solving disruptions automatically. It is permitted to alter the process when necessary.

This method is a tool that can generate a process, considering the immediate state of shop floor, and do it within a split second.

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.

The simulation results are shown in Table 5.10.

Table 5.10 Comparison of scheduling strategies

Optimization criteria	No. of periods to process	Unit cost
Maximum production	35	162
Minimum cost	32	76.2
Semi flexible	23	131
Book method	21	102

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