A Systems Approach to
AMT Deployment

A SYSTEMS APPROACH TO AMT DEPLOYMENT

Edited by

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Preface

The *raison d'être* for writing this monograph is to encapsulate the experiences of colleagues in the University of Wales College of Cardiff and from the University of Central England in Birmingham (formerly Birmingham Polytechnic), who have been working together for many years on solving startup problems in the introduction of advanced manufacturing technology (AMT). This research has required considerable shop-floor involvement. It is our firm belief that the latter activity is an essential ingredient in ensuring quality research into improving the performance of modern manufacturing systems. Furthermore, to better guarantee good collaboration from industrialists so that real plant may be used as a live laboratory, it is also reasonable to expect that the problems identified and solved during such research shall have direct user benefit. It is also logical, therefore, that the output from research programmes should be presented in a form which can be readily accessed by production managers and vendors' engineers alike.

For this reason, the Science and Engineering Research Council ACME Directorate encourage wide publication of research results, within the bounds imposed by commercial confidentiality. One avenue is to write up methodologies and experiences in the form of a "work book". This monograph is thus the "work book" which has resulted directly from the SERC ACME grant "Systems Engineering Methodology for Efficient AMT Introduction", which has been executed jointly by the University of Wales College of Cardiff and at the University of Central England. The editors were two of the four principal investigators, and most of the team who took part in the research appear as chapter authors within the book. In addition to SERC ACME support it has also been possible to integrate within the monograph the results of supplementary studies undertaken by postgraduate students studying for the MSc in systems engineering at Cardiff (strongly supported by SERC). A further vital input to the programme has been via the UK Teaching Company Scheme (strongly supported by both Cardiff and Birmingham colleagues) which is cosponsored by the SERC and the Board of Trade.

The principal investigators who had prime responsibility for the SERC ACME research grant were, in addition to Denis

Towill and John Cherrington, Alan Davies at Cardiff and David Coward at Birmingham. This team of principal investigators collectively have very wide experience in industrial engineering, production technology and production management. We trust that this range of expertise is self-evident throughout the monograph. It is also highly appropriate to pay tribute to Mr G. Waterlow, SERC ACME Consultant, who through his wise inputs at SERC Panel Review meetings rendered considerable guidance on the execution of the project, and significantly influenced the nature of the output. His enthusiasm was infectious.

In providing a "work book" of immediate use to production managers and manufacturing systems engineers responsible for the planning and implementation of advanced manufacturing technology, we have brought together a number of different aspects which we believe to be important in ensuring smooth startup. This includes the problem of predicting long-term future performance, a subject which is very important but is often overlooked. After all, there is a shop-floor argument that the initial (low!) performance obtained from new machinery should form the basis of future wage settlements. Production management, on the other hand, will estimate the theoretical (high!) maximum output rate from the new product line, and use that as the datum for the same negotiations. What we show is that the difference between these two levels can be extremely large; they are both influenced by the quality of management, and in particular by the strategic planning used and implemented. The time scale over which the improvement is obtained is also a function of management inputs. Hence, throughout the volume we adopt an air of realism on what good targets should be, and on the degree of variability about the instantaneous trend line which management should regard as acceptable.

There is rightly a great deal of attention focused on the payback period for AMT. The initial performance, the final performance, and, perhaps even more so, the rate at which improvement is obtained, critically influence the payback period. In this sense it is not as simple a calculation as accountants might wish. The payback time scale is instead critically dependent on production management getting it right. Indeed, it could be argued that in UK industry the extremely tight payback periods which are usually laid down are extremely difficult to meet in terms of AMT investment. On the other hand, the case for AMT implementation can become overwhelmingly strong in terms of satisfying customer needs in terms of variability of product, flexibility of order patterns and consistency of delivery. These are important facets when seeking to compete in world-class manufacturing. Indeed, it is argued that in achieving international competitiveness UK industry is all too often excessively wedded to the concept of high machine utilization and low labour costs, unfortunately to the detriment of customer service. The contrary approach, that of total quality management, seems to pay off, since there is rapidly increasing evidence that although price remains important it is less critical to business stability than satisfying customer demands on time and to the right quality standards. Indeed, to ensure that these criteria are met, customers are often willing to pay a price premium! It is in this context that the case for AMT investment becomes extremely powerful.

In some respects, ensuring smooth introduction of AMT is similar to any other learning curve, or progress function application. There are, of course, many differences and these are also made apparent throughout the book where the causal paradigms become highly significant. The history of our involvement in this topic is extremely interesting. The senior (in terms of age!) editor, D.R.T., first became interested in learning curves as far back as 1968. A former colleague of his (Fred Bevis) was at that time a principal investigator on an ESRC research project engaged on studying the long-term performance improvements of operators performing repetitive tasks under "typical" industrial conditions. Fred built up a huge database, but needed some "inspiration" in terms of data processing and exploitation. It was at this stage that D.R.T. conceived the idea of relating learning curve performance to models of the industrial dynamics type. Not only does this concept lead to very clear definitions of the curves which might be used to represent learning curve phenomena, but it also has the considerable advantage of providing a "structured" family which may be tested until the simplest adequate model is found which will suit the specific application.

Since those early days, this family of learning curve models has found worldwide recognition, and uses far beyond the areas envisaged originally. Perhaps the most interesting applications, which certainly could not have been imagined in 1968, have included modelling the reliability of human operators controlling nuclear plant, forecasting the future needs of the UK electricity supply industry, and predicting the number and distribution of particular kinds of Australian chemical process plants which are needed to meet anticipated market demand. Maybe imitation *is* the finest form of flattery! More importantly, our approach is firmly based on well-established systems principles which are natural tools for engineering graduates to use.

The prediction side of learning curve modelling has also taken off on a global basis. The original predictive method was published in 1970 and became widely known as the Bevis–Finniear–Towill algorithm. This was based on the classic iterative least-squares-error curve-fit approach based on a Taylor series expansion to cope with the non-linear form of the model. Further developments (and incidentally PhD theses) have included Kalman filter representations, and a number of maximum-likelihood curve-fit procedures. Improved convergence properties have recently been added to the original Bevis–Finniear–Towill algorithm, a development which has been found particularly helpful. Whether or not companies investing in AMT use such algorithms to predict performance online is not so much the issue (although we clearly believe that targeting and monitoring in this way is valuable). It is even more important to build up (and keep adding to) the world wide database of AMT startup curves for comparison and guidance, especially under circumstances where causal relationships can be added.

We have, in this volume, consistently referred only to learning curves. We know that there is considerable debate between social scientists and engineers on subtle (though important) differences between "learning curves" and "progress functions", but for the vast majority of our projects, and management investigations, we have needed to use the learning curve representation. This is because for management control we need the information available in the output-rate-vs.-time format. However, we accept that there are other instances in which it may be helpful to plot information in the form of cumulative average costs against accumulated output, or indeed, in many of the other forms in which progress functions have been plotted.

Nevertheless, our need is to be able to guide production management on *what the performance of the line should be today*. This is so that corrective action can be taken, including additional resources being made available on a properly conceived priority basis. It is also the form in which production management needs predictions to be made in order that we can forecast delivery times, payback periods, etc. For our industrial environment, the learning curve format does appear to offer overwhelming advantages. At the same time, we accept that perhaps not enough attempt has been made to reconcile the two approaches. The best that we know of was due to the late Graham Harvey (formerly of British Aerospace). He was also a prime-mover behind a very important international conference on learning curves and progress functions which took place in London in 1981. It was curious to us to find that it took so long to hold the first truly international conference on a topic which is clearly extremely important in terms of enhancing business performance.

Turning now to the actual contents of the book, Chapter 1 sets the scene for AMT introduction into an industrial company. A brief description is given of the problems of organizational and operational control, and a proposed implementation strategy listed which covers a seven-year time span. Ten major traps in corporate planning are then highlighted, together with the reasons why relatively limited attention appears to be given to these important factors. Since the implementation of AMT invokes the principles of project management, these are reviewed as background for the substantive later chapters.

Organizational factors found to influence the successful introduction of AMT in small companies is the major contribution of Chapter 2. A combined top-down–bottom-up systems approach has been adopted, which includes a study of the investment culture of the company. Classification techniques were used to analyse the data summarizing the culture of some thirty UK companies. Of particular significance is the result that 70% of the small engineering companies interviewed make capital equipment investment decisions unaided and in very difficult circumstances. A further interesting feature to emerge is that although computer-based data collection and interpretation systems are now comonplace, so that more reliable data are available to aid decision-making and to help provide performance standards, the strategic benefits of AMT to a company, e.g. the removal of bottlenecks, increased throughput etc., did not appear to be a significant factor in AMT selection. (As is shown, this is an opportunity lost.) It is emphasized that before introducing AMT, a manufacturing assessment, a marketing assessment and an innovation and manpower assessment must be undertaken. This is a prelude to establishing the project culture in which the AMT is to be introduced, and the operational culture which will ultimately drive it, successfully or otherwise.

In Chapter 3, the argument is put forward that "profiling" a range of industrial companies is helpful in arriving at guidelines for AMT selection and implementation. The "clustering" technique used is based on a number of factors relevant to the background of an individual company. These include resources, planning, marketing and training, experience with new technology, and manufacturing methods. As a consequence of the output from this chapter, it is possible to group companies in terms of the likely problems which they will face when introducing AMT, and how their anticipated difficulties may be minimized.

Learning and startup curve models are the subject of Chapter 4. Much emphasis is rightly placed on the time constant model, which has been historically found to be a very good descriptor of a wide range of industrial startups. The sources of modelling errors are discussed, which leads naturally to reviewing the criteria to be used in model selection. This conveniently introduces the industrial dynamics family of learning curve models, and the "plateau" phenomenon. The chapter concludes with a set of paradigms covering sources of lost production in AMT startup, and provides a simple formula whereby such losses may be established directly from the learning curve parameters.

Learning curve modelling is of little use to the production manager if it is all undertaken historically. Chapter 5, therefore, provides an introduction to forecasting future performance via learning curve models. Only one algorithm is described in depth, which is based on least-squares-error interative curve-fitting following a Taylor series expansion in terms of the unknown parameters. Some typical industrial forecasts are included which give an indication of long-term accuracy.

The dynamics of AMT capacity planning form the basis of Chapter 6. Such planning makes extensive use of the time constant learning curve model, and defines the very useful index of performance known as the "standard cost of startup". Some examples of discontinuities in industrial operations are included, as is the "accounting" view of using best previous peak performance in estimating payback periods. An alternative viewpoint based on the Las Vegas modelling concept is also introduced. Despite the difficulties in determining the Las Vegas curve parameters, we believe the concept does have a role to play in setting future performance standards.

Chapter 7 changes the emphasis of the monograph towards facilities design. This involves the use of discrete event simulation techniques to predict flexible manufacturing system performance. In particular, there is the need to determine possible future bottlenecks, and hence remove these by providing the right ancilliary equipment as part of the vendor specification. Thus the chapter answers such questions as how many automatic guided vehicles (AGVs) are needed in order that these do not become the bottleneck which limits overall machine utilization or product flexibility.

Some FMS shop-floor experiences are described in detail in Chapter 8. These anecdotes relate particularly to system utilization, and the technological causes by which production is lost. This is the chapter in which statistical information on repair times and the technical nature of specific equipment failures are to be found.

The equivalent experiences in introducing AMT into machining cells are described in Chapter 9. Extensive accounts are given of the problems encountered with three particular companies. These are used in the form of case studies and include considerable "we were there" evidence which many production managers will identify with. They will also benefit from the implementation lessons thus learned. The chapter is exemplary in its description of the difficulties that are encountered in introducing shop-floor monitoring equipment in new areas of application.

It is a major thesis within this volume that the problems associated with the successful introduction of AMT may be categorized as arising from organizational, technological or attitudinal factors. Chapter 10 concentrates on the organizational factors which affect particularly the introduction and efficiency of AMT operation in the large firm. This includes a description of the methodology by which the factors were identified, and required extensive interviews with a wide range of company personnel. It is in this chapter that the reader will find much reference to the role of "product champions".

Chapter 11 is particularly interesting, since we were able to seek the opinion of a major international vendor of FMS/FMC concerning the implementation of a large number of AMT installations. The procedures adopted, and the preferred way the vendor wishes to interact with the end user, is extremely enlightening. A brief history of the technological enhancements available from this particular vendor are also included. Also, some lessons learned from an international machine tool show are described; yet again, these bring us back to the old adage that the routine for successful introduction of AMT involves simplification, automation and integration, *and in that order*.

Finally, Chapter 12 summarizes our preferred methodology for smooth AMT startup. It includes the importance of defining corporate strategy, the determination of the current level of AMT within the company, the requirements for the step change in technology which is to be introduced, the design of suitable implementation plans, the commissioning and installation of AMT, and the "on-line" monitoring and control of startup. The need for proper selection and training of staff at all levels is important, as is the continuous improvement action programme. Lastly, investment appraisal for AMT is discussed, and advice given on net cashflow concepts to be used in this particular area of application.

Acknowledgements

Many executives, industrial engineers, and shopfloor operatives have freely communicated their experiences to us to use. Not only have they been generous with their time, but their honesty in facing up to mistakes made during planning, implementation and operation has been exemplary. To them we owe a great debt of thanks.

To preserve anonymity, collaborating companies have been referred to by letters of the alphabet. Such designations are specific to the chapter concerned. In particular, there is no relationship between the industrial organizations concerned in Chapters 9 and 11.

We have already mentioned the wise counsel offered by Gerry Waterlow, the SERC ACME Consultant. Hopefully he will feel that this monograph is a reasonable tribute to his involvement. Nicholas Pinfield of Springer-Verlag was a great source of encouragement. Margaret Price and Carol Docker also learned to cope with the gestation phases of the book, and to deal with a crotchety senior editor to whom God has decided never to grant a "normal year"! Lastly, but not least, many thanks are due to all our partners and families for being so understanding and patient.

D.R. Towill
J.E. Cherrington

Contents

1. **Setting the Scene**
A. Davies and J.E. Cherrington 1

2. **Organizational Factors Affecting the Introduction and Efficiency of AMT Operation in Small Firms**
D.G. Coward and E. Schott 19

3. **Combined Company Profiling**
T.H.A. Burden 35

4. **Learning Curve Models**
D.R. Towill and J.E. Cherrington 57

5. **Forecasting via Learning Curves**
D.R. Towill and M.M. Naim 77

6. **Dynamics of AMT Capacity Planning**
A. Davies and H. Lewis 91

7. **Use of Discrete Event Simulation in Evaluating FMS Performance**
M.M. Naim and S.M. Hoh 109

8. **FMS Shop-Floor Experience**
A. Davies and M.M. Naim 125

9. **Case Studies Based on Three AMT Users**
D.G. Coward and J.E. Cherrington 141

10. Organizational Problems in the Introduction of AMT into the Large Firm
E. Schott and M.M. Naim 175

11. AMT Vendor Experience
M.M. Naim and E. Schott 191

12. General Methodology for Smoothing the Introduction of AMT
J.E. Cherrington and D.G. Coward 205

Index 221

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1 Setting the Scene

A. Davies and J.E. Cherrington

1.1 Introduction

Over the last few decades there have been countless surveys which have disclosed the difficulties involved in introducing new technology into manufacturing industry. Such surveys are usually conducted by external observers and consultants, who examine the attitudes of senior management to these difficulties. Our approach is to concentrate more on the behaviour of middle and lower managers, with emphasis on the detailed analyses of industrial performances in real time. These analyses involve a unique comprehensive system of information gathering including questionnaires, structured interviews, analysis of company data and the generation of our own data.

Another unique aspect is the detailed use of laws or learning curves to model the gradual improvement, if any, in industrial performance associated with the introduction of new technology. In the literature these curves are labelled learning, startup, productivity improvement, manufacturing progress and experience curves. In Chapter 4 the different structures of these curves are examined in some detail.

This book is derived from the research efforts of two academic organizations, the University of Wales College of Cardiff, and Birmingham Polytechnic. Active co-operation between the two organizations started in the early 1970s and has continued steadily since then. The initial stimulus for this co-operation was provided by the work of the Dynamic Analysis Group at the University of Wales, led by Professor D.R. Towill, in their research into the modelling of industrial startups in a wide range of market sectors. Subsequently, in 1986–9, the two institutions have collaborated on an SERC-supported grant for the development of a methodology for the successful implementation of advanced manufacturing technology (AMT). This investigation explored specifically the use of pallet-changing machining centres in stand-alone modes of operation as well as in flexible manufacturing cells and systems. Differences in the way these machines were utilized revealed different approaches by management to the formulation of implementation strategies. The main factor in the process was the amount of pre-planning undertaken before installation of the AMT.

Prior to this time a range of startup models had been produced to handle a variety of organizational activities from single-operator tasks, through group working to the modelling of complete process lines and factories. The developments and applications of these models are fully discussed in Chapters 4, 5 and 6.

Learning curve modelling has its roots in behavioural science around the turn of the century [1]. A famous initial industrial application was in aircraft manufacture as far back as 1926. Learning in most industrial situations is synonymous with and measured as improvements in productivity. In many cases it can be merely a change in working methods with hardly any input from new equipment *per se*.

Historically, it was noticeable that as the complexity of the applications increased a clear distinction occurred between organizational and operational learning. Indeed, many authors have preferred the term "experience curve" to denote organizational learning. Here the measure of performance is based on costs and profitability as well as direct labour output.

As described in Chapter 5, operational learning, though prone to wide variability in individual human performance, is easier to model and hence "explain" than organizational learning. In addition, the hierarchical nature of industrial learning means that organizational decisions in effect precondition operational learning performance.

A more detailed breakdown of the factors involved in operational and organizational learning is given in Fig. 1.1.

The three results of organizational learning, namely improved task

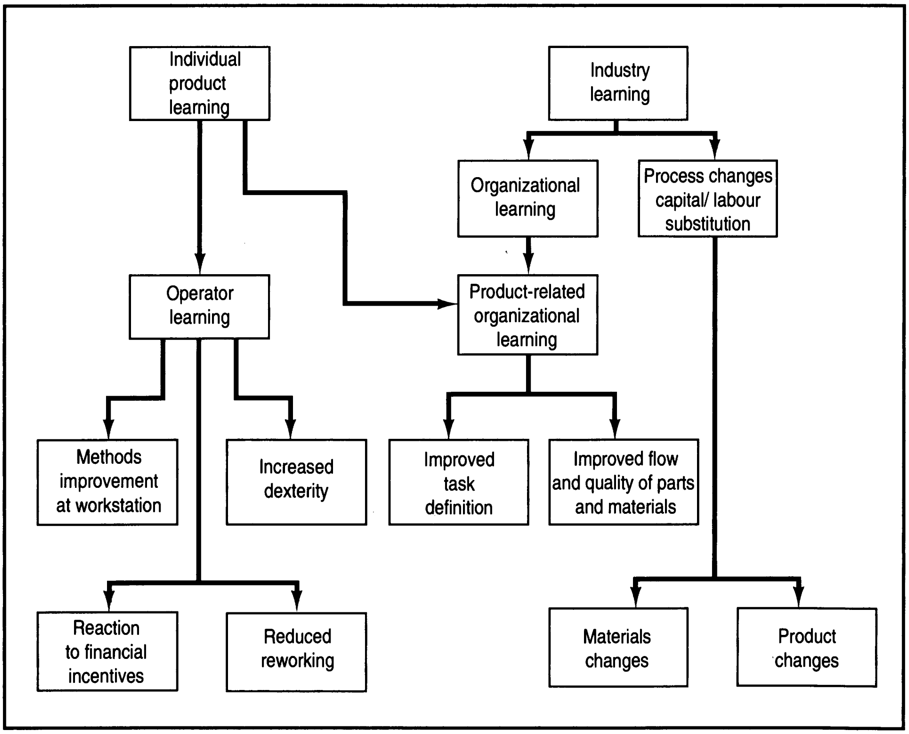

Fig. 1.1. Interaction of "product" and "industry" learning in a factory.

definition, material flow and quality, relate directly to the requirements for company competitive advantage, whereas results obtained from operational learning are usually categorized as productivity improvements.

Conceptually, it is possible to visualize the type of startup curve we may expect to occur when introducing a new item of production equipment. Figure 1.2 illustrates the "best" and "worst" case possibilities for 24-hour unmanned machining. The target values with respect to machine utilization, contingencies, and planned maintenance are typical of a wide range of manufacturing companies who realistically define 100% performance as the equivalent of an 18-hour working day.

In the majority of companies there is no intention to regard 24-hour unmanned machining as a practical production schedule. Most firms recognize that to attempt to achieve such utilization could be counter-productive. There would be no slack left for routine maintenance, or for any of the many contingencies which are bound to arise in unmanned machining. The effect of unforeseen events, particularly when they "get out of hand", can result in a delay in system startup and an extension of the time required to achieve steady-state output.

Three possible startup curves are shown in Fig. 1.2; each is linked to the professionalism and planning expertise exhibited by the engineering staff of a company. Ideally, pre-production trials should eradicate all the problems associated with both the equipment and the organization which will support it. In practice, however, the time allowed for debugging is usually restricted by payback considerations and consequently problems tend to occur in production startup. The resulting utilization curve is usually a function of the depth of involvement and detailed planning undertaken by the company prior to the equipment installation.

Bad planning contributes to a poor startup performance, and this is characterized by a low initial output with high scatter around a slowly rising mean utilization. Conversely, good planning produces a quick, low-scatter startup, in which there is a fast rise to the steady-state output from a high initial value.

Many companies appear to add advanced manufacturing technology to their organization in a very "*ad-hoc*" manner, often based on dubious justification and an emotive presentation by a dynamic personality within the management team. This is obviously not the best way to proceed when a large amount of capital is involved, for without a corporate plan which lays down the precedence and conditions for each stage of AMT introduction, the company runs the risk of investing in a system which they cannot use efficiently and which may have an extended implementation time.

The lack of experience of AMT at any particular level, along with the lack of an effective organizational infrastructure appropriate to that level, will combine to reduce the possibility of either a good system startup or satisfactory progress towards total integration. Accordingly, each stage of AMT introduction must be carefully considered in relation to the company as a whole and senior management satisfied that conditions "within and without" the company are correct before implementation is allowed to proceed.

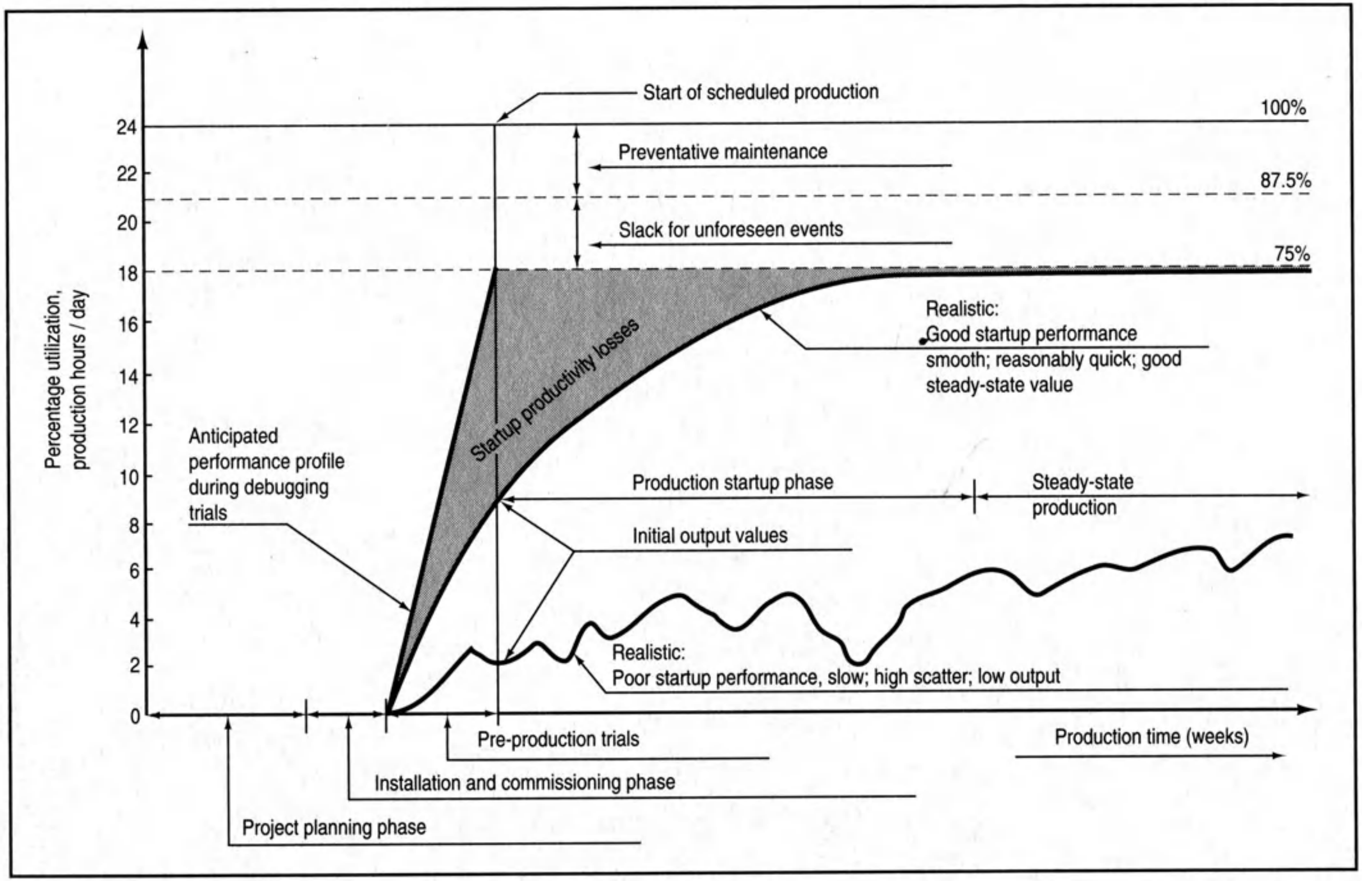

Fig. 1.2. Conceptual startup curves for unmanned production using AMT.

1.2 Organizational and Operational Control

It is a well-known tenet of classical control theory that the major outside loop determines overall system performance. This principle is illustrated in Figs 1.3 and 1.4 by showing strategic organizational decisions in the major control loop.

Figure 1.3 follows classical theory in its identification of desired input, control decisions, measured feedback and controllable output. From time to time we will refer to the setting of targets and the responsiveness of firms in meeting these targets as part of a closed-loop control philosophy. Control theory modelling has been the prime source for the "time constant" learning curve models developed as part of our previous research. In Chapter 4 servomechanism examples are quoted to show the historical basis for the time constant models.

A simplistic version of the decision-making process required for the successful implementation of AMT is shown as Fig 1.4. The block "organization of facilities" is identified once again as the controlling element for both major and minor loop performance.

It is generally accepted that effective organizational control ensures that strategic improvements can be achieved in overall company performance. Examples of these are enhanced capacity and improved quality, delivery times and stock levels. Conversely, if improvements are limited to the operational level and more specifically to a single stage in a multi-stage process then quite often the improvements are localized and do not contribute to overall performance. This unfortunate situation is not uncommon and results from a resource utilization approach to manufacturing strategy. This aspect will be covered in detail in Chapter 2.

1.3 Background of AMT Research

Both academic institutions bring to the study of the implementation of advanced manufacturing technology (AMT) experience in the use of startup

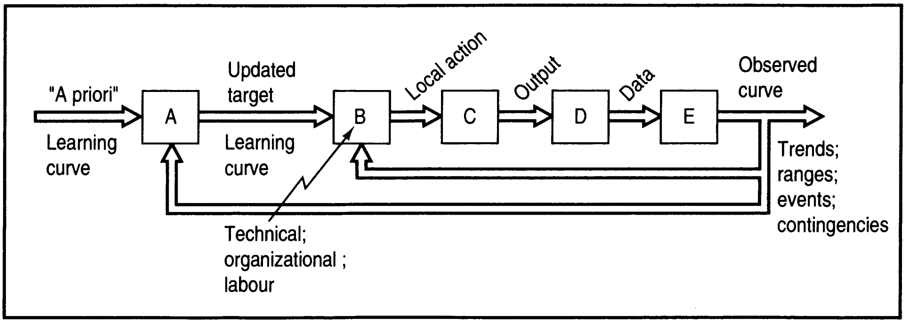

Fig. 1.3. Concept of using a learning curve model within a computer-based management information and control system. A, strategic decisions; B, operational decisions; C, manufacturing activity; D, performance logging; E, trend modelling; arrows denote direction of multivariable flow.

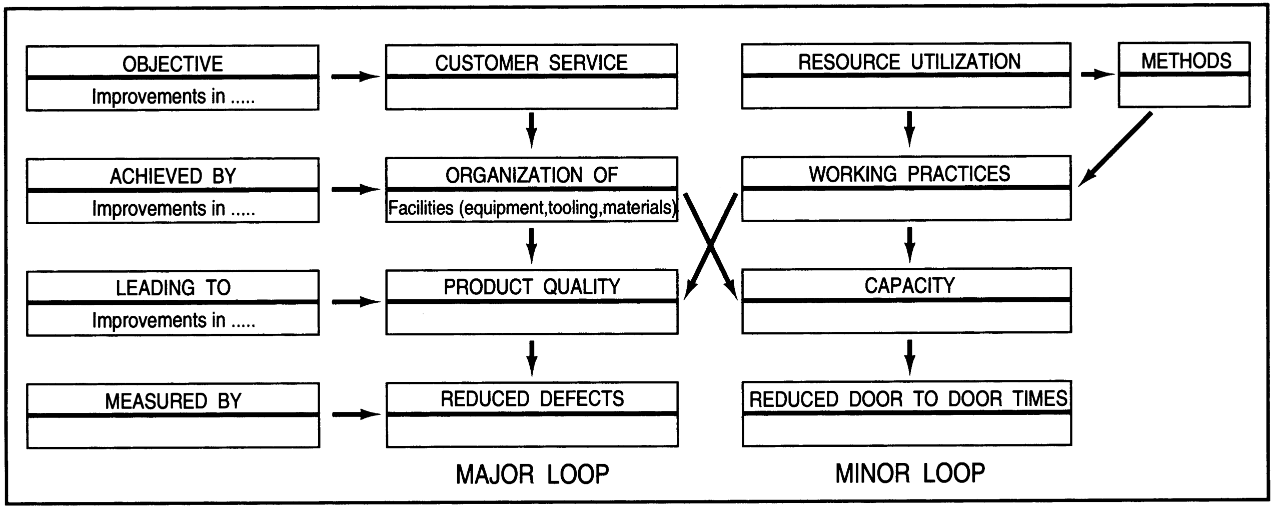

Fig. 1.4. Decision-making in implementing AMT.

learning curve models based on classical control theory, which is by definition a necessary component of the general systems approach.

We argue that the introduction of AMT into any company may be modelled, monitored and controlled using the systems approach as simply another startup situation, subject to the required organizational facilities being available. It is perhaps advisable now to define what is meant by AMT and to comment generally on experiences quoted by industry.

We are indebted to the report on AMT [2] produced by the National Economic Development Office (NEDO) in May 1985 for their definition of AMT. The publication is also useful for a variety of other reasons. The report refers to AMT as being *any* technique, technology or system that represents the best modern practices successfully implemented in the UK. This wide-ranging definition includes some applications which have already been modelled successfully by standard learning curve models. Other applications, such as those described in Chapters 5, 6 and 8, require modifications to be made to the standard models.

In order to construct a general methodology which encompasses *all* AMT applications it is necessary then to include other techniques such as project planning and method study.

Returning to the NEDO report, it suggested that most of these best modern practices are computer-based. In fact the report proceeded to examine the impacts of computerized inventory control, production control, numerically controlled machining, design, manufacture, assembly, testing, storage and parts issue.

Furthermore it proposed a four-stage, seven-year strategy for implementing AMT in batch manufacturing. The product examples quoted are similar to the ones we studied, so the strategy is of extreme relevance.

Activities forming the strategy are here reproduced as Table 1.1. The report also identifies the main areas where organizational problems may arise. Some of those listed are:

Unsuitable organization structure
Inadequate detailed planning
Lack of management commitment
Insufficient training
Poor communications
Incomplete involvement of employees

All of these aspects directly affect the compatibility of organizational and operational planning and control. The other areas mentioned, inaccurate records, poor engineering data, piecemeal investment approaches, reliability of equipment and underestimation of software requirements, also influence this compatibility, if indirectly. References to all these problems are made in later chapters when describing specified case studies.

The stated ultimate objective of the NEDO strategy is to produce a fully integrated factory. This implies that the introduction of any computerized system should ensure the full compatibility of information flow with existing and planned systems in order to achieve the "intangible benefits" of AMT implementation. This requirement should be evaluated again during the organizational planning stage of the methodology.

Table 1.1. Implementation strategy

Stage 1 (1 year)
Review of manufacturing strategy
Consultation with employees and their trades unions
Selection of applications and technologies
Specification of equipment
Start of training programmes
First equipment ordered

Stage 2 (2 years)
Computerized inventory control
Initial installation of CNC machines
CAM in support of new machine tools
CAD

Stage 3 (2 years)
Computerized production control
Further investment in CNC machines with supportive CAM
Improvements/automation of assembly and test areas
Integration of CAD with CAM

Stage 4 (2 years)
Flexible machining systems
Automated handling and storage of parts and material to manufacture and assembly

Ignoring compatibility with other computerized systems will at best reduce the success rating of the implementation or at worst make it a failure, perhaps even leading to liquidation or loss of autonomous control.

1.4 Development of Manufacturing Strategy

Prior to the work of Skinner [3] the analysis and construction of manufacturing strategies had been neglected by both academia and industry. Manufacturing had been seen traditionally as supporting the formulation of corporate and marketing strategies, which have themselves been thoroughly investigated in the literature. Many studies of the various pitfalls in the corporate planning process have been made, so the design and implementation of corporate strategy follows apparently established procedures. Table 1.2 was published in 1972 and identifies ten well-known traps in corporate planning which are just as relevant to today's problems.

Many reasons have been advanced for the limited attention given to the formulation and implementation of manufacturing strategy. These range from the low social status given to everyone associated with manufacturing to the fact that the hard data obtained under controlled conditions which academics require cannot often be found in manufacturing departments.

A number of authors have reported that there is a growing recognition of the need to examine the process by which manufacturing strategy is developed. Anderson et al. [4] differentiate between the process or "how" of strategy and the content or "what" of strategy. The process components include analysis, organization and implementation issues as distinct from the content features of objectives, decision and final results. Again, Adam

Table 1.2. The ten major traps in corporate planning

1. Top management assuming that it can delegate the planning function to a planner
2. Top management becoming so engrossed in current problems that it spends insufficient time on long-range planning and the process becomes discredited among other managers and staff
3. Failure to develop company goals suitable as a basis for formulating long-range plans
4. Failure to obtain the necessary involvement in the planning process of major line personnel
5. Failure to use the plan as standards for measuring managerial performance
6. Failure to create a climate in the company which is congenial and not resistant to planning
7. Assuming that corporate comprehensive planning is something separate from the entire management process
8. Injecting so much formality into the system that it lacks flexibility, looseness, and simplicity and restrains creativity
9. Top management failing to review with departmental and divisional heads the long-range plans which they have developed
10. Top management consistently rejecting the formal planning mechanism by making intuitive decisions which conflict with formal plans

Adapted from a study of 215 companies by George Steiner: published as *Pitfalls in Comprehensive Long Range Planning*, Planning Executives Institute, 1972.

and Swamidas [5] suggest that the vast majority of existing literature in this field is of the case study type, where the emphasis is placed on the analysis of manufacturing strategy rather than its synthesis. Hayes and Wheelwright [6] state that general guidelines to the formulation of manufacturing strategy are available. Their work on the focusing of resources has been widely accepted as a means of designing such strategies. Focusing implies concentrating resources in terms of volume, product/market and process splits. In their later work they suggest that specific rather than general advice is now required.

All the above authors have influenced us in our motivation to produce this monograph and in the shaping of its contents. One of our objectives is to encourage the collection and evaluation of learning data and to provide analytical tools which will be of service to both academia and industry. As is shown in Fig. 1.2, the construction of a learning curve enables productivity losses to be determined from the area between the curve and the target level. Analyses of these losses for several startups are detailed in Chapters 4 and 6. These analyses will, we trust, be of direct interest to practitioners. Quite often we find that statements of the type, “Do you know that you have lost X productive hours due to fault Y over the last Z weeks, and the estimate for the next Z weeks is even worse?” have a galvanizing effect on manufacturing managers who have hitherto displayed little interest in learning curve parameters.

The aspect of differentiating manufacturing strategy into process and content components has influenced the design of the book. The initial chapters concentrate on process features identified as organizational factors, while the later parts of the book refer to specific case studies which address the content of manufacturing strategy and which have enabled us to synthesize a general methodology for the implementation of AMT. Emphasis in these later chapters is consequently on technological factors.

The definition of a manufacturing strategy is a prerequisite for successful corporate planning, for which typically Hill [7] adopts a sequence such as: define corporate strategies; determine marketing strategies to meet these objectives; assess how different products or services qualify for and win orders; establish appropriate mode of manufacture; finally, provide the manufacturing infrastructure to support production. This text concentrates on the last two steps and assumes that the first three have been developed, although they may require refining by suitable iteration.

There is also universal agreement that the formulation of a realistic corporate strategy relies on the simultaneous, two-way transmission of information to and from senior management. The so called "top–down" and "bottom–up" approaches to strategy development interface at the junction between organizational planning and operational control and it is at this critical interface that any mismatch between corporate, functional and individual objectives is recognized. Information in some forms, such as that contained in market planning and utilization reports, by nature flows primarily one way, but in other cases such as product and process development this is not so. An inability to encourage two-way movement of information between individuals and systems may have disastrous effects on the successful implementation of AMT. Harrison [8] also advises that any approach involving infrastructure, product development and process selection must emphasize a policy of continual adjustment, analogous to the philosophy of JIT (just-in-time), while this policy has to take place against a background of continual training and changes in the attitudes and skills of all employees.

One of the reasons often quoted for the failure of AMT is that its specifications were incorrectly defined in terms of the market/product requirements. A particular disappointment is the performance of some flexible manufacturing systems (FMS), which not only are unable to produce the full range of components they were designed for [9] but also suffer badly from reliability problems.

Traditionally this function would be the responsibility of middle management. Many companies recognize the importance of controlling the flows of information necessary to ensure compatibility of strategic and operational planning, and have consequently undertaken detailed examinations of the role and education of middle management. In some cases, complete levels of management have been removed. Such a step has of necessity been preceded by a comprehensive training programme to remove both the technological illiteracy of senior management and the lack of business knowledge of supervisors and technical support staff. Encouragement of team working is essential to remove the natural scepticism of senior managers as regards the enthusiasm of technical staff. Senior managers must be convinced that their company will secure some competitive advantage by increasing the level of AMT usage. This conviction can arise only from a perceptive and unbiased analysis of the benefits of AMT in relation to the firm's current and future trading position. Preparing such an analysis is not normally the province of technical staff alone, and really requires a project team with diverse skills in manufacturing management plus sometimes the support of specialist consultants. Voss [10] stresses the need for integrative effort between the line manufacturing function and the manufacturing technical support function. We would expand this requirement to include extensive consultation with shop-floor personnel. Failure to do so will compromise the integrity of the information fed back to management and lead to unsatisfactory performance of the AMT. This aspect of shop-floor data collection is explored more fully in Chapter 9. It is widely recognized that the collection of reliable data depends generally upon the state of industrial relations and specifically upon the design of reward systems. Our research methodology involved different approaches to this perennial problem. In some situations, as described in Chapters 8, 9 and 11, we analysed performance reports both formal and informal. In others we used sensors on machines to input data directly to quarantined microcomputers and thus to determine operating patterns of work. We strove continually to verify our data, either by using different methods of data collection or by building in logic checks. In this way we nullified the tendency for shop-floor personnel to distort information either deliberately or accidentally. It is difficult for consultants to obtain information in this manner, but we feel that in difficult situations particularly the effort expended is worthwhile.

1.5 Supporting Techniques

The implementation of AMT into a company invokes the principles of project management. These involve such features as top-level management support, close liaison with the main business functions of marketing, design, production and finance, a project team of technically qualified people led by an experienced manager, and communication procedures which consult and inform employees at all levels of the implications of the project for the company's strategic and operational plans – in fact all the essentials required to control the critical interface. Project planning and control specifically relies on the setting of project milestones, budgetary control and the scheduling of resources.

Each project has its own life cycle. As shown in Fig. 1.5, its progress is closely monitored using techniques such as cashflow analysis and network control. Sometimes corrective action is required to modify the progress or even in extreme cases to terminate the project. Arguably, then, project management is an essential sub-methodology of the AMT implementation methodology. The additional requirements for the overall methodology include the consideration of the effects of the implementation of AMT on the manufacturing strategy. Unlike the case with projects, there appears to be a reluctance in AMT implementation to hold post mortems. For this reason, recorded instances of the termination of AMT projects are rare. It appears that there is a tendency to accept performance below target provided it is superior to previous performance from manual machines. Any disappointing island of automation is then "lost" in a sea of manufacturing technology. However, progress curves are widely employed to monitor large-scale engineering and construction projects where long delays occur before acceptable performances are achieved.

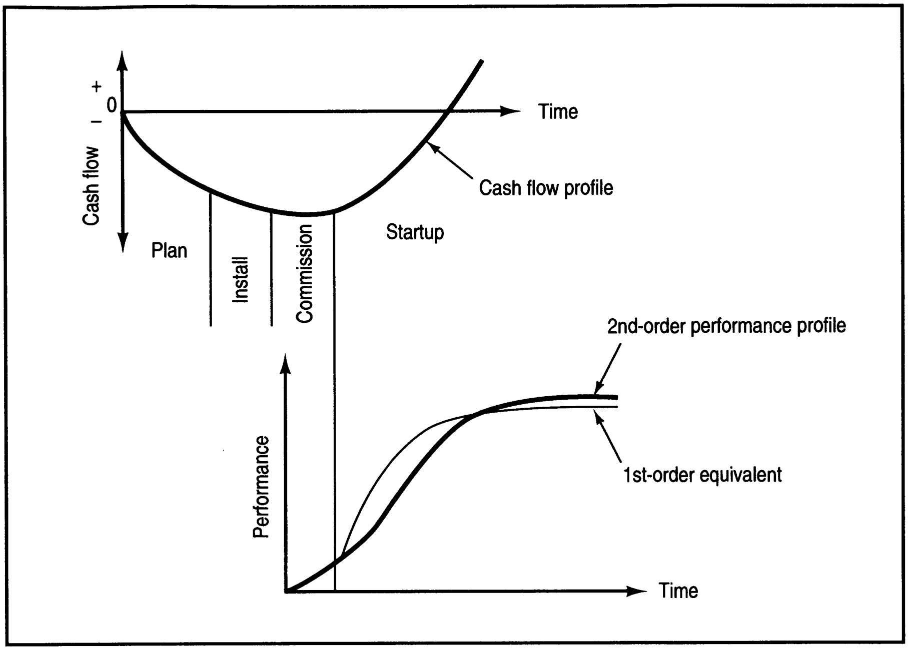

Fig. 1.5. Relationship between cashflow and startup performance.

Interpretation of the progress or learning curve parameters and associated productivity losses in these cases does require judgement. The interaction between time and cost as shown in Fig. 1.5 can produce surprising evaluations of the success or failure of an implementation.

Two examples spring to mind where there were excessive delays and consequently high time productivity losses. In the first example the company claimed back significant penalty costs due to "warranty" faults so that the total cost losses due to a delayed startup were insignificant. In the other example a firm was replacing a complete process line. At that particular factory space was not at a premium. Management simply cleared a space alongside the existing process line and instructed the vendor to install the equipment by a certain date. After this date if the equipment had not been accepted the vendor would have to make penalty payments for lost production, as well as a contribution to departmental overheads.

Before acceptance the supplier had to demonstrate several days of continuous trouble-free processing. In both these cases the users had enough knowledge to implement at least partially the AMT in-house. They preferred however to adopt a turnkey type of installation policy, because they had substitute production facilities available and could avoid undue interruption to their delivery schedules. Consequently, what appear to be implementation failures due to excessive time delays were in fact marginal successes when analysed with regard to costs. The transfer of responsibility for the AMT from vendors or project teams to users is a critical activity and must be planned in detail. To reveal fully the effectiveness of this transfer it is necessary to monitor and control performance well beyond the end of the startup stage, which is normally the point where a project team ceases its work. There are many examples quoted of plateauing and even decremental operator performance after the initial stage of learning.

One of the essential stages of work study involves maintaining control over a change in method well into the steady-state phase. This is also a desirable feature for AMT implementation methodology. Another step in method study relates to the detailed recording of performance by means of a set of standard charts, which detail non-value-added activities. Similar recordings should also be built into the manufacturing strategy, so that time cost comparisons can be made between existing and proposed methods of production. Charts showing man and machine working methods are particularly useful in determining the capacities of flexible manufacturing cells. Reference is made in Chapter 5 to a typical application.

Many AMT reports [11] infer that there are as many failures as successes and that all users are disappointed to a degree in their implementation of AMT. These users include companies who have received extensive government funding. Our experiences confirm this situation and we cannot identify a single company who have avoided all the pitfalls. Indeed, we have evidence that some well-publicised "successful" AMT installations do not in fact achieve all of their targets.

The success rate for engineering projects generally is not very high (as judged against UK accounting procedures). Cost overruns and tendencies to fall short of target performance are quite common. The reason perhaps most often quoted for poor performance in these cases is the fact that the project involves completely new technology, with associated risks in its application. This feature is not necessarily encountered when implementing AMT, although the technology may be new to the specific company.

In order to measure success accurately and to compare company effectiveness, the first requirement is to determine, by auditing, the starting performance capability of the company in terms of its structure and infrastructure, including existing AMT and the resources available to implement further AMT. In our studies the co-operating firms were interested and/or committed to the implementation of AMT. They were also prepared to allow us to conduct in-depth analyses of performances both off-line and on-line. They were, however, at very different starting positions with regard to their existing levels of AMT. For convenience we had previously defined five levels of AMT [12] which model the "step-by-step" approach for the implementation of AMT.

This approach ensures that engineering expertise and company experience is not outstripped by too rapid a technological change.

This gradual increase in corporate experience and its relationship to AMT usage is shown in Fig. 1.6, which provides a model for the prudent introduction of AMT and illustrates the links between learning curves, company profiles and the percentage of AMT used. Learning curves of the conceptual, time-constant type outlined in Fig. 1.2 exhibit a logical progression between the levels of system integration and AMT usage.

When evaluating the design of prospective AMT systems, each company must assess its own situation in this regard and weight the factors involved according to its own corporate objectives. Accordingly, management must create the conditions in which the company and the people working for it

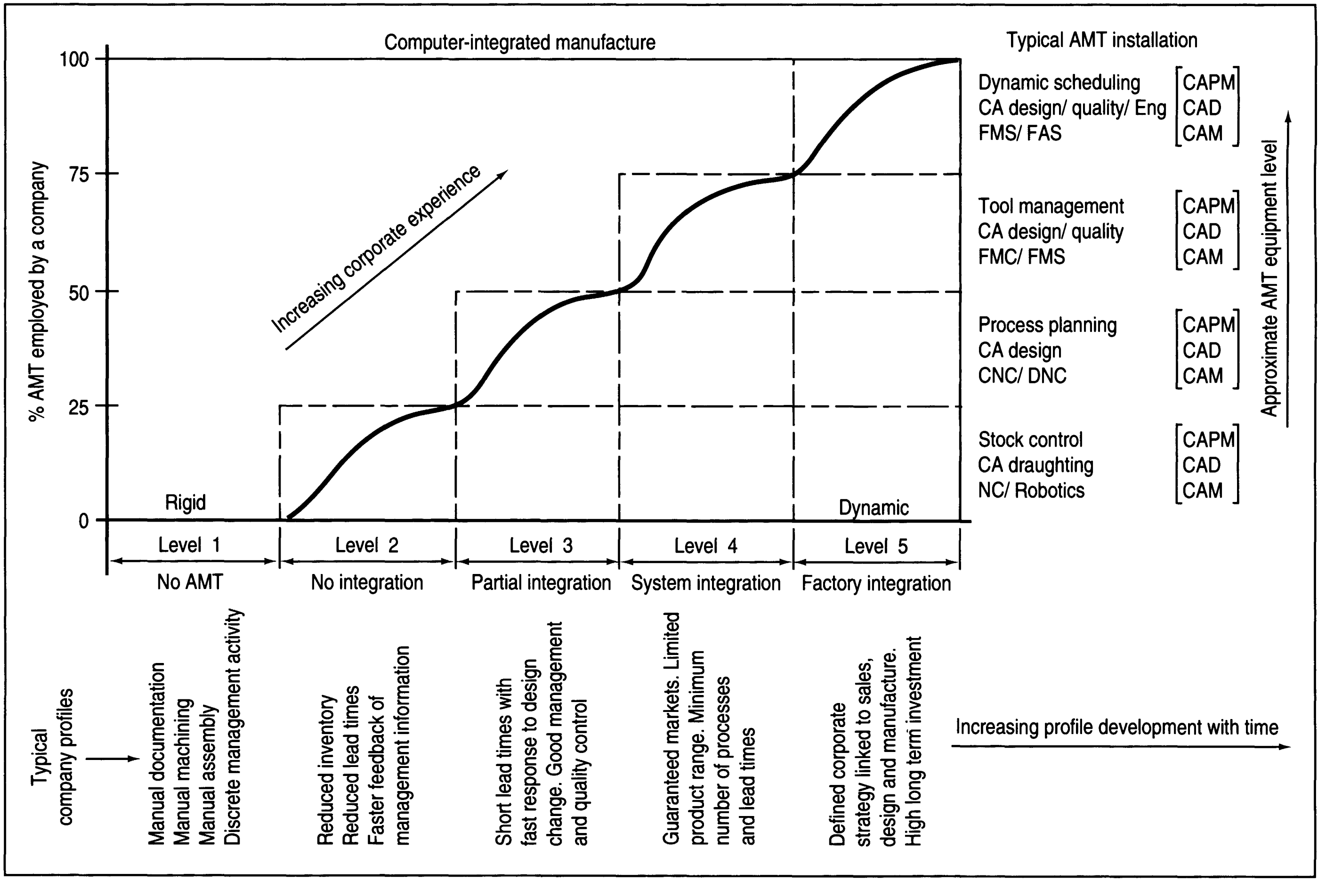

Fig. 1.6. Conceptual experience curves for increasing levels of AMT.

can absorb the changes which arise as a consequence of AMT introduction, and, as previously outlined, adapt the organization to new circumstances. The structure of manufacturing operations, the work environment, the nature of jobs and the ways in which jobs are organized all need to be rethought for the successful introduction of AMT.

As shown in Fig. 1.7, this inevitably requires a deliberate effort to be made by management in the areas of flexibility, teamwork, communication and consultation. In particular, trades union and supplier attitudes to AMT introduction must be considered. The effective implementation of new technology requires that it be a joint venture between all involved. The

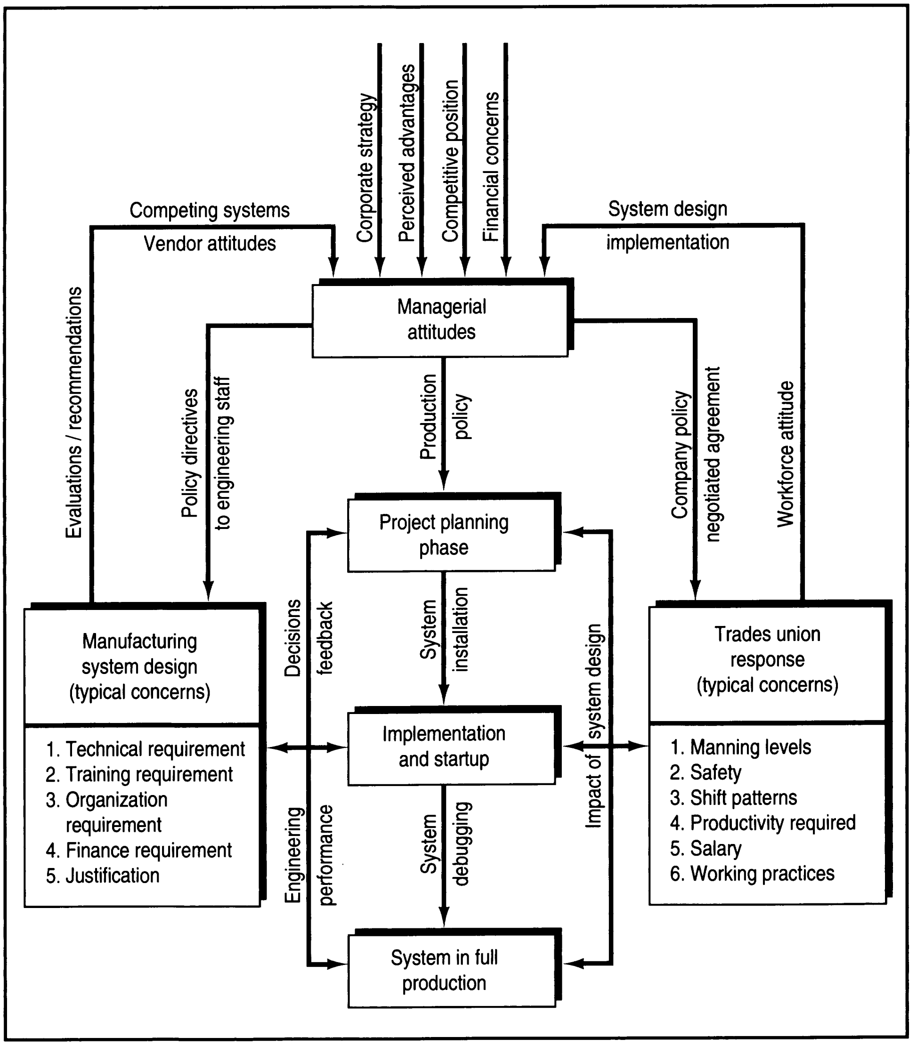

Fig. 1.7. Simplified attitudinal interactions present during AMT project planning and implementation.

obligation of the supplier and the client towards establishing a meaningful working relationship must be clarified at an early stage to ensure trouble-free installation. At the same time, trades union priorities with regard to new technology must be recognized as centring around, in the long term, the general enhancement of job security and the assurance that jobs related to AMT will remain within union jurisdiction.

The major changes in skill and responsibility, coupled with the actions and attitude of outside specialists, are likely to lead to tensions and insecurity among existing personnel at every level within the company. Consequently one prerequisite of successful company reorganization around AMT is the issue of adequate training, as without this there will be insufficient internal skills to grasp fully the highly complex and computerized new technology. An increase is needed not only in level of skill but also in breadth and types. Experience and integrated skills allow for flexibility and the ability to anticipate where problems are likely to occur. Thus the importance of information flow, teamwork and training on workforce attitudes should not be underestimated, since each can be critical to the acceptance and smooth introduction of an AMT system.

1.6 Preview of the Work in Succeeding Chapters

Recognition of the relative importance of organizational and operational control and of the formulation of manufacturing strategy has influenced the sequence and content of the following chapters. Chapter 2 reviews the general organizational and associated attitudinal problems involved in the introduction of advanced manufacturing technology into small business firms. Many writers have identified three problem areas, namely organizational, attitudinal and technological, in describing the introduction of new technology into industry. We feel that it is sufficient to subsume attitudinal factors into the other two categories because in our experience attitudes are the results of organizational and technological decisions taken in the past and are the basis on which such decisions will be made in the future. This approach is described more fully in Chapters 2, 8 and 10. The use of various knowledge acquisition and factor analysis techniques is described in these chapters as a means to define organizational attitudes to different aspects of manufacturing strategy, including investment strategy. These factors were grouped to enable organizations to be classified as dynamic, flexible or rigid. A rigid organization would be unable to incorporate new AMT and would typically lie at the lowest level of AMT shown in Fig. 1.6. As one would expect, there is a range of organizational profiles which lie between the ends of the spectrum of this figure. For instance, some companies may have profiles which overlap the neat demarcation lines shown therein, indicating that they are in the process of transition between the given levels. A precise definition of these levels may be difficult to ascertain in practice, giving rise to the concern that many firms do not effect the transition in a structured way [13]. The analysis and classification of companies continues into Chapter 3, where techniques such as cluster analysis are used to present the AMT starting positions of firms in the form of organizational and technological profiles.

From then on, through Chapters 4, 5 and 6 the organizational content per chapter decreases and is replaced by increasing technological content as shown by learning curve models, cusum analysis and other planning and monitoring techniques.

Chapter 4 examines the modelling of productivity losses in terms of strategic and operational planning and control. A series of learning curves is shown as an aid in classifying these losses. Planning decisions are identified by the availability of resources. The use of startup models as a dynamic capacity planning tool is described in Chapter 6 and the advantages of simulation as a planning tool for FMS are described in Chapter 7. Up to Chapter 7 the material is of a general nature, relating to implementation of AMT at all levels. From Chapter 7 onwards this feature diminishes and specific reference is made to higher-level AMT in the form of flexible manufacturing systems and cells. Individual case studies are presented in Chapters 7, 8, 9 and 10. Chapter 8 introduces the concepts of AMT service profiles as part of an analysis of systems and equipment performance. The magnitudes of failures of systems and equipment are shown to be extremely serious.

The difficulties experienced in installing shop-floor data collection systems are described in Chapter 9, as part of an exercise to examine operating practices. The last two chapters introduce more organizational content at the expense of technology. Finally, Chapters 11 and 12 review the experiences of AMT vendors and present the general methodology for implementing AMT, respectively.

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2 Organizational Factors Affecting the Introduction and Efficiency of AMT Operation in Small Firms

D.G. Coward and E. Schott

2.1 Introduction

A number of authors have stipulated that organizational and human factors are more critical than technological factors in advanced manufacturing technology (AMT) project management and implementation programmes [1], but what are "organizational factors" and how can we identify them?

Are organizational factors the same as non-technical factors or are they (indeed should they be) restricted to human factors? Organizational behaviour theorists [2] characterize organizations by their formal structure, i.e. by size, the degree of centralization or decentralization, lines of authority and formal reporting chains [3]. Some consider the culture of an organization the most significant factor in the organization's profile, defining the culture in terms of the *modus operandi* of the organization, its overt and covert operational philosophy and the political interests of the "influencers" [4, 5].

A dictionary definition of the term organization [6] is "an act of organizing a body of people, a system or a society". The term structure is circularly described as "providing organization". However, because an organization is a physical entity it can be described objectively in terms of specific dimensions such as size, geographical distribution, the number of levels of authority within it, and the level or levels of existing technology [7].

The structure of a particular organization reflects that organization's primary purpose. The resulting structure may be scientifically designed and thus deliberate, or it may evolve informally on the basis of operational necessity. As the needs of organizations change (or more precisely, as the perceived needs of those in a position to propose and influence changes in organizations change), so the structures of organizations are modified to accommodate such changes.

Organizations are therefore dynamic entities; they have specific dimensions, they have histories and they are staffed by individuals whose personal influence, attitudes and experience help and continue to help determine both the organization's culture and its structure.

The assimilation of new technology puts the existing structure and culture of an organization under pressure. There will be new, previously unconsidered demands made on staff and the various support systems needed to supply and maintain new systems. Because new technology is a strategic asset it must be carefully managed [8]; senior managers of a company considering such an investment should therefore examine an organization's history, current structure and culture when considering the ability of the organization as a whole to accept and fully utilize the benefits of new technology. The appropriateness of an organization's "receiving" structure and culture (which includes the attitudes of those in a position to influence the culture) determines both the speed of the implementation and the degree of integration possible, i.e. the organization's ability to integrate new technology with existing technology and its ability to support new technology so that it is fully utilized and its full potential realized.

The authors have investigated the culture and the "receiving structures" of more than thirty companies considering and using advanced manufacturing technology (AMT). The purpose of the investigation was to establish if a "best fit" exists between the structure and culture of organization and the efficient introduction of AMT.

From a survey of over thirty small companies (employing less than 500 people) in the English West Midlands specific dominant organizational characteristics – cultural, structural and attitudinal – were identified using principal component analysis [8].

2.2 A Top-Down–Bottom-Up Approach

In all cases a thoroughgoing top-down–bottom-up systems approach to the investigation was adopted [9]. A professional engineer used questionnaires with a specific agenda, the analysis of company records and the independent collection of shop-floor data to investigate the organizational aspects of AMT investment.

The compilation of company profiles on the 30-odd companies investigated allowed the authors to identify significant organizational factors influencing AMT implementation and its management. The concept of a homogenous organizational culture or a single, identifiable management style to describe the operational procedures of an organization is naive. Just as an organizational structure reflects functional subdivisions of the main body of an organization, so the culture of an organization can be subdivided into separate domains or "functional" cultures. As a result of the authors' in-depth investigation of AMT investment, three specific subcultures have been identified within an organization which affect AMT installation, utilization and development. They are:

Investment culture
Project culture
Operational culture

The nature and effect of all three subcultures on AMT projects are discussed in detail in this chapter.

2.3 The Investment Culture

In order to establish prevailing attitudes among managers of small companies towards AMT investment, more than thirty company managers in the West Midlands were interviewed over a period of eighteen months. The companies were selected from the metal products and machine and equipment section in the Kompass Directory [10] as potential AMT users. Some were familiar to one of the authors who has over a decade of shop-floor management experience in the West Midlands and some were included on the advice of the Industrial Liaison Officer from Birmingham Polytechnic.

A handwritten letter was personally addressed to a named managing director or works manager informing the addressee of the intent and nature of the research and suggesting a time and date for a visit to discuss the matter. Failure to reply was interpreted as tacit agreement to the proposal. Some direct refusals to be interviewed were received, but every company approached completed a questionnaire and/or provided some background information on its structure and working environment.

The interviews were informal, lasting between one and two hours, and a full report was written up immediately after the visit. Answers to twenty-one questions were obtained on the following subjects:

The recent investment history of the company, i.e. capital investment levels

Investment proposal procedure and project evaluation

Financial returns required

Project management

AMT project proposals

Each company was coded by Standard Industrial Classification (SIC) and a Minimum Head List (MHL) number.

The results were tabulated (see Tables 2.1 and 2.2) as an example of a numerical representation of informed but subjective data and principal component analysis (PCA) applied in an attempt to quantify the results obtained. PCA is a statistical method producing weighted averages indicating the importance of a number of factors among many. A computer package, e.g. a statistical package for the social sciences (SPSS) allows the user to input 20, 30, 50 or 100 factors affecting a situation and the package produces a series of indices which are weighted averages of the most significant factors. The standard work on PCA is Harmon [11]. A set of variables with responses of different company types is shown in Table 2.3.

An array of correlation coefficients for a set of PCA variables enables the user to determine whether an underlying pattern of relationships exists between the principal components or most significant factors and whether the "source variables" are responsible for observed interrelationships in the data. In this instance PCA was used as an exploratory technique and applied to the information or data collected from the thirty-odd companies to detect correlations and groupings of significant factors affecting AMT investment.

When the results were interpreted and decoded, three sets of correlation coefficients emerged, accounting for 92% of the total variability.

The first factor or set of significant correlation coefficients accounted for

Table 2.1. A typical company response profile

Firms with more than 100 employees

Topic II *Capital expenditure* *Sheet no. 4.65*

SIC MLH	Industry description (interviewee)	Number of employees	Who originates capital expenditure proposals?	Are replacement suggestions positively encouraged from subordinates?	How rigorous is the project evaluation?
332	Centreless grinder manufacturer (production manager)	150	The production manager, who is also a director, plans the future of company's production.	Rarely gets any from inside his own office, but all proposals are evaluated.	Variable. Sometimes main group insist upon a second-hand machine from group or one of group products. Other times they can freely evaluate.
390	Gun trade and tools (works director)	200	Works director's job to plan the spending on essential projects.	No need for encouragement. Machines are replaced when necessary, according to age.	Very loose. The director relies on personal intuition.
339	Specialized machine builders (works manager)	150	Not much to do except to modify the policy laid down. Works manager is responsible.	No need. There is a continuous process of replacement.	Very general. Appraisal of new products and sizes. Often purchase a slightly larger machine.

Table 2.2. Typical answers to the twenty-one questions asked

Time elapsed since last investment

Years	0–1	1–2	2–3	3–4	4–5	5–6	6–7
< 100 employees	19%	32%	25%	6%	6%	6%	6%
100 < 500 employees	19%	50%	25%	0%	0%	6%	0%
Average	19%	41%	25%	3%	3%	6%	3%
Cumulative	19%	60%	85%	88%	91%	97%	100%

"How large is the capital budget?"

Employees	< 100	100 < 500	Average
Only occasionally spend	44%	32%	38%
Highly variable	32%	37%	35%
Regularly large: over 10% of turnover	12%	25%	18%
Regularly small	12%	6%	9%

"How detailed was the investigation into AMT?"

Employees	< 100	100 < 500	Average
"Rigorous"	6%	18%	12%
"Fair"	32%	32%	32%
"Poor"	50%	25%	38%
"None at all"	12%	25%	18%

"At what level of return does a proposal become acceptable?"

Employees	< 100	100 < 500	Average
Payback in 3 years or less (30% return)	19%	25%	22%
Payback in 3 to 5 years (20 to 25% return)	43%	12%	27%
Payback in 5 years plus (15% return)	0%	12%	6%
Variable with risk etc.	19%	19%	19%
Other criteria used	19%	32%	26%

42% of the total variability. In 42% of the companies visited the following findings occurred:

1. AMT was considered too expensive.
2. Low cost and secondhand equipment were favoured.
3. Detailed investigations into investment proposals were uncommon.
4. Equipment was frequently selected intuitively.
5. Payback within 3 years was not required.
6. Poor costing methods were acknowledged and modern methods, e.g. discounted cashflow (DCF), were used infrequently.

Table 2.3. Variables identified for principal component analysis grouping: variables identified versus type of company (actual numbers recorded)

Variable identified		Classification of firm*					
No.	Type	A	B	C	D	E	F
1	Recent capital investment	10	8	3	7	11	10
2	No investment for 3 or more years	6	8	9	2	12	8
3	Have a yearly capital budget	5	2	1	2	5	4
4	Need payback inside 3 years	4	9	4	3	10	7
5	Will accept 20% return on capital	6	3	2	1	8	7
6	Make detailed investigation	1	6	2	0	7	6
7	Use intuitive methods	15	9	10	9	16	12
8	Short delivery favoured	6	6	7	3	9	5
9	Low-priced plant favoured	6	2	5	3	5	4
10	Manpower more critical than machine investment	8	4	9	4	8	5
11	Low priority for plant renewal	5	5	7	2	8	6
12	Admit costing method poor	10	6	8	5	13	10
13	Favour secondhand plant	3	0	3	1	2	2
14	Labour shortage big problem	5	4	6	3	6	4
15	Carry out some post-installation studies	3	3	2	1	4	4
16	Use discounted cashflow methods etc.	0	1	0	0	1	1
17	New plant bought by present profit	11	12	9	9	15	12
18	AMT has not been considered	6	8	5	3	11	5
19	Do not have AMT plant	13	13	9	5	21	15
20	AMT not considered too expensive	12	3	8	3	12	8
21	Use digital readout or sequence machines	6	3	2	1	3	2
22	Suffer from cashflow problems	7	6	12	2	11	7

* Classification of firm:

A	less than 100 are employed
B	between 100 and 500 are employed
C	profit margins are depressed
D	owners run the business
E	management run firm for group or owners
F	manufactures own products

Factor 2 accounted for 30.9% of variability; i.e. in 31% of companies the following factors applied:

1. Plant renewal was given low priority.
2. There had been no investment in new technology in the last 3 years.
3. There was no capital equipment budget.
4. Cash flow was problematic.
5. Almost immediate delivery of new equipment was required.

Factor 3, accounting for 18.6% of the companies interviewed, demonstrates that 18.6% of small companies:

1. Buy plant when current profits are not high.
2. Have no AMT.
3. Accept a 20% return on capital.
4. Conduct a post-implementation review.

An analysis of the group of variables in Factor 1 is necessarily subjective, but collectively these factors effectively describe management attitudes to AMT investment.

Those interviewed admitted that poor costing methods and a lack of detailed investigation into alternative technologies resulted in managers using subjective and intuitive criteria for AMT investment, which in turn (with hindsight) resulted in the purchase of inappropriate, often secondhand, equipment. It was reported that a history of poor investment decisions produced as a legacy a rigid approach to investment in manufacturing equipment in general.

A lack of available funds is the main issue in Factor 2. This results in the lack of regular investment for a number of years – operating with a background of plant renewal is always a low priority. The absence of a capital budget is to be expected and the consequence is that when plant is needed it is an urgent unplanned activity and fast delivery of any available plant dominates the selection made.

Factors 1 and 2 together show that 70% of the small engineering companies interviewed make capital equipment investment decisions unaided, in difficult circumstances. Factor 3 is more encouraging because it suggests a more progressive attitude towards investment. In 18.6% of the companies there was an ability and a willingness to purchase plant using financial resources other than direct manufacturing profits. Accepting a 20% rate of return on investment demonstrates a company's confidence in their managers' previous capital equipment investment decisions.

Some type of post-investment, post-project investment appraisals were conducted in the 18% of the companies interviewed who contributed to Factor 3.

Collectively, these three factors and their associated correlation coefficients illustrate the most significant factors operating in the investment cultures of over thirty small companies in the English West Midlands at a time when Britain's economy was relatively healthy. The data collected and the interviews conducted at various levels in these companies over a period of 4 years demonstrate that managers of small companies typically place investment in new technology low on the agenda and are concerned more with short-term gains than long-term strategic advantage. This may be due to the fact that small firms tend to have "flatter" organizational structures, fewer strata and shorter chains of command. Senior managers are therefore primarily "hands-on" managers responsible for the day-to-day operation of the company and hence have less time than corporate planners to devote to medium to long-term strategic planning.

Traditional difficulties experienced by small firms (and reported in interviews) include a cashflow priority in order to stay solvent. In small companies revenue and expenditure are audited at frequent intervals over a short time-scale in order to monitor cash flow, solvency and continued viability. Small companies have neither the time nor the dedicated specialists available to investigate medium- to long-term investment alternatives as thoroughly as they would like under these conditions.

Earlier work [8] suggests capital investment in small firms is often undertaken piecemeal in the year following a favourable annual financial report as opposed to following a planned 3-to-4-year investment programme. Many small firms are not producing sufficient income to cover their overheads (owing to inflation and high interest rates) and are therefore not in a position to invest in capital equipment at all, while until recently the quality of data available in small firms was unreliable, inaccurate and/or inappropriate. Computer-based data collection and interpretation systems are now commonplace, so more reliable data is available to aid decision-making and to help provide realistic performance standards. However, some firms are still unable to explain their decision-making process completely; for example, when asked why AMT had been purchased the reply from some of the managers of the firms surveyed was that AMT was purchased because it produced a particular part well or performed a particular operation well. The strategic benefits of AMT to the company, e.g. the removal of a bottleneck, increased throughput, etc., were not mentioned.

The lack of in-house specialist knowledge in the areas of AMT investment appraisal, its long-term benefits and "less-tangible" benefits, i.e. increased process control, increased productivity, the ability to quote and meet shorter lead times, etc., are dealt with more fully in Chapters 10 and 11.

Typical summaries from questions answered by managers in over 30 companies surveyed are shown in Table 2.2, which distinguishes between companies employing less than 100 people and those employing more than 100 people.

Seven years after this survey 14 companies have ceased trading owing to bankruptcy or because they have been absorbed into some other aspect of the groups governing their operations.

The conclusions drawn from this survey are that without appropriate data, the personnel to produce an appropriate scientific analysis of those data and the availability of the necessary resources (men, money and machines) to respond appropriately to the analysis, the acquisition of appropriate new technology is unlikely. Investment in inappropriate technology is equally unlikely to produce hoped-for "solutions" to pressing operational problem areas, and a potential strategic resource will be underutilized and produce suboptimal results.

Another important aspect of an investment culture is the relationship that exists between company managers responsible for investment and local bank managers. A company manager supplies historical data related to the company's current and predicted cashflow when requesting loans and/or overdraft facilities for capital equipment investment, for example. A bank manager rarely appreciates the potential cashflow improvements that AMT can produce by reduced lead times, increased turnover and flexibility and consistent quality, for example, and company managers are rarely able to provide convincing arguments for AMT benefits in financial terms.

Coward and Cherrington have produced a performance assessment (for managers considering applications for capital equipment loans) for a major bank which includes non-financial criteria and is intended to bridge this traditional information gap.

The bank realized that historical financial data are of limited use when considering the commercial advantage of manufacturing equipment, and the consultancy produced a routine that enables local branch managers to assess loan applications on new, "non-financial" criteria covering three main areas:

1. A manufacturing assessment
2. A marketing assessment
3. An innovation and manpower assessment

A series of important basic questions were supplied for the assessor that provide insight into the culture of the organization and its financial indicators. The subjects of the questions include the managing director's perception of a wide range of factors affecting company performance, e.g. current manufacturing constraints, due date delivery performance, stock levels, investment plants, training programmes and market knowledge. Typical answers and supplementary questions are provided in this package. Figure 2.1 demonstrates the interview procedure, which is designed to elicit all the relevant 'non-financial' information affecting capital equipment investment decisions.

2.4 The Project Culture

The characteristics of an organization's investment culture obviously affect support for new projects, while the current economic climate determines the ability to invest and the advisability and viability of a particular investment proposal. A company's project history, its current and previous levels of investment and its project successes and failures undoubtedly affect its willingness to invest. The availability of suitably qualified and experienced staff to undertake such projects is also a critical factor affecting the project culture of an organization.

AMT projects involve substantial capital investment and an "AMT champion" to generate support for a project proposal and to take responsibility for the investment. Ideally, a company's culture should encourage a number of champions (see p. 177 of M. Harrison's *AMT Management* [12]). In the authors' experience it is essential for an AMT champion to have board level authority (a) so that he is in a position to persuade other board members of the appropriateness of the investment and (b) to ensure there is commitment to the project at the highest level.

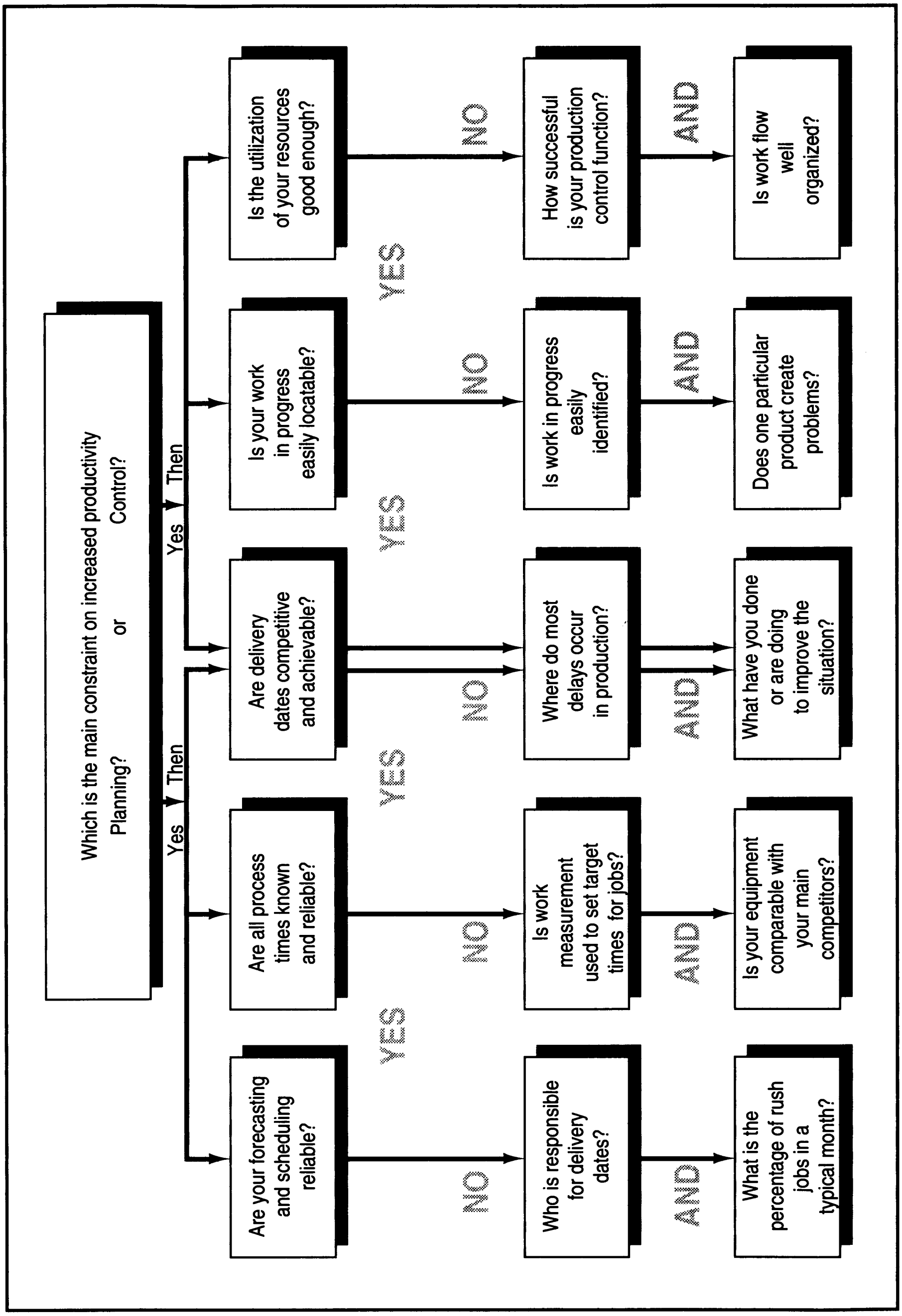

Fig. 2.1. An interview agenda.

The champion is therefore "an influencer" and in a position to influence. Whatever the champion's motives (improved career prospects, personal prestige, etc.) the onerous responsibility of an AMT ensures the champion will do everything in his power to meet the operational targets set by the board [13].

Project management may be the responsibility of the champion or may be delegated to a "project manager" who has the necessary enthusiasm, expertise and commitment to protect the champion's and the company's interests by ensuring the new technology is installed and is operational, on time, and within budget. It is also the project manager's responsibility to recruit and train system operators and supervisors. Training is usually carried out in-house, if necessary supplemented by specialist short courses which are supplied by the vendor in many cases [14].

Project management may be allocated to an in-house project team, or alternatively consultants may be engaged. A very successful AMT implementation which was investigated owed its success in part to the fact that two senior managers in a company employing only sixty people devoted a considerable time to the various AMT alternatives available as part of the selection of the most appropriate form of new technology for their particular company. To the work force the novelty of appointing two managers (rather than one) to appraise alternative technologies and the consultative and cooperative approach of the two executives was impressive evidence of the management's commitment to the project. The managers' commitment generated shop-floor commitment, and the resulting installation of a multi-pallet CNC solution was revolutionary for this company because the operators were trained to optimize production and not just to operate the new system. It was possible to introduce unmanned machining within 6 months. Operator intervention was reduced to a maximum of 2 hours over 2 shifts and operators were provided with alternative employment when they were not required on the new system [15].

At the proposal stage payback targets are established and production targets set to achieve payback, usually within 3 years. It is the AMT/project champion's responsibility to reach and maintain these targets so that the capital invested in the new technology is recouped. When the system has been installed and trials confirm that the targets set are achievable the project is complete and operational control of the system is usually handed over to shop-floor supervisors [8, p. 3; 12].

A programme of planned continuous investment provides more opportunities for project champions to gain experience and expertise in project management than does spontaneous investment, profit margins permitting. The more experience project managers have of (financially and operationally) successful projects the more likely will the board be to invest in new projects. Willingness to invest in new technology and the use of in-house rather than "bought-in" expertise are also interpreted as an expression of confidence in the company, its products or services, its staff and the future [16].

In a particular company visited in the West Midlands, workshop personnel reported that they had calculated the investment in machinery in that company by dividing the total number of machines in use on the shop-floor by the number of machines replaced in a year and they had discovered that at the present replacement rate it would take 150 years to replace the existing machinery [8]. If the replacement of plant is such a rare experience then how can companies considering investment in AMT appreciate the expertise involved in AMT project management, how can they appreciate the pitfalls and how can they hope to optimize the installed systems?

2.5 The Operational Culture

The operational culture of an organization strongly reflects the management style favoured by the board of directors and the senior staff of the organization. The management structure of an organization may be centralized or decentralized. Where authority is centralized, important decisions on the day-to-day running of the company are taken "at the top" by a small number of senior staff. Staff lower down the scale have to constantly "refer decisions upwards" because they lack the authority to do otherwise. An alternative organizational structure involves decentralization, where strategic decisions are taken at board level but the authority to make day-to-day decisions is delegated to a supervisory level within the organization. A centralized structure is normally associated with bureaucracy, a decentralized one with autonomy. It is possible for a single organization to exhibit both characteristics simultaneously, for example where the R & D section of a company is a relatively autonomous unit in a largely centrally controlled organization, or for a company to move more towards one form of organization or the other, depending on new leadership and new objectives over time.

Management style and structure also influences the degree of control over new technology which the board and senior managers will wish to exercise, delegate or retain. Because AMT is a critical asset, senior managers need to be confident that operational control is delegated to those who understand the board's priorities and its concern to recoup capital expenditure as quickly as possible. The management structure and management style in an organization therefore dictate how new technology will be operated and for how long. Senior management and the payback period determine appropriate manning levels and the number of shifts per day and per week needed to recover the cost of new technology [8].

Management "ownership" of an AMT project provides the authority to progress a project, but if ownership stops at the implementation stage of the project then medium- to long-term problems cannot be dealt with effectively [16]. Shop-floor managers and supervisors who are tacitly or technically responsible for the day-to-day running of the system do not have the time or the authority to eliminate larger, non-technical "organizational problems" such as the flow of goods and services across various sections of the organization serving the AMT, which causes interruptions, delays and stress for AMT managers and suboptimal production for the company.

Our research shows that an AMT champion who understands and is capable of operating new technology is far more likely to be sympathetic to the long-term operational problems encountered by shop-floor personnel than a champion who regards AMT primarily as a capital asset [15].

2.6 The Synergy of Complementary Cultures

It is essential for all businesses is to make a profit in order to continue to trade. Resources must be organized and distributed to provide products or services as effectively as possible in order to satisfy customer requirements, given the skills and expertise available. Customer satisfaction must be balanced against profitability, strategic decisions against short-term operational requirements and the resources available. These are the prerequisites of good business practice and good management.

Figure 2.2 shows how profit margins are affected as the target point is "pulled out" of the profit zone into a loss zone when there is a weakness in the monitoring, investigation and corrective action taken by management in any of the four areas indicated.

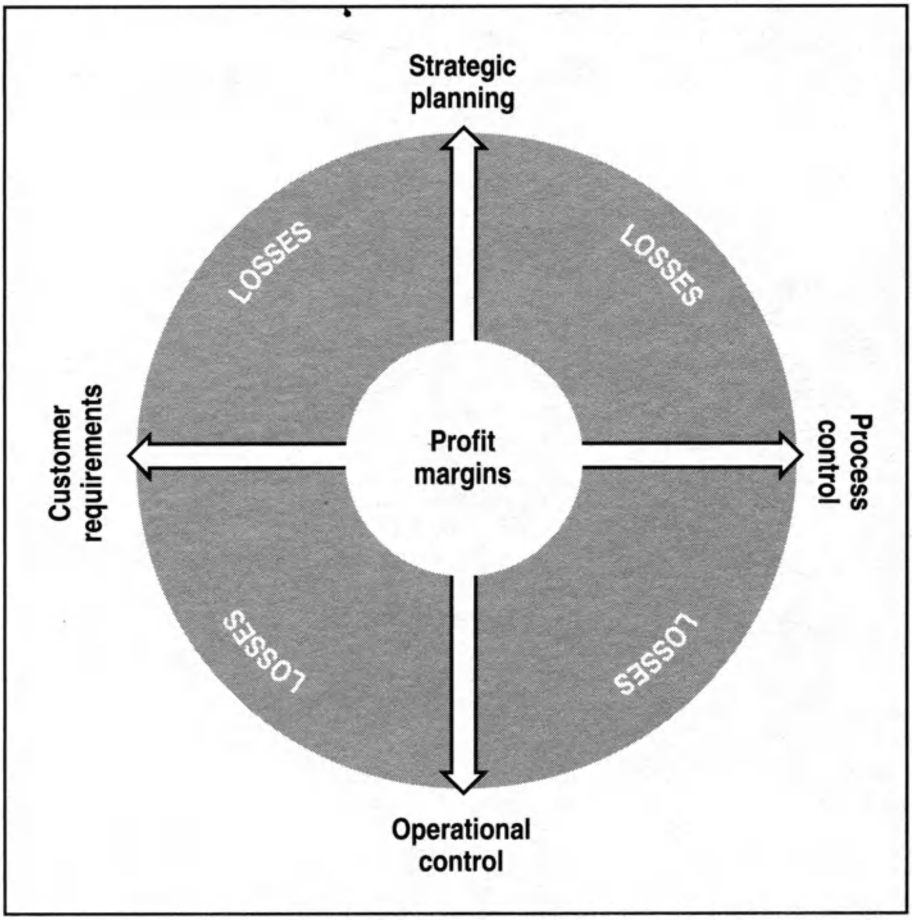

Fig. 2.2. How operational profits can be lost if a balanced set of conditions do not apply to overall strategy.

Strategic planning, or "long-term decisions", reflects the investment culture of a company. The project culture of an organization requires investment, so it is part of that culture, but the monitoring and feedback of short-term (day-to-day) decisions and operational management are in most cases functions of the operational culture of a company, which illustrates how inappropriate it is for existing or traditional structures and cultures to monitor, optimize and provide relevant data on the development of new technology and AMT in particular.

The size of the profit zone in Fig. 2.2 is also a reflection of the accuracy and appropriateness of information obtained from monitoring all four activities (together with the effective interpretation of the information and an effective response to such information) and a "weakness of response" in any of the four areas is considered a weakness in the various cultures of the company, which is frequently attributable to a lack of communication between the parties involved in successive stages of the production of goods or services.

In the various areas of research and in the application of the various techniques described in this book the authors have discovered the importance of the role that non-technical factors play in engineering projects in a production environment. For AMT project managers and supervisors technical specifications, time and money constraints are the priorities and it is part of the culture as a whole that the organization will somehow mould itself around the new technology on the basis that the new technology is more expensive, is usually more sophisticated than the existing technology and is the focus of senior managers' attention. The efficient installation and operation of AMT is an imperative because of the investment in capital and man-hours for the company. The reputation of the proposer of an AMT project is at risk if a project takes longer and costs more than was originally estimated and/or does not provide the returns anticipated in increased productivity, so considerable economic and organizational pressure is exerted by senior managers to ensure that the investment they have so vigorously defended appears profitable.

The appropriateness of the "receiving" company's structure, i.e. the ability of the flow of goods and services to flow smoothly across the various sections of the plant in which the AMT will be housed and the various aspects of the company's culture involved in AMT selection, implementation, maintenance and optimization, should be examined carefully by all those involved in the process of AMT implementation and support, while the implications for the organization as a whole should be reviewed and openly discussed at regular intervals, as seen from Fig. 2.3.

Organizational changes should be planned and not precipitated if expensive delays, production losses and suboptimization of the system are to be avoided. AMT exacerbates acknowledged and previously unacknowledged organizational problems which may have been tolerated in the past but will cause bottlenecks when new technology is introduced. Reducing and/or eradicating bottlenecks to speed the flow of goods and services to and from high-speed technology can also be expensive in money and man-hour terms. The flow of goods and services to and from AMT should complement AMT's speed and proficiency if the optimum financial, business and production advantages are to be gained from new technology. A "receiving"

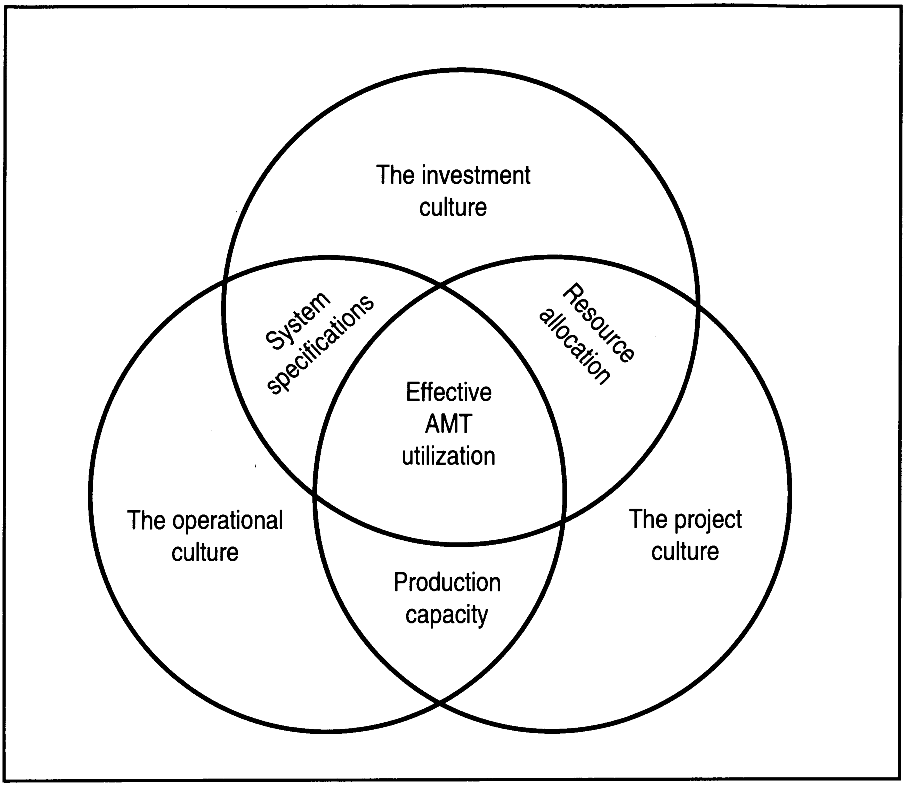

Fig. 2.3. Integration of cultures and organization to ensure effective use of AMT.

company's organization structure and culture should therefore be tailored to support AMT at the planning stage of such a project in order to facilitate its introduction and to maintain efficient production. The alternative is a series of costly compromises and continued suboptimal production.

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3 Combined Company Profiling

T.H.A. Burden

3.1 Introduction

The successful implementation of advanced manufacturing technology can result in substantial improvements in productivity and competitive advantage. The key words are "successful implementation"; the use of computer-aided production management systems and CNC machine tools has been widely documented. Unfortunately many implementations have not performed anything like as well as expected. The question has to be asked: Why? An obvious answer is the fact that manufacturing companies can vary enormously in terms of product, management, manufacturing technology, labour and last but not least financial backing. One of the first steps along the path to discovering what makes a successful user of AMT is the development of a classification system. If one company can be assessed against another then the possibility of defining the characteristics or elements required for the successful implementation of AMT should be greatly enhanced.

Perhaps the most significant feature in the successful implementation of AMT is the realization that it affects the whole company. Potential improvements in performance will be achieved only by integrating the objectives and strategies of the different organizational functions, particularly sales, design, manufacturing and finance. This chapter describes a technique which has been developed specifically for company classification. It is called "combined company profiling" and it allows organizational, technological and fiscal factors to be combined into an overall assessment of a manufacturing company. A combined company profile can be constructed to represent an individual company or a group of companies. Two sets of data will be used to demonstrate by example the construction and use of combined company profiles.

The first set of industrial data was collated under the auspices of a joint research project sponsored by the SERC. The results of this work were first published by Lewis et al. [1]. Subsequent developments in combined company profiling have been published by Burden and Cherrington [2]. The second set of data has been collated by a team investigating the use of company profiles as an aid to strategic planning in the jewellery industry; this project is also sponsored by the SERC. The results of preliminary investigations into the use of new technologies in the jewellery industry have been published by Burden and Draisey [3].

Table 3.1. An example of a simple technology-based classification index

Department	Hand tools in use	Power tools in use	CNC machine tools in use	FMC in use
A	Yes	Yes	No	No
B	Yes	No	No	Yes
C	No	Yes	No	No

3.2 The Development of Organizational and Technological Profiles

Before we go any further, one burning question must be answered: What is a profile? An example of a very simple technological index is given in Table 3.1. The profiles associated with this index are illustrated in Fig. 3.1. The profile allows the use of particular types of production equipment such as powered hand tools to be identified and compared with different departments in a company. One of the first technological profiles of this type was named Bright's index [4], after the American researcher who developed the technique in the 1950s.

More recent work by Bullinger et al. [5] and by Barber and Hollier [6] has further developed technology-based profiling techniques. They attempt to classify a very wide range of equipment including CNC machine tools,

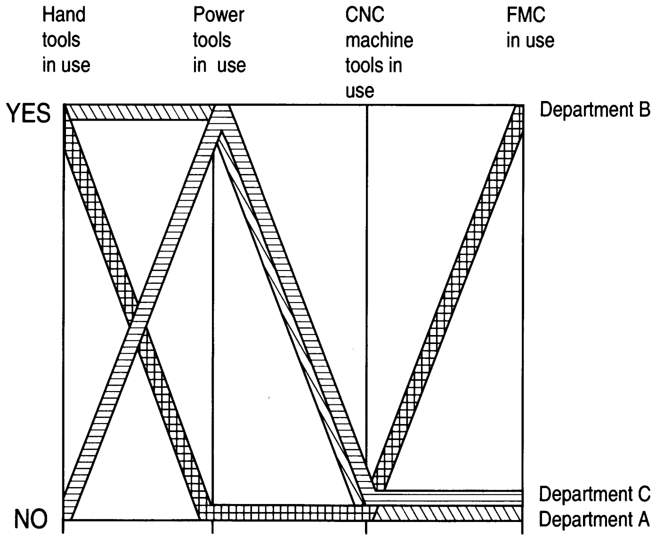

Fig. 3.1. Technological profiles of departments A, B and C (based on Table 3.1).

flexible manufacturing cells and computer-aided production management systems. A study of computer-aided production management in UK batch manufacturing by Monniot et al. [7] has commented on the overlap of modern manufacturing technology and company structures and organization. Take for example the use of materials requirements planning (MRP) to reduce inventory and work in progress. A successful implementation of MRP not only requires the introduction of computer-based systems to perform the MRP calculations and subsequent report generation but is also a challenge to the company's management to reappraise the entire manufacturing operation. The result is a manufacturing operation that is governed by management via the control mechanisms offered by MRP software.

The use of technological profiles originates from a "bottom-up" approach to the analysis of manufacturing companies. "Top-down" analysis based on the business and financial aspects of manufacturing companies has also been a topic for many research teams. One of the most prominent UK-based authors in this area is Hill [8], who has stressed the importance of order-winning as well as order-qualifying criteria as necessary prerequisites for an integrated manufacturing and sales strategy.

The problems involved in modifying traditional functional organizational concepts have been reported by Primrose and Leonard [9], who have extended the conventional manufacturing cost savings approach to the financial justification of AMT to a more detailed methodology embracing many factors which have been regarded as unquantifiable. Take for example the cost justification of a computer-aided design system. An improved draughting speeds of 3 : 1 are often quoted, but what other benefits does CAD offer? The ability to implement a design methodology around a standardized range of components can result in a number of advantages including:

1. Reduced time to design and develop new products
2. Reduced range and quantities of components

Such factors are difficult to quantify but can give a company considerable competitive advantage in the market place.

The classification and assessment techniques just discussed allow a number of different views and measures of a company to be gained. Unfortunately an overall assessment or measure of a company's ability to apply a single AMT system or range of systems cannot be achieved.

The desire to gain an overall assessment of a manufacturing company's ability to apply AMT, and the increasing overlap between the technology and the organizational structure employed by a modern manufacturing company leads naturally to the creation of combined technological and organizational profiles. The combined company profiling technique attempts to integrate "top-down" and "bottom-up" assessment methods, and the final outputs are profiles which indicate a company's "personality" and "state of health" in regard to the successful application of new technologies. Manufacturing companies who can not rapidly utilize new techniques and technologies are not likely to remain in business.

3.3 How to Create Combined Company Profiles

The first stage in the development of a combined company profile is the creation of a company model. The company model drawn in Fig. 3.2 shows the progression through three mainstream technological paths of design/quality, manufacturing technology and production management, plus a fourth path of business planning and strategy. This model was designed to illustrate profiles of companies who have their own product as well as ones who offer subcontract services. A profile is determined by assessing the stage states of a company or group of companies along each path.

The stage states are in turn determined by a classification index which includes factors relating to each path. The classification index for the company model shown in Fig. 3.2 is given in Table 3.2. This is based on thirteen variables which were selected in an attempt to maximize the extraction of information from existing questionnaire returns. The data-

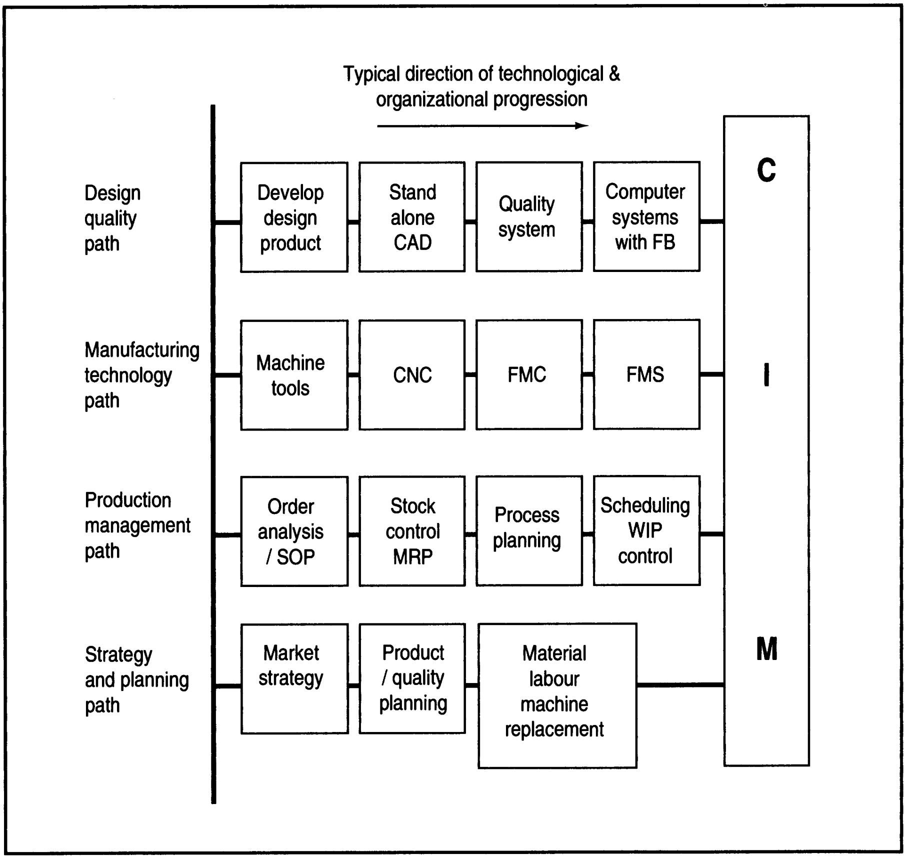

Fig. 3.2. Diagram of generic company model showing paths leading to computer-integrated manufacture (CIM). FB = feedback exists.

Table 3.2. Combined technological and organizational classification index

Path	Factors	Characteristics and scores		
		Low	Medium	High
Strategy/ policy	Demand forecasting	1 Is demand assessed	2 Computer system	3 Integrated comp system
	Training	1 On the job	2 Some external	3 Formalized programme
	Planning	1 Little management effort		2 Significant management effort
Design/ quality	Product specification	1 Low tolerances and standard materials		2 High tolerances and special materials
	Quality systems	1 Quality standards	2 Quality systems	3 Computer-based QA
	CAD systems	1 Stand alone	2 CAD/CAM linked	3 CAD/CAM integrated with other systems
Computer-aided production management	Wages/invoices	1 Computerized		
	Materials control	1 Stand alone	2 Integrated with other systems	3 Integrated with PC
	Production scheduling	1 Stand alone	2 Integrated with other systems	3 Integrated plus shop-floor feedback
	Order processing	1 Stand alone		2 Integrated with other systems
	Capacity planning	1 Stand alone		2 Integrated with other systems
	Shop-floor feedback	1 Manual		2 Computer system
CAM	Process technology	1 Stand alone NC	2 NC linked to CAD	5 FMC/FMS

gathering aspects of combined company profiling will be discussed in the next section.

Cluster analysis provides a relatively quick and simple method of assessing multivariate problems. The results of the classification index have been subjected to cluster analysis using Ward's method [10]. A more detailed explanation of the technique is given in the section "Cluster Analysis" below. Analysis utilizing Ward's method of cluster linkages tends to generate data which share a number of common characteristics. The output from the cluster analysis is shown in Fig. 3.3, the cluster analysis in this example being carried out via an SPSS-X mathematical software package.

The dendrogram shown in Fig. 3.3 indicates five distinct groups which are defined in Table 3.3. The five group profiles indicate an overall level of performance combining technology, management organization and work force attitudes. For example, group one companies have a very fragmented approach to AMT with little planning and low levels of system integration. On the other hand, group five companies have highly integrated manufacturing and business systems.

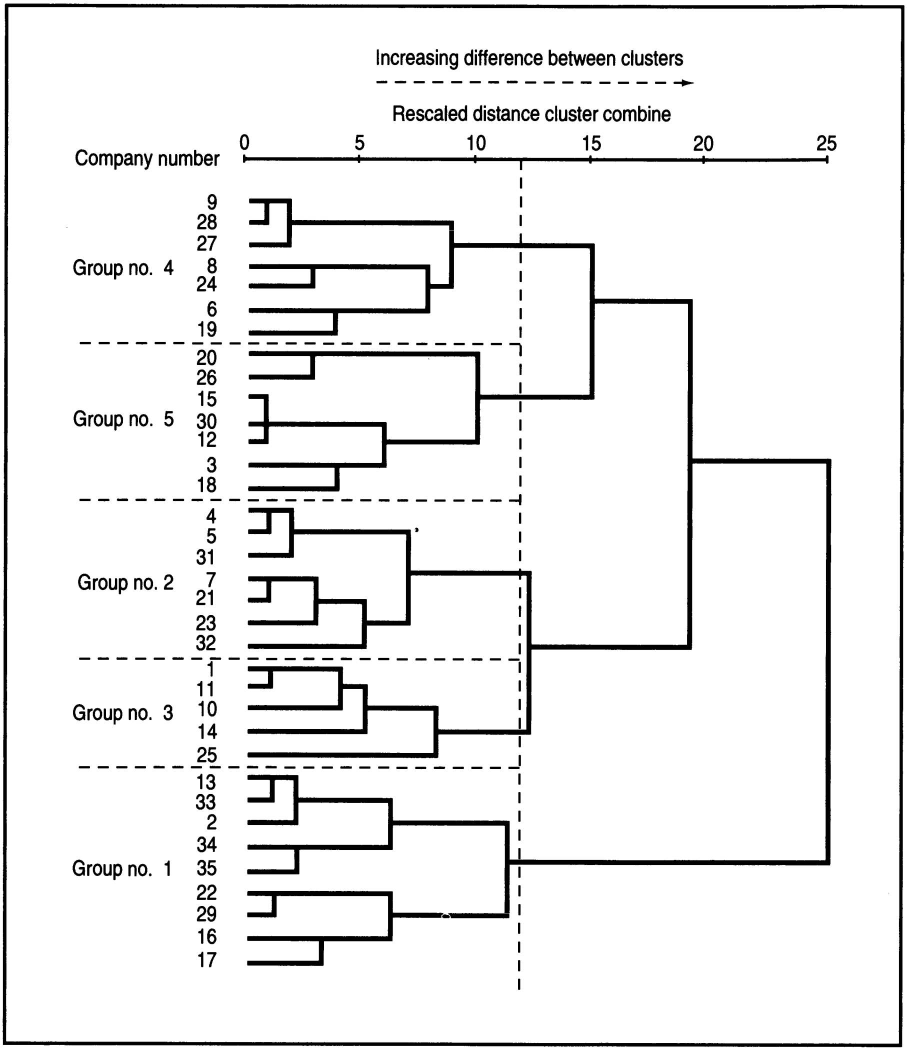

Fig. 3.3. Results of cluster analysis, dendogram showing company classification by combined technological and organizational index. Dotted line indicates boundaries of combined company profiles.

Table 3.3. Company stage states for combined company technological and organizational index

Group number	Description of corresponding group stage states/profiles
1	Some stand-alone CNC machine tools, first stages of computer-aided production management (CAPM) implemented. Companies tend to react to the marketplace; little planning is carried out.
2	Companies in this group use CNC technology without any direct links to CAD. Some CAPM systems in use, although feedback of shop-floor data is performed manually. Basic quality assurance (QA) systems have been implemented.
3	Companies in this group use CNC/DNC, CAD, CAPM and QA systems. The systems are not as integrated as group 5. Demand forecasting is seen as a priority.
4	Advanced manufacturing technologies such as a FMC or FMS have been implemented without major use of CAPM systems. Training, QA and planning are seen as priorities. Product demand is constant.
5	Implemented advanced computer-aided manufacturing and CAPM systems with attempts at integration of systems. The design and QA functions are integrated with manufacturing. Planning, training and demand forecasting are seen as essential.

An overview of the seven steps required to construct a group or set of combined company profiles is shown in Fig. 3.4.

3.4 Data Gathering

The raw data analysed by way of the company classification index and cluster analysis processes is normally gathered by a combination of questionnaires and company visits. Questionnaires provide a relatively cheap and speedy means of gaining raw data. However, a number of problems arise. For example:

1. It can be difficult to define the right questions to cover all areas of interest without creating a very lengthy document which very few people would attempt to complete.
2. A particular question can often have a number of interpretations, even within the same company or organization.
3. Difficulties can arise when data is in a qualitative form rather then in the form of quantitative measures. The very nature of combined technological and organizational profiling where direct measures of performance are often difficult to interpret can result in ambiguous data sets.
4. Answers to questions are biased in the manner the company or company representative wishes to adopt. For example, many production managers would not readily admit that they have delivery problems. However, questions on finished stock levels or WIP are usually answered quite accurately.

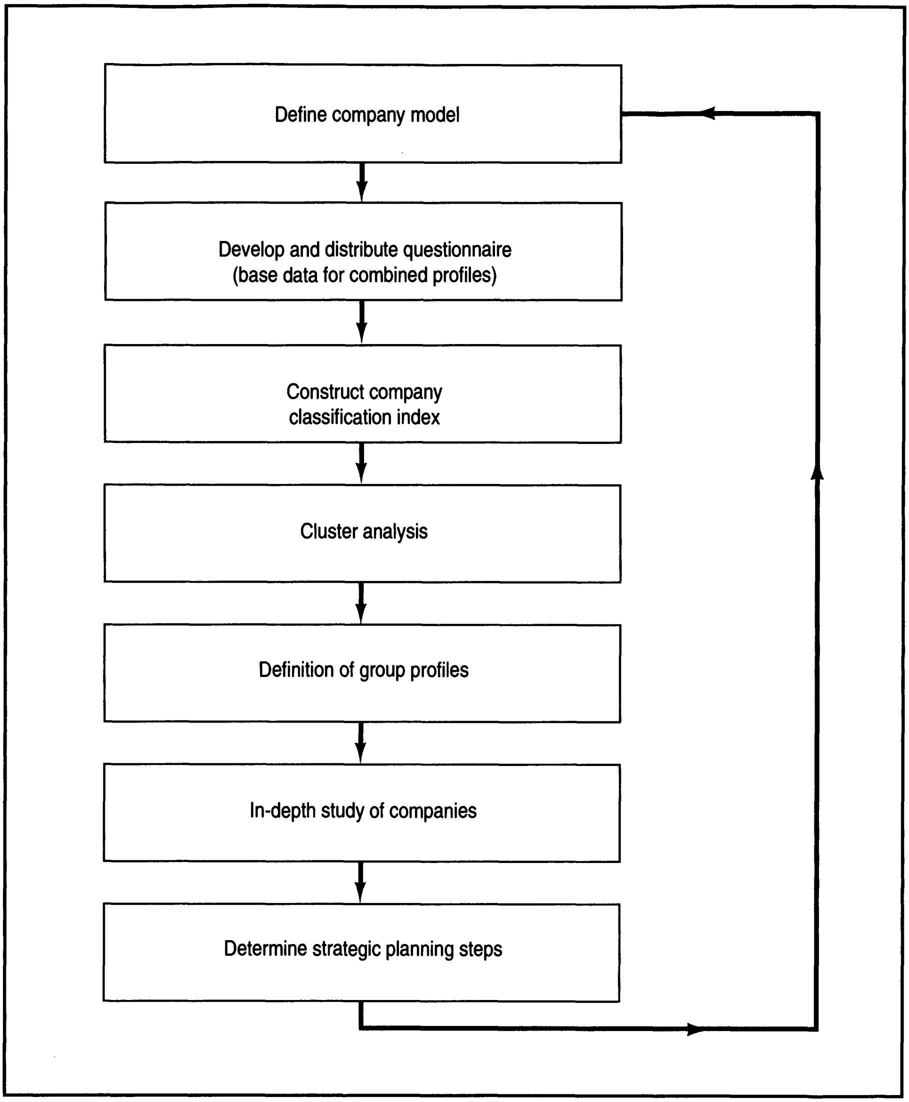

Fig. 3.4. Flow diagram of steps required to produce combined company profiles.

In an attempt to reduce the effect of the problems listed above, it is recommended that questionnaires should only be used in conjunction with factory visits. A combination of data gathering via questionnaire and factory visits has proved very successful in collating databases relatively quickly and accurately. The most important aspect of the databases collated to date is that the information contained within them relates to the real problems facing manufacturing companies.

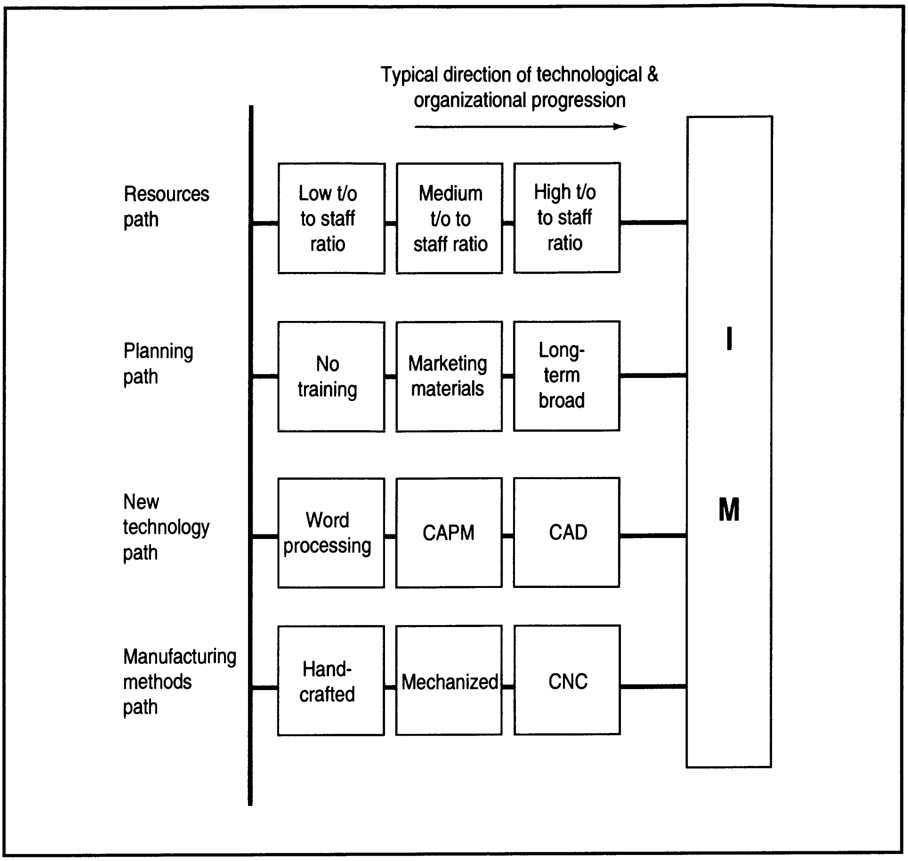

Fig. 3.5. Diagram of company model for jewellery manufacturing companies. IM = integrated manufacturing.

3.5 Linking the Implementation of New Technologies with Manufacturing Strategy

We will now consider how combined company profiles can be used to help plan and link the implementation of new technologies to a company's manufacturing strategy. Let us now examine a second set of data, based on a specialized light-engineering industry located in and around the centre of Birmingham, namely that producing jewellery.

Many manufacturers produce jewellery in large quantities using various engineering processes such as casting, stamping and rolling. Birmingham is the centre of the UK's volume jewellery manufacturing industry, and many of the companies are undertaking the implementation of new technologies such as personal computers, CAPM, CAD and light CNC machine tools.

A company model has been developed specifically for jewellery manufacturing companies and is shown in Fig. 3.5. A short questionnaire was devised and distributed in order to gain the data necessary for company

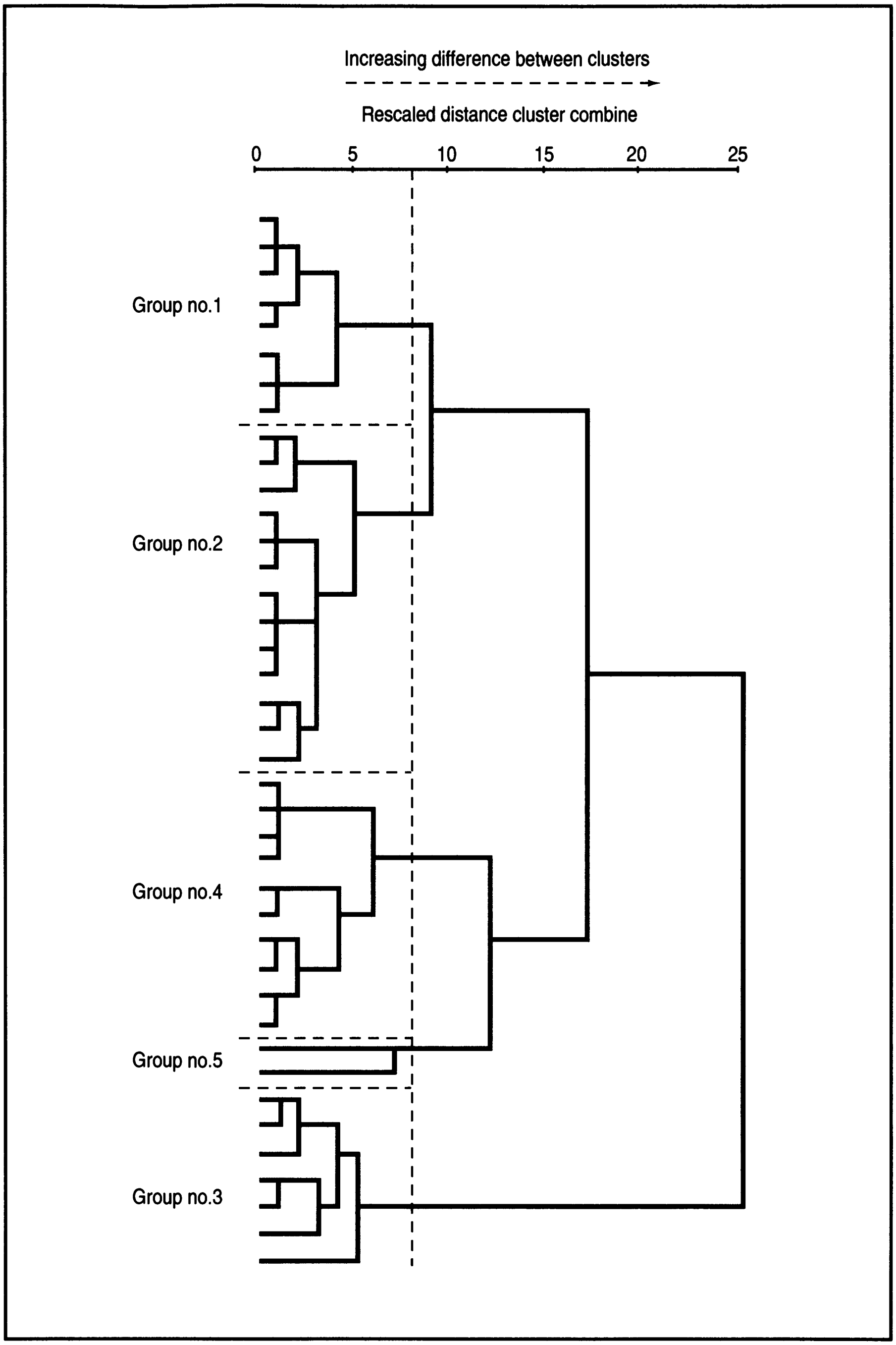

Fig. 3.6. Jewellery industry cluster analysis output. The dendogram shows company classification by combined organizational, financial and technological index. Dotted line indicates boundaries of combined company profiles.

Table 3.4. Combined technological, organizational and financial classification index developed for jewellery manufacturing companies

Path	Factors	Characteristics and scores		
		Low	Medium	High
Resources	No. of people	1 Below 10	2 10–35	3 Above 35
	Turnover, £000	10–50	51–500	Above 500
Planning	Market plan	1 No plans	2 Some marketing	3 Long-term
	Overall B's planning	1 Materials	2 Stock	5 Computers
	Training	1 Recruit	2 On site	3 External
New technologies/ computers	Use	1 Word processing	2–3 CAPM	5 CAD
	Plan AMT expansion	1 Evaluate	2 Plan	
Manufacturing methods	Production methods	1 Handmade	2 Mechanized	5 CAD/CAM
	% products manufactured	1 Handmade 70–100%	2 Mechanized 30–100%	5 CAD/CAM Above 30%

profiling. The help and assistance of the local city council and the British Jewellery Association proved invaluable in the speedy collation of questionnaire returns and later company-based investigations. A classification index was developed, based on nine factors covering the four main paths along the road to integrated manufacturing; these factors and the associated processing scheme is given in Table 3.4. The scores awarded in this example are subjective and based on the author's experience. As with the previous example the data obtained from the application of the combined classification index have been subjected to cluster analysis using Ward's method. The output from the cluster analysis is given in Fig. 3.6; the dendrogram shows five distinct groups which are defined in Table 3.5. A detailed explanation follows of each path used in the company model and classification index developed for the jewellery industry.

Path no. 1: resources

A large number of small to medium-sized (SMS) companies can be found operating in the jewellery industry. Most of these companies are privately owned and run on an entrepreneurial basis with relatively high turnovers, owing largely to the high cost of materials (precious materials such as gold and silver and gemstones). An investigation into the use of NC machine tools by small to medium-sized general engineering companies carried out by Coward [11] described three types of management (rigid, intermediate and mobile). Many of the mobile companies were those run on an entrepreneurial basis and succcessful implementation of new NC manufactur-

Table 3.5. Jewellery manufacturing company groups (defined by cluster analysis) and associated characteristics or stage states

Group no.	Company code	Stage states/profile
1	B, E, S, FF, HH, II, JJ, MM	Small number of personnel Low turnover Limited planning (materials) In-house training No computers Manufacturing centred on machine-based processes and hand skills
2	V, Y, C, G, R, O, Q, GG, Z, D, EE, I, N	Small number of personnel (<35) Machine-oriented processes High turnover Planning restricted to materials No computers Limited expansion planned
3	BB, M, X, AA, KK, NN, T, DD, A, K	Employ 10–35 people Turnover varies Have a specific market Plan material usage Training in-house Computers present WP, SOP, majority plan expansion in computer systems Mechanized processes
4	CC, LL, H, F, P, U	Under 35 people employed Wide-ranging turnovers Long-term market plan Plan in terms of computers Present computers used for SOP and stock control Plan to expand use of computer to include CAD/CAM systems Processes at present mechanized
5	L, W	Relatively small number of employees High turnover Long-term market plan Forward planning in computers In-house training Computers used for CAD, expansion planned CAD/CAM processes

ing tools was based on the company owner "believing" that the NC equipment would benefit his company rather than trusting a thorough financial justification. Indeed, it was often found that investment in new NC equipment followed a particularly profitable period in business. The similarity in management style between the jewellery manufacturers and the small to medium-sized general engineering companies led to the development of a resource path. An attempt to measure resources is made by comparing turnover and number of employees. Obviously this is very crude and takes no account of the effectiveness of a company's management team and profit margins.

Path no. 2: planning

The planning path is assessed on three factors: overall business planning, marketing and training. The success of any business is centred on the ability to sell a product or service. Hence the inclusion of a marketing factor helps to determine how effective a company is when matching its manufacturing capabilities to products and the hoped-for resultant sales. The effective running of a business is ultimately in the hands of the staff employed and their mode of operation; hence the inclusion of training and overall planning factors.

Path no. 3: new technologies

The use of a wide range of computer-based tools has increased dramatically in the last 10 to 15 years. The new technology path is concerned primarily with the use of microcomputer- and minicomputer-based systems. A general trend from the use of word processor and spreadsheet packages toward computer-aided production management and finally CAD systems has been detected in the jewellery manufacturing companies. The relative position of a company along this path gives an indication of the complexity, power and cost of the systems in operation and the level of technical expertise to be found within a company or group of companies.

Table 3.6. Summary table showing group profile number, associated strategic planning steps and anticipated results for jewellery manufacturers

Group profile no.	Strategic planning steps	Results
1, 2	A SWOT* analysis should be carried out. The results of analysis should lead to the development of a marketing plan to match manufacturing capabilities	Increased turnover and improve general management
3	Implement CAPM, including stock control, SOP,† production control and finance. Investment £5k–£50k.	Increased efficiency of manufacturing support services and increased control
4	Implement CAD/CAM. The use of CAD/CAM is closely associated with a new "designs policy" (short product life cycles). Investment £10k–£200k.	Greatly reduced lead times in development of new products and improved quality
5	Interface computer systems to form an integrated manufacturing system.	Optimum manufacturing methods employed; group 5 companies have the maximum opportunities to respond to changes in marketplace or introduce future technologies.

* Strengths, weakness, opportunities and threats.

† Sales Order Processing.

Path no. 4: manufacturing methods

Here we attempt to index the manufacturing systems in terms of manufacturing equipment employed and level of use. Previous research has indicated that an index based only on technology employed can be misleading. For example, a questionnaire return may state correctly that a company operates a highly sophisticated flexible manufacturing cell; however, further investigation may show that only 5% of the company's products are manufactured via the cell. In fact the majority of the company's manufacturing processes are performed via manually controlled machines. To counter this

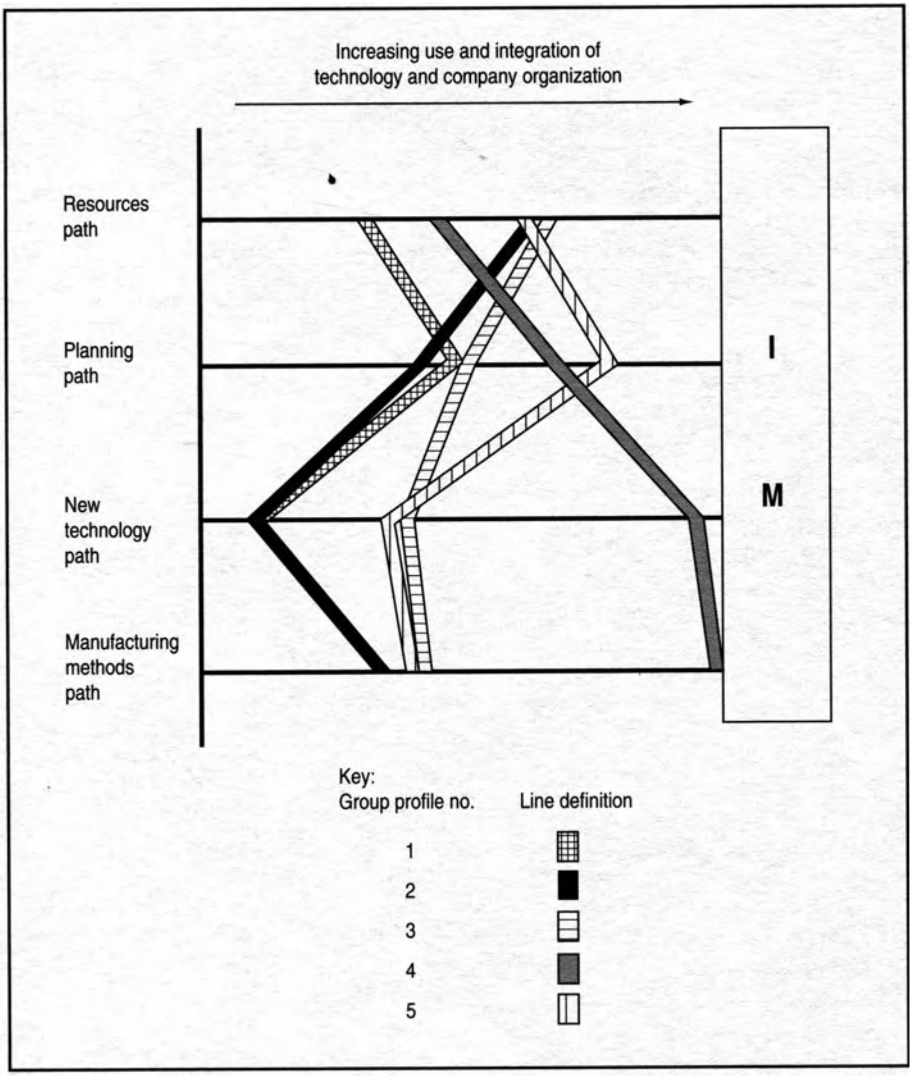

Fig. 3.7. Graphical representation of jewellery manufactures combined group profiles. IM = integrated manufacturing.

Table 3.7. Example calculation of stage state values for group no. 3 of jewellery industry data set

Company identification	Resources path		Planning path		New technology path		Manufacturing methods path	
BB	2	2	3	1	2	0	0	2
M	2	1	2	1	1	2	1	2
X	2	0	2	1	2	2	1	2
AA	2	2	3	1	2	0	0	2
KK	1	2	2	1	1	2	2	2
NM	2	3	2	1	1	2	2	2
T	2	3	2	1	2	2	0	2
DD	2	3	2	1	1	2	0	2
A	2	2	2	1	1	3	1	2
K	2	2	1	2	2	2	1	2
Column total	19	20	21	11	15	17	8	20
Maximum path score	60		110		70		50	
Group path score	39		48		25		20	
Group stage state level or score	65%		44%		36%		40%	

situation, two factors, production method and percentage of manufacturing performed by specific method (i.e. handmade, mechanized and CAD/CAM), have been used.

As recommended under "Data Gathering" above, the initial questionnaire survey was supported by company visits. Analysis of the resultant combined company profiles and data collected from company visits has led to the development of strategic planning steps (SPS) associated with the process of moving from one profile to another. A summary of SPS and associated company groups is given in Table 3.6. Combined company profiles for the five groups defined for the jewellery manufacturers are shown in Fig. 3.7. The relative position of each profile along a particular path or stage state is based on the following calculation:

$$\text{path stage state value} = \frac{\text{group score}}{\text{maximum possible value}}$$

An example set of calculations for group profile no. 3 is given in Table 3.7.

3.6 Cluster Analysis

Cluster analysis is a very powerful tool which enables multivariate data to be analysed. Given a number of objects or individuals, each of which is described by a set of numerical measures, cluster analysis techniques will automatically classify the objects or individuals into a series of subgroups or classes. The results of cluster analyses described in this book have all been performed via PRIME-750-based SPSS-X software. A number of cluster analysis packages are now available, including PC-based systems.

An example of an SPSS-X-based cluster analysis run follows. The data collated by the joint SERC-sponsored research team is used to illustrate this example. Cluster analysis has three main steps:

1. Create matrix data file.
2. Create analysis file, choose cluster linkage criteria, distance measure and format of data output.
3. Run software and analyse results.

A detailed account of each step follows.

Matrix data file

A matrix data file must first be created. The file contains the data collated from the questionnaire returns following processing by classification index. An example matrix data file is shown in Table 3.8. The first thirteen single-digit numbers are the values of the classification index factors; the letters are for identification purposes only.

Table 3.8. Cluster analysis matrix data file (cluster analysis input data file)

Each numerical value shown below the data heading represents the score each company has achieved as defined by classification index shown in Table 3.2, the alpha characters are used as company identifiers.

File line no.	Data	File line no.	Data
1	1224221221213a	19	1211210000014s
2	1111101000000b	20	3322220130025t
3	3122111332125c	21	2212311221111u
4	1222201332011d	22	2323211110111v
5	1222210322011e	23	1323310322211w
6	0322201011123f	24	0222221013013x
7	2222201321211g	25	1121322302223y
8	1323131002023h	26	1322320330025z
9	2322221112125i	27	2322321112123aa
10	2222221322023j	28	2323211111125bb
11	2222221222213k	29	3333211111020cc
12	3322220332225l	30	3323331332225dd
13	1122201000011m	31	0213211323011ee
14	1222101332223n	32	3233311322011ff
15	3322321222225o	33	2212201100011gg
16	2322101101000p	34	0113100000001hh
17	1321200202011q	35	0022110101111ii
18	3332121322214r		

Analysis file

A listing of the analysis file including notes is provided in Table 3.9. The SPSS-X cluster package offers six methods of calculating the proximity measure (similarity between each two rows of data) and six cluster linkage criteria (nature of clusters formed by analysis). In this particular illustration the seuclid, or squared Euclidean, distance measure was used in conjunction with Ward's method of cluster linkage.

Analysis of results of clustering

When the analysis file detailed in Table 3.9 is executed an output file is created. The output file includes an agglomeration schedule, as shown in Table 3.10. Ward's method joins the two clusters, which results in the minimum increase in value of the distance measure (column 4 in Table 3.10, labelled "coefficient").

Table 3.9. Listing of example (cluster analysis) analysis file

```
 1   TITLE TIM BURDEN CLUSTER ANALYSIS 20.06.88
 2   FILE HANDLE TEMP/PATH = 'DATA20'
 3   DATA LIST FILE = TEMP RECORDS = 1/
 4        V1 TO V13 1-13 V14 14-50 (A)
 5   N OF CASES 35
 6   VAR LABELS  V1,DEMAND FORECASTING/V2,TRAINING/V3,PLANNING/
 7               V4,PRODUCT SPECIFICATION/V5,QUALITY SYSTEMS/
 8               V6,CAD/V7,INVOICES/V8,MATERIALS CONTROL/
 9               V9,PRODUCTION SCHEDULING/V10,ORDER PROCESSING/
10               V11,CAPACITY PLANNING/V12,SHOP FLOOR FB/
11               V13,PROCESS TECHNOLOGY/V14,COMPANY NAME/
12   CLUSTER V1 TO V13
13    /METHOD=WARD
14    /ID=V14
15    /PLOT=DENDROGRAM
16   FINISH
```

Line no.	Command	Comments
1	TITLE	Title printed on computer output file.
2	FILE HANDLE TEMP/PATH	Name of file containing data defined.
3	DATA LIST FILE = TEMP RECORDS =	Variables defined, V1 to V13 numeric variables single character. V14 36 * alpha characters (company name).
5	N OF CASES	Number of objects (number of company data sets)
6	VAR LABELS	Labels assigned to each variable
12	CLUSTER V1 TO V13	Objects 1 to 35 are clustered on variables V1 to V13.
13	/METHOD=WARD	Proximity measure and cluster linkage method defined.
14	/ID=V14	Object identifier defined for use on output file.
15	/PLOT=DENDROGRAM	Results of cluster analysis to be output as a dendrogram.
16	FINISH	Defines end of file.

Table 3.10. Agglomeration schedule resulting from cluster analysis of engineering industry data set

Agglomeration schedule using ward method

Stage	Clusters combined		Coefficient	Stage cluster first appears		Next stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	9	28	1.500 000	0	0	11
2	1	11	3.000 000	0	0	17
3	4	5	4.500 000	0	0	9
4	13	33	6.500 000	0	0	10
5	15	30	8.500 000	0	0	6
6	12	15	10.500 000	0	5	23
7	7	21	12.999 998	0	0	15
8	22	29	15.999 998	0	0	24
9	4	31	19.166 664	3	0	25
10	2	13	22.499 996	0	4	22
11	9	27	26.333 328	1	0	28
12	34	35	30.333 328	0	0	22
13	8	24	34.333 328	0	0	27
14	16	17	38.333 328	0	0	24
15	7	23	42.499 992	7	0	20
16	20	26	46,999 985	0	0	29
17	1	10	51,499 977	2	0	21
18	3	18	56,499 969	0	0	23
19	6	19	61,999 962	0	0	27
20	7	32	67,833 282	15	0	25
21	1	14	73,833 267	17	0	26
22	2	34	80,499 924	10	12	30
23	3	12	87,499 908	18	6	29
24	16	22	95,999 893	14	8	30
25	4	7	104.547 501	9	20	31
26	1	25	113,747 498	21	0	31
27	6	8	123,997 482	19	13	28
28	6	9	134,914 124	27	11	32
29	3	20	149,556 946	23	16	32
30	2	16	168,056 915	22	24	34
31	1	4	188,059 265	26	25	33
32	3	6	234,559 204	29	28	33
33	1	3	295,538 025	31	32	34
34	1	2	395,599 426	33	30	0

A typical method of deciding a cutoff point for the number of clusters is to look for sudden jumps in the coefficient. A significant increase is not always obvious from the coefficient values. However, a graph of increases of coefficient values at each agglomeration can emphasize a sensible cutoff point.

The coefficient values and increases of successive coefficient values at each agglomeration and cluster linkage order are given in Table 3.11 (agglomeration schedule). A graph of increase in coefficient value versus number of clusters is given in Fig. 3.8, where it can be seen that a major step occurs between the four- and five-cluster levels. Further information on cluster analysis techniques can be obtained from SPSS (UK) Ltd [12].

Table 3.11. Cluster analysis agglomeration coefficient values and increases of coefficient values derived from Table 3.10

No. of clusters	Coefficient value	Successive increase in coefficient value
1	396	
2	296	100
3	234	62
4	188	46*
5	168	20*
6	150	18
7	135	15
8	124	11
9	114	10
10	105	9
11	96	9
12	87	9
13	80	9
14	74	7
15	68	6
16	62	6
17	56	6
18	51	6
19	47	5
20	42	4
21	38	5
22	34	4
23	30	4
24	26	4
25	22	4
26	19	4
27	16	3
28	13	3
29	10	3
30	8.5	2.5
31	6.5	2
32	4.5	2
33	3.0	2
34	1.5	1.5

* Indicates a significant change in the successive increase in coefficient value and sensible clustering cutoff point.

3.7 Summary of the Steps to Combined Company Profiling and Future Developments

As previously mentioned, a graphical representation of the steps required to develop a combined company profile is given in Fig. 3.4; the process is iterative in nature and the results subjective. However, the technique is a very powerful tool, allowing different companies to be compared.

When used within a specific industry the technique allows the link to be assessed between manufacturing capabilities, implementation of new technologies and market share. Work is currently being conducted to further

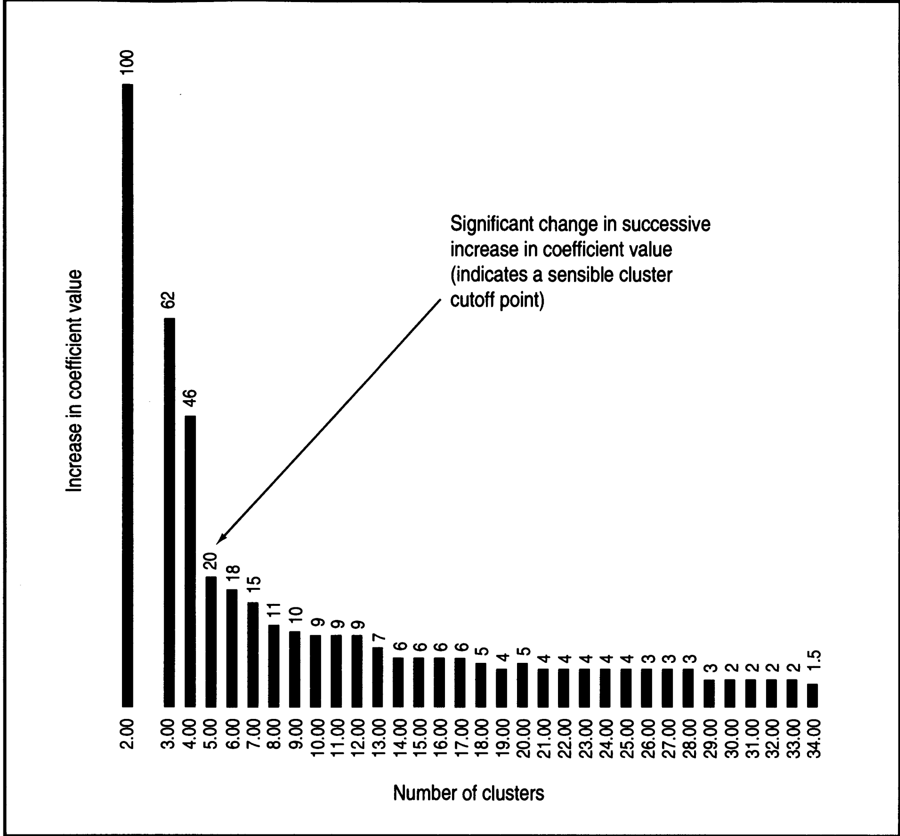

Fig. 3.8. Graph of increase in coefficient value versus number of cluster for engineering industry data set.

develop the combined company profiling technique and associated data gathering methods. The aim of the current work is to facilitate an implementation of the technique as an expert system via knowledge-based software. It is envisaged that such a system would eventually be available to any persons or bodies to assist in creating a company's manufacturing strategy.

A simple pilot system has already been created. This allows the data gathering process to be carried out via interactive questioning using simple menu-driven screens. Potentially the knowledge-based software offers greater flexibility and improved tailoring of a proposed strategic plan to an individual company. To operate the computer-based system successfully the user will require only a good knowledge of his or her company. This is obviously not a trivial matter.

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4 Learning Curve Models

D.R. Towill and J.E. Cherrington

4.1 Introduction

In using learning curves for AMT startup, we seek to identify a number of patterns in the basic data, each of which is an important source of information to be fed into the management control machinery. These patterns may be classified as follows:

1. A trend line, which in some "best" sense can be used for predicting future output. This line can be influenced by proper design and planning of the product line.
2. "Normal" scatter about the trend line, which constitutes a natural and acceptable variation, and which can be used for setting the upper and lower bounds of predicted output.
3. "Abnormal" scatter about the trend line, which results in an unacceptable variation. It indicates an avoidable loss in production which can be traced to an assignable cause and hence eliminated by management control.
4. "Deterministic" changes in the trend line. These may be long- or short-term, and have an assignable cause. An example of a management-induced cause is a planned change in the size or constitution of the direct labour force.

To derive a learning curve model which will cope with these four patterns simultaneously is a complex problem. There are considerable advantages in selecting the simplest model which is adequate for the purpose, so we review a procedure for doing this. We are, after all, dealing with huge cost savings if we properly plan and control AMT activity. Understanding and implementing a simple model is often very profitable. This chapter concentrates attention on the time constant model and its variants, as found appropriate to "industry learning".

4.2 Historical Review

There are many papers in the engineering and management literature which record an experience-linked improvement in task performance typically observed when plotting a suitable performance index as a function of time. These observations have been made for both long- and short-cycle-time tasks, and appear to apply both to individual operators and to groups of operators, and also in a wide range of industries. It is then common practice for such experimental data to be curve-fitted with an equation which it is hoped adequately describes the trend line through the inevitable scatter in results. Such curves have variously been called "learning curves" [1], "startup curves" [2], "progress functions" [3] and "improvement curves" [4]. The axes used to display the data also vary widely according to the particular industry and task force being studied. For example, three typical sets of data are shown and we note the following:

1. In Fig. 4.1a the axes used are quantity produced per unit time versus cumulative time spent on the task.
2. In Fig. 4.1b the axes are cumulative average time per item versus cumulative number of items made (the latter plotted on a log scale).
3. In Fig. 4.1c task time is plotted versus the logarithm of cumulative number of items manufactured.

Depending on the nature of the experimental data, various "laws" or trend equations describing the data have been proposed, each generally bearing the author's name: for example the de Jong model [5]. As in all empirical curve fitting, the best type of equation is determined by trial and error. The best values of the equation parameters can be chosen on the basis of a computer algorithm which minimizes the least-square error of the curve fit. One method of deriving such an algorithm is detailed in Chapter 5.

In general, there is no logical progression in moving from one type of equation to another, should the initial choice be found wanting, although it is to be hoped that the progression will always start with the simplest plausible solution available. The one exception to this empirical approach is to be found in the family of models which includes as the focal point the time-constant model, and for which the data need to be in the form shown in Fig. 4.1a (as is usually the case for AMT startup). The vertical axis can be any convenient (but agreed and well understood) performance index which is known to increase with experience.

In this chapter we review the family of "transfer function" models (so designated because each member has an analogy with a physical system), thus aiding the understanding of any particular model [6].

By progressing through the family in order of increasing difficulty, it will then become obvious when we have reached a good compromise between model complexity and accuracy of curve-fitting to the available data.

The practical use of learning curves in management decision-making can be illustrated graphically, as shown in Fig. 4.2. Additional productivity losses resulting from a variety of industrial phenomena can be determined from the shaded area under the curve in each case. Losses due to slow startup and the phenomenon of artificial plateaux are shown. However, it is equally possible to estimate the benefits due to improved work organization and to the introduction of new methods.

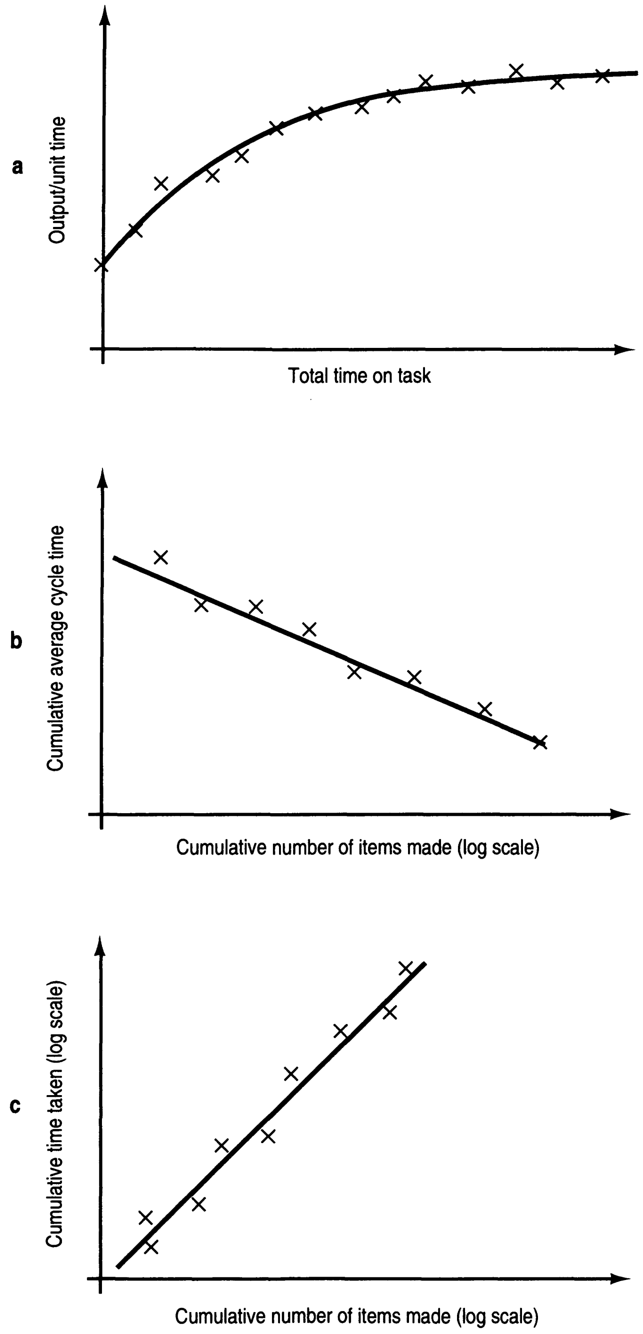

Fig. 4.1. Three ways of plotting learning curve data.

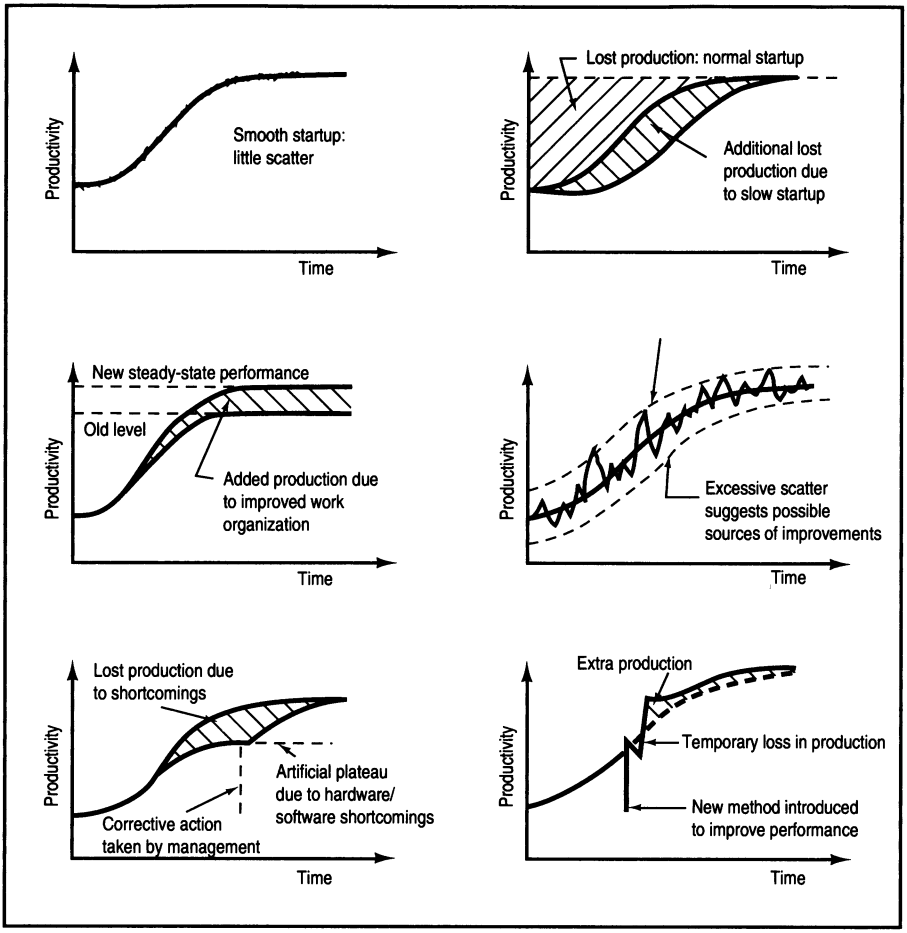

Fig. 4.2. Graphical interpretation of productivity losses via a time constant learning curve model.

4.3 The Time Constant Model

An exponential model was first proposed at least as far back as 1950 [7], but was restated in transfer function form with a suitable physical analogue in reference [8]. Since then a number of studies have been published which indicate the utility of the time constant model. If we denote by $Y_M(t)$ the model output at time t; Y_c the model output at time $t = 0$; Y_f the incremental gain; $(Y_c + Y_f)$ the model output at time $= \infty$; and τ the model time constant, then the equation relating model output to time is

$$Y_M(t) = [Y_c + Y_f(1 - e^{-t/\tau})] \qquad (1)$$

which is the equation of the curve shown in Fig. 4.1a. Hackett [9] applied the time-constant model as one of 14 alternative learning curve laws to 88 sets of data recorded on widely different tasks. He found that the model was on average as good a curve fit as any competitor. Also, the only model which occasionally gave a better curve fit to some sets of data failed completely in about half the test cases! Such unreliability of any model for widespread use is a serious fault, rendering its use suspect in all but the most closely defined circumstances [10].

Y_c, Y_f and τ are functions of the task and many other variables. To give some guidance on typical ranges of model parameters, Table 4.1 is based on a worldwide collection of industrial case studies and is an augmented version of a previously published account [11]. It can be seen that the parameters vary enormously from situation to situation, suggesting that in the management of new product lines, adequate monitoring and forecasting techniques must be available [12] to help avoid the manufacturing *system* becoming unstable due to bad timing and bad-quality decision-making. Reference [2] quotes a particularly worthwhile example of this happening in the startup of a new steel mill. Variations in model parameters are also to be expected between operators performing the same task. The extent of the variability again depends on management planning, motivation and control functions.

4.4 Modelling Errors

Although the time-constant model has found wide application, it does not work in absolutely every case. With modification of the type suggested later in this chapter, it does seem to work in most applications which may be described as "industry learning". The latter term is defined by Harvey [13] (and referred to in Chapter 1) as describing performance improvement in processes of continuous-flow industries as distinct from situations where the unit of production, e.g. one aircraft, is readily apparent. Clearly AMT startup may be classified as "industry learning".

Table 4.1. Time constant models for various industrial tasks

Industry	Task	Country	$\frac{Y_c+Y_f}{Y_c}$	τ (weeks)
Pharmaceuticals	Packaging	Japan	1.60	24
Printing	Startup of two-colour press	USA	1.23	7
Steel mill	Startup of rolling mill	USA	2.26	20
Chemical	Sampling and adjustment of product mix	UK	1.71	14
Cigar-making	Leaf selection and processing	UK	2.35	3
Electrical	Switch assembly	UK	6.50	3
Watchmaking	Watch train assembly	UK	2.26	3
Heavy engineering	Anneal plates	UK	1.37	8
Mining equipment	FMS startup	UK	2.50	24
Mechanical engineering	FMC startup	UK	4.68	3

At any time t, the observed data $Y(t)$ will not agree exactly with the model output: the difference between the two is the model residual, $N(t)$, defined by

$$N(t) = [Y(t) - Y_M(t)] \tag{2}$$

The residuals are, of course, also the curve-fit errors, which, in some curve-fit procedures, are chosen to minimize the sum of squared errors calculated over all data points [9,14]. In general, the lower the average value of $\{N(t)\}^2$, the better will be the curve-fit, and the better will be any prediction made via the model. In general, there will be three main sources of prediction error:

1. There are *errors due to "natural" fluctuations* in performance, with the fluctuations random (uncorrelated with each other) or deterministic, such as a sinusoidal oscillation. Random errors usually show up as quickly varying scatter, which is often Gaussian in pattern [14].
2. *Deterministic errors* usually vary more slowly, and include plateaux for which there may well be physiological, psychological or environmental causes.
3. A complete description of the experimental data is achieved only by taking account of *modelling errors*; that is, the form of the model may not permit adequate description of the trend line.

As an example of modelling errors occurring, an exponential equation could be curve-fitted to a straight line, as shown in Fig. 4.3. However, there will be considerable modelling error at almost every point on the curve. A statistical analysis, such as the run test [15], would show up this phenomenon as a correlation between the model residuals. The block diagram also shown in Fig. 4.3 uses the common representation found in texts on system dynamics to represent the summation and subtraction of signals in order that the model plus errors plus residuals equals the observed behaviour of the real world.

4.5 Model Selection for a Hardware System

We now digress to consider how an engineer would distinguish between these three error types, in anticipation that guidelines may thereby emerge for model selection in learning curve situations. When modelling the behaviour of physical systems, the engineer will write down the differential equations governing the behaviour of the system, making such assumptions as are necessary to obtain a reasonable solution in the time available. The relevant fundamental laws such as those of Newton, Bernoulli, Ohm and Kirchhoff are enlisted for this purpose [16]. Now the engineer is particularly interested in the solution of these differential equations for idealized operating conditions. The latter are usually chosen to enhance the mathematical tractability of the solution and are then reproduced on the test rig at the commissioning stage of the equipment.

One common method of solution of these differential equations is to use the Laplace transform method, which may be regarded as a handle-turning

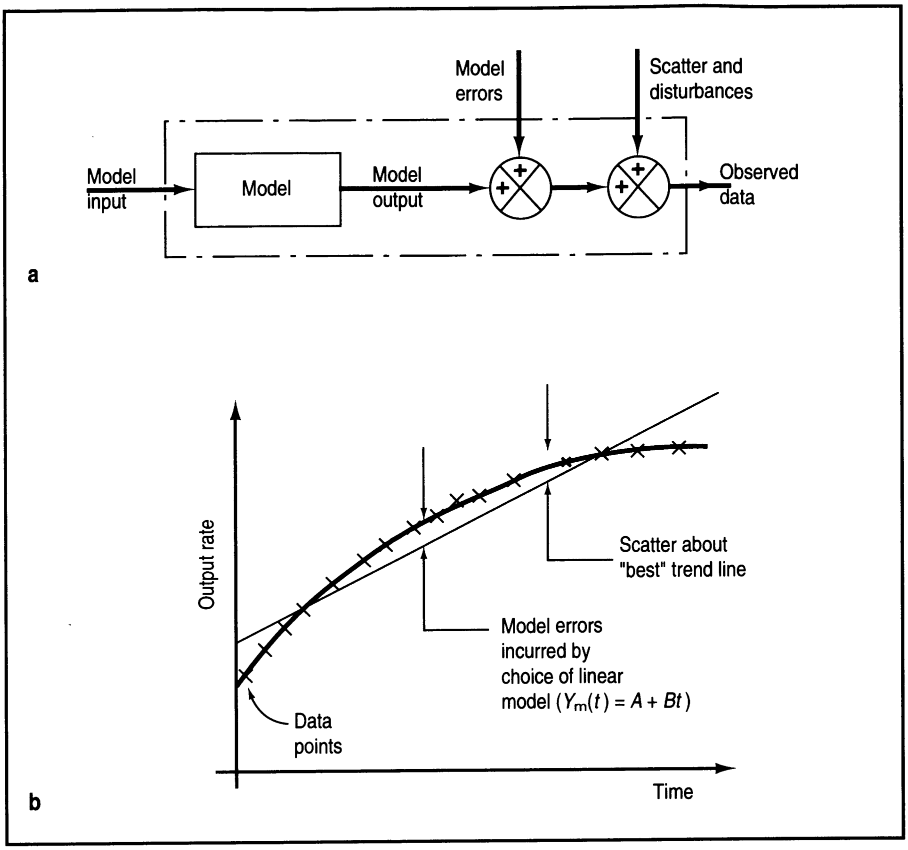

Fig. 4.3. Matching models to experimental data. **a** Relating model and observed outputs. **b** Example of model errors.

exercise once the system transfer function has been obtained [17]. Now the system transfer function relates system output to system input, and is the ratio of two polynomials in the Laplace operator.

It is axiomatic that all systems with the same transfer function have the same behaviour to the same stimuli! Consider, as an example, the simple time domain equation

$$u(t) = (1 - e^{t/T}) \tag{3}$$

which can be recognized as the time-dependent part of the time-constant learning curve model of equation (1). Equation (3) is the step response of all systems with transfer function:

$$F(s) = \left[\frac{1}{1 + Ts}\right] \tag{4}$$

The unit step stimulus which excites the system is zero until time $t = 0$, then suddenly changes at $t = 0$ to a value of unity, thereafter staying at this value. Equations (3) and (4) are related via the inverse Laplace transform

$$u(t) = \mathcal{L}^{-1}\frac{F(s)}{s} = \mathcal{L}^{-1}\frac{1}{s(1 + Ts)} \tag{5}$$

which is solved using standard "look-up" tables. The existence of these standard tables provides a powerful incentive to use transfer function analogies in learning curve modelling [6]. Thus, if the time constant model gives a large "modelling error", we can engage in a structured search through the tables to find a more complex model capable of yielding a better curve fit, rather than add extra terms which have no physical analogue.

Whether or not a transfer function is a good descriptor of an *actual* system performance depends on the validity of the assumptions made during the analysis. For example, the hydraulic jack shown in block diagram form in Fig. 4.4 is described by the transfer function $[1/(1+Ts)]$ only if the oil in the system is infinitely stiff. In practice, this is impossible, as the stiffness is certainly materially affected by any air trapped in the oil [18]. *Thus, the validity of the assumption is relative to the design of the system, and the*

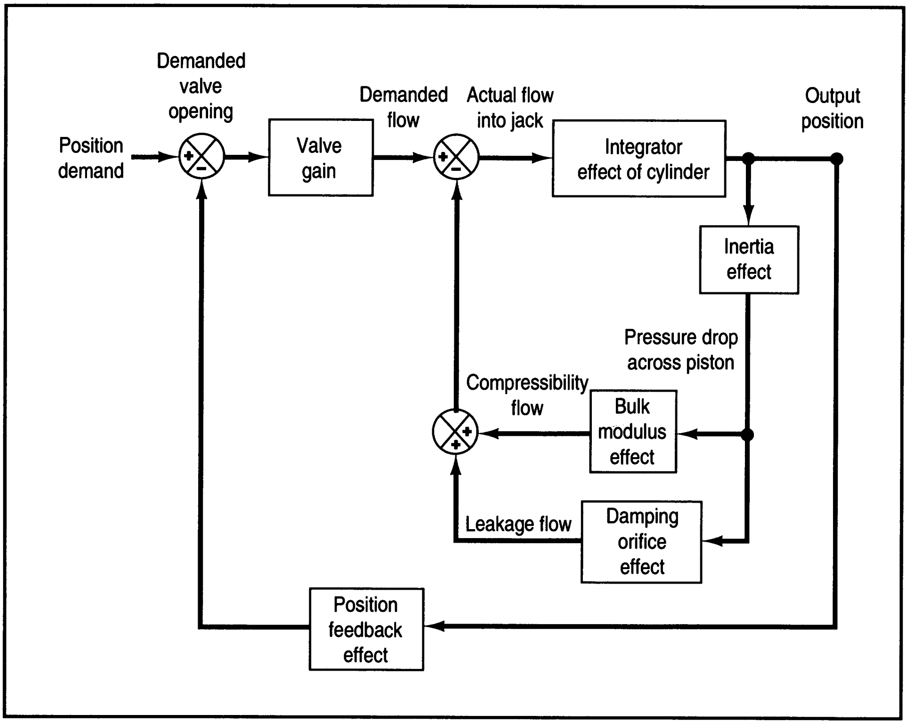

Fig. 4.4. Block diagram depicting physical functions in a hydraulic jack servomechanism.

environmental conditions under which it operates. With finite oil stiffness, the transfer function of the hydraulic jack becomes third-order, and is then somewhat more difficult to analyse.

The practical problem resulting from finite oil stiffness is the "ringing" which then characterizes the jack response. This is clearly shown in Fig. 4.5a, which could represent an oscilloscope trace from which the measurement noise has already been removed. The resulting equation describing $u(t)$ is then

$$u(t) \approx \{1 - e^{-10t} + e^{-5t}[\sin(5723t - 180°)/9.987]\} \tag{6}$$

and is known as a "ripple" model. However, if the "compressibility mode" is adequately damped, for example via leakage across the piston, then the ringing disappears, leaving the exponential type response of Fig. 4.5b. This can be approximated somewhat crudely by a simple equation such as

$$u(t) \approx \{1 - e^{-9.09t}\} \tag{7}$$

For reasons which are beyond the scope of this chapter, but are fully described in reference [19], an even better approximation to the response of Fig. 4.5b is given by

$$\begin{aligned} u(t) &\approx 0 && \text{for } t \leq 0.01 \text{ s} \\ u(t) &\approx \{1 - e^{-10(t-0.01)}\} && \text{for } t > 0.01 \text{ s} \end{aligned} \tag{8}$$

which is the delayed time constant model. We would therefore conclude that in this instance the first-order approximation is good enough to commence the basic design of the jack, but it does not forewarn us of the possibility of oscillations in the response. These may well be a hazard as the fatigue life of the system is then affected. Under these circumstances, the engineer must design the system in sufficient depth to predict the existence of phenomena of this nature. The test rig then serves to confirm the goodness of the design rather than raising questions of redesign.

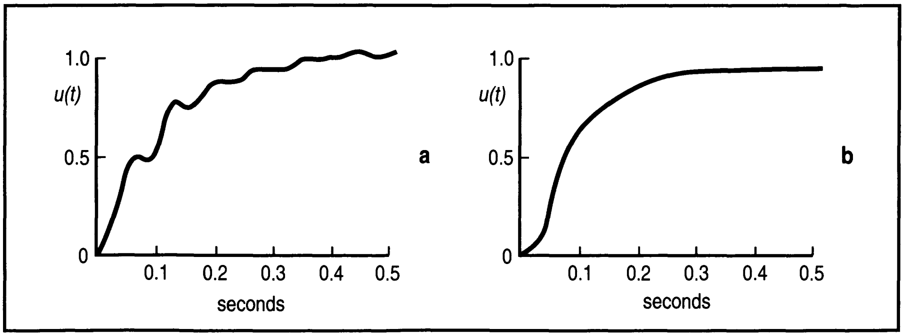

Fig. 4.5. Typical experimental step responses obtained for hydraulic jack servosystem. **a** Oil compressibility effect (ripple model). **b** Reduction of "ringing" effect by providing piston leakage (approximating to "S" models *or* delayed time constant models).

4.6 Is Our Learning Curve Model Adequate?

At the test rig stage, the engineer faces a problem of interpretation. Suppose that an oscillation appears on the response of a system which was initially assumed to be first-order. The oscillation may be a characteristic of the system under test, or it might be induced by the test rig, or it might be a characteristic of the measurement transducers. Repeatability of tests and further engineering analyses are required to resolve this situation to the satisfaction of the system user. There is, however, a similar but causally more difficult problem facing the learning curve modeller.

When using learning curves for forecasting purposes, we need to estimate model parameters early on in the improvement process. If the data are well-behaved, as shown in Fig. 4.6a, modelling and forecasting are reasonably straighforward. If the data (from the modelling point of view) are less well-behaved then we may need to exercise considerable care in modelling and forecasting. For example, in Fig. 4.6b the time-constant model, religiously fitted to the early experimental data will give a negative τ and useless prediction. Either an S-shaped curve or an oscillatory mode superimposed on the exponential would be more appropriate at this stage.

Unlike the systems engineer concerned with hardware design and development, who has some opportunity for associating causality via the laws of physics, the learning curve analyst may have little opportunity for discerning whether the oscillation is due to an assignable cause or not, or even whether it is likely to continue or die away. In industrial modelling there is added difficulty in ensuring an adequate data collection scheme so that true causalities become apparent. As shown in reference [20], the true production rate (i.e. output/unit of time actually worked) is far less variable than appears at first sight. We therefore need to interact with the modelling process, or build suitable filtering into the data processing to suppress the effects of certain behaviour. When filtering is used, it is recommended that the *range* of daily performance can be used to indicate the state of the process, and to suggest occasions where an industrial engineering investigation of present operating practice is desirable [21].

4.7 Industrial Dynamics Family of Learning Curve Models

How can transfer functions assist in pointing the way forward? Let us turn to the problem frequently facing the systems engineer of describing the performance of a physical "black box" in responding to a step stimulus. Here there is a logical path commencing as shown in Fig. 4.7 and which corresponds to an extremely structured search through Laplace transform tables. Our first assumption is that the "black box" will faithfully transmit the stimulus undistorted and perfectly timed, thus having a transfer function of unity. The next level of assumption is to assume the "black box" does not distort the stimulus, but delays the stimulus by a time increment D. Then comes the time constant model, followed by a delayed version of the time constant model. A second-order (S-shaped) version with real roots then follows. Note that this response is frequently met in behavioural science descriptions of human performance.

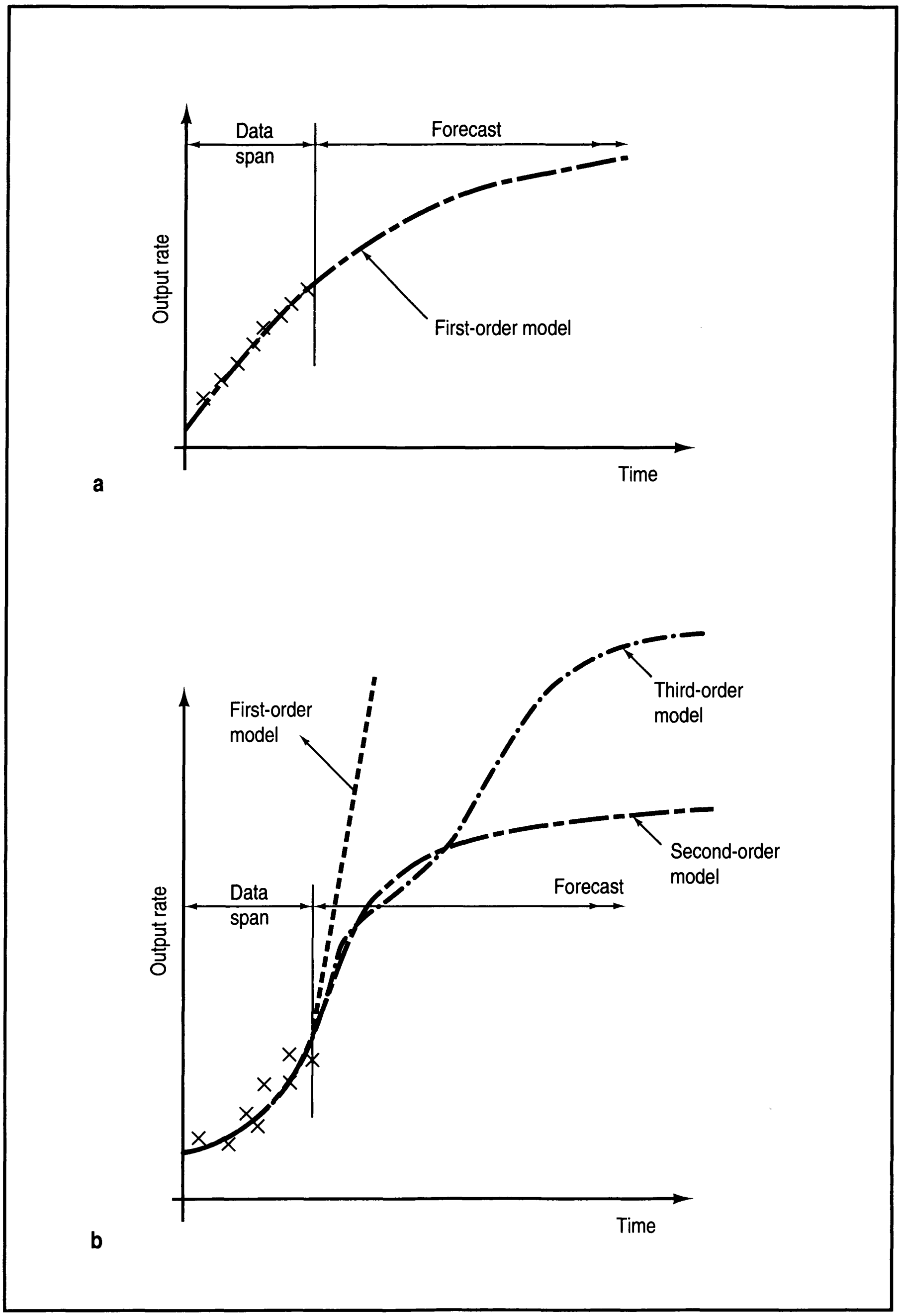

Fig. 4.6. Learning curve prediction problems. **a** Well-conditioned data. **b** Poorly conditioned data.

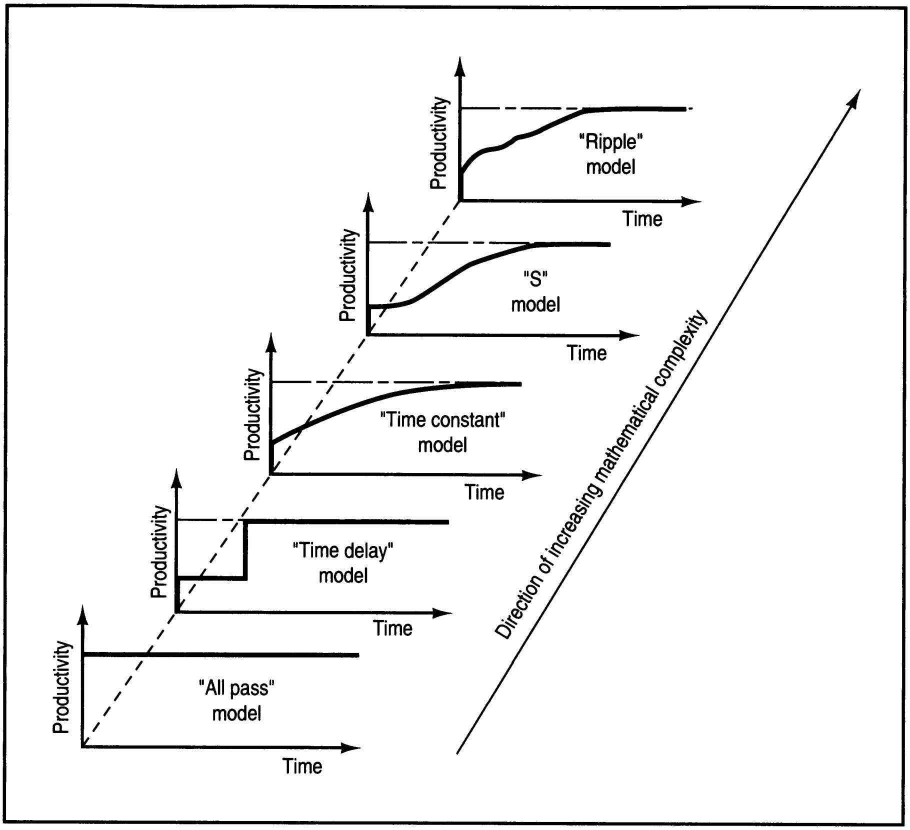

Fig. 4.7. Family of transfer-function-based learning curve models arranged in order of increasing complexity.

Finally, the only third-order system shown is for the case which particularly interests us. This is the ripple model, which has an oscillation of the oil compressibility type. Note particularly that as the transfer function increases in order, the corresponding equation in the time domain for $u(t)$ becomes *very* much more involved. This increasing complexity is even more noticeable when parameter estimation is attempted. It is obvious that for the first-order system only τ must be estimated, for the second-order system τ_1 and τ_2 must be estimated, while for the third-order system τ, ζ and ω_n must be estimated. As the order of model increases, so does the probability of computational instability. There is thus a tradeoff between curve-fit and convergence [22, 23].

4.8 An Example of Model Selection

To emphasize the options open to the modeller, consider the improvement curve resulting from the Crossman theory of the human operator selective process [24]. The data shown in Fig. 4.8 result from the transformation of the original Crossman calculations to the axes necessary for the transfer function approach. By eye we can see a slight S-curve in evidence (Fig. 4.8a), so that a *good* curve fit attempt is with the time constant model (Fig. 4.8b), which results in large errors only near the origin, first negative then positive in sign. The second curve-fit accepts that there is more to the process than simply the time-constant model, and represents the process by a delayed time-constant model (Fig. 4.8c). This delayed time-constant model fits the data well at the origin and also beyond $t = (D + \tau)$, with a maximum error at $t = D$. The accuracy of this model increases rapidly as $D \gg \tau$. Finally, the second-order model closely matches the S-curve and in this case is clearly the best model to use (Fig. 4.8d). It is a matter of judgement by the modeller as to whether or not either the time constant or the delayed time-constant models are adequate for this purpose without resorting to the second-order model. It must be remembered that models are required in the first place in order to facilitate the comparison between different subjects, processes and experimental conditions, so the simpler they are the better.

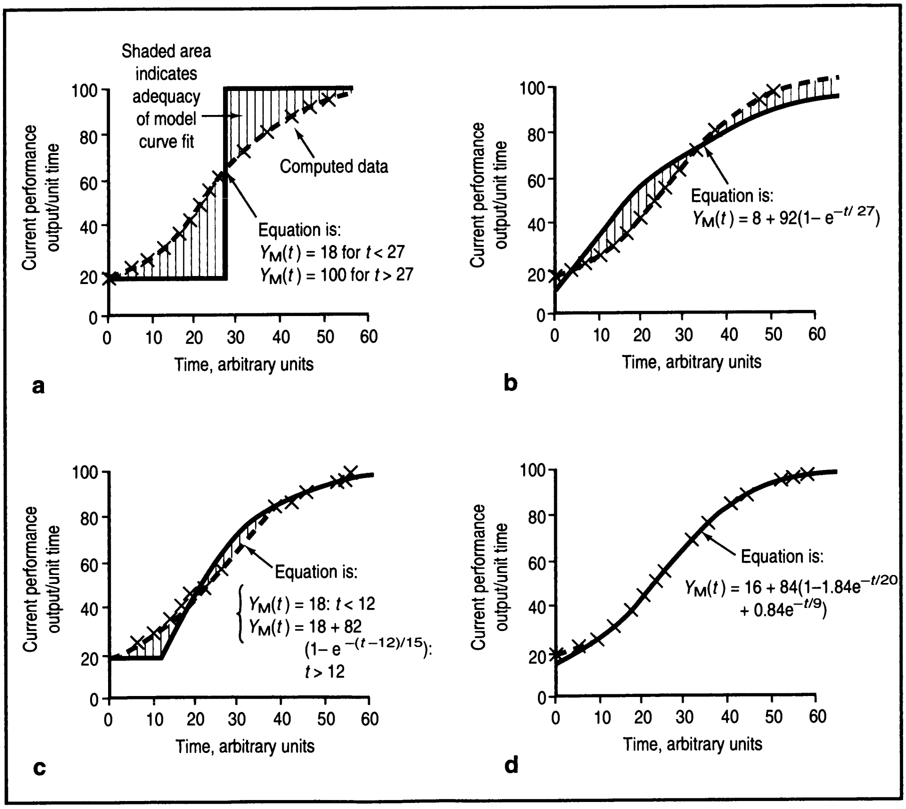

Fig. 4.8. Progressive stages in modelling the results obtained from the Crossman speed–skill theory. **a** Approximation by time delay model. **b** Approximation by time constant model. **c** Approximation by delayed time constant model. **d** Approximation by second order model.

The delayed time-constant model has one advantage over the S-curve in that it fixes a discontinuity change point. As mentioned in Chapter 1, this value identifies the changeover between the “commissioning” and “startup” phases, and consequently could be used as an indicator to accountants as to when it is reasonable to start allocating fixed costs to the process.

4.9 Sequential Learning Curve Models

Transfer function models may also be used to describe improvement processes where the plateau phenomenon is observed. This is done by using two time-constant models, one of which curve-fits the data up to the start of the plateau. A second model then curve-fits the data subsequent to the initiation of recovery, as shown in Fig. 4.9. Often it is found that the recovery phase model time constant is approximately the same as for the initial phase model, the second curve then being simply the initial curve translated in time by the plateau length. Note that for the recovery phase model we have the choice of time origin. We can start counting time from the recovery initiation point, calling the new time variable t', hence the equation set would be as follows:

$$\begin{aligned} Y &= Y_{c1} + Y_{f1}(1 - e^{-t/\tau 1}) && \text{for } 0 \leqslant t \leqslant D_1 \\ Y &= Y_p && \text{for } D_1 \leqslant t \leqslant D_2 \qquad (9) \\ Y &= Y_{c2} + Y_{f2}(1 - e^{-t'/\tau 2}) && \text{for } t > (D_2) \\ &\left(\text{i.e. } \frac{t'}{\tau_2} = t - D_2\right) \end{aligned}$$

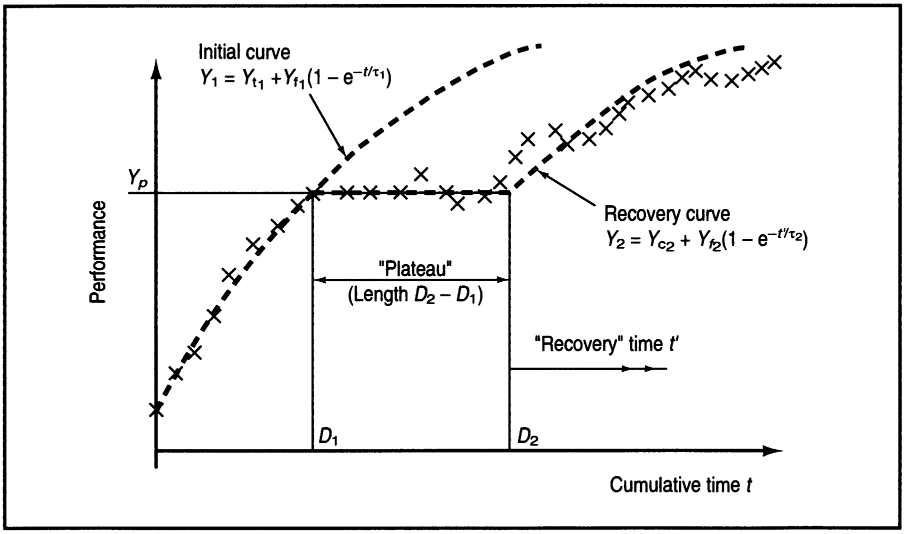

Fig. 4.9. Single-plateau case with two time constant models.

Alternatively, we can count time from $t = 0$, in which case the model is meaningful only if we use a Laplace delay operator each time there is a change in slope in the learning curve.

However, Y_c and Y_f will be different depending on which definition is used. In fact, if the recovery phase model is counted from $t = 0$, Y_{c2} may well be negative, but this of course does not mean there is a negative output at $t = 0$ for the process, since it is the initial model which is used to describe performance in this region, as shown in Fig. 4.9.

In Chapters 6 and 7 other industrial examples will be given where the use of sequential curves is clearly advisable. Significant falloffs in production followed by lengthy recovery phases and their different steady states are shown. Indeed, explanations for these changes confirm that there have been permanent changes (planned or otherwise) within the production system. In these situations, long-range predictions based on a single curve would be relatively meaningless. However, there are situations where there is no permanent change to the AMT, and any disturbances are of limited duration once corrective action has been taken. Figure 4.10 illustrates a data set where 8 points out of 37 represent abnormal scatter due to assignable causes, to be described later in Chapter 9. These points could *either* be treated as "outliers" and removed from the data set prior to modelling, *or* be labelled as zero–one exogenous variables (see pp. 83–6) and modelled accordingly. If the effects of this abnormal scatter are neglected, the estimates of the parameters will be distorted dramatically. For example, the final value of 114 hours per week with the abnormal scatter retained

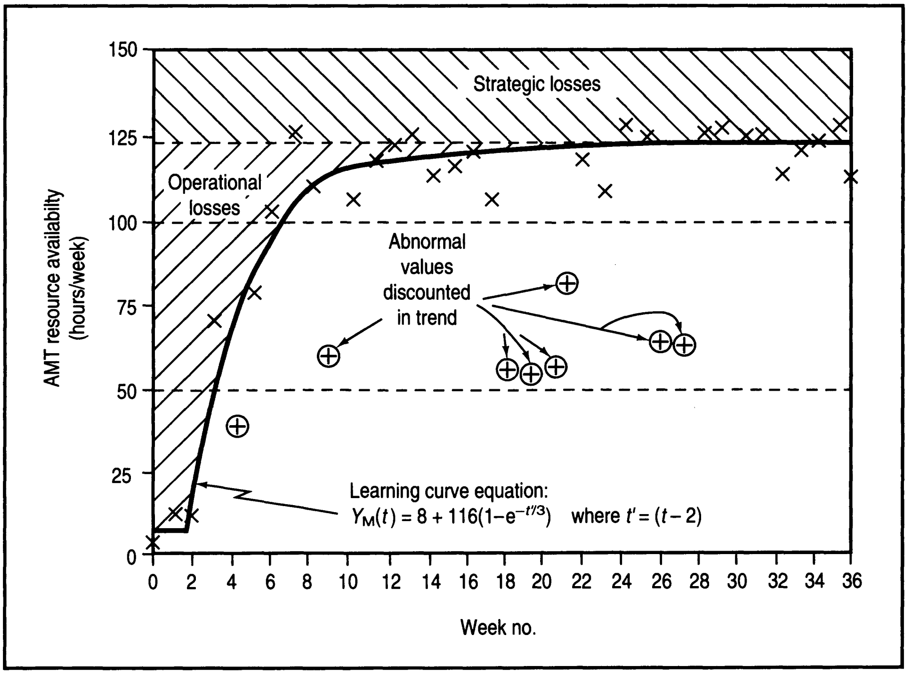

Fig. 4.10. Treatment of "abnormal" AMT startup losses.

becomes 124 when the abnormal scatter is compensated for. The latter long-range steady state estimate is clearly observable via the "normal" scatter of the last 10 weeks. The delayed time constant learning is appropriate in this case with the following equation set:

$$Y_M(t) = 8 \qquad 0 \leqslant t \leqslant 2$$

$$Y_M(t) = 8 + 116\,(1 - e^{-t'/3}) \qquad 2 \leqslant t \leqslant \infty \tag{10}$$

again, $t' = (t - D)$ where $D = 2$ weeks. Hence, if we follow the arguments of the previous section then the two weeks' delay could be argued to be the shop-floor commissioning phase of this FMC. Note from equation (10) that in this case 95% of planned resource capacity is available within 11 weeks of startup.

4.10 Some Paradigms Covering Sources of Lost Production in AMT Startup

In using learning curve models as a tool to aid management startup, a number of paradigms are assumed, but correlate with our experience of both FMC and FMS installations. These may be summarized as follows:

1. *Paradigm of planned maintenance* It may appear at first sight counterproductive to remove a planned maintenance slot, from the time availability of an island of automation. However, this is likely to increase significantly the productivity of the AMT in both the short and long terms.

2. *Paradigm of increasing productivity* The average output rate will increase with the cumulative time spent in operating the AMT. The *rate* of increase in productivity will however decrease with time, hence the practical use of exponential curves to model the startup behaviour of the installation.

3. *Paradigm of maximum productivity* The actual output rate achieved will on average be less than the theoretical maximum, even for a well-run plant. However, the level of variation about the final average output rate and the "offset" of this average from the "theoretical" maximum output rate will be critically dependent on the managerial, technological and organizational skills of the individual company.

4. *Paradigm of daily variability* It is inevitable that there will be a daily variability in output rate. In a well-run plant this variation will be small. A running estimate of this variation is helpful in assessing when the plant is operating out of control and hence when corrective action is needed.

5. *Paradigm of lost energy* A major loss in productivity can occur because AMT is operating but not cutting metal. It is therefore essential to monitor cutting time and not merely "lights on" time. The reasons for output shortfall due to "lost energy" are manifold, including no operator cover, inefficient part programming, etc.

6. *Paradigm of "lights off"* A major loss in productivity can occur because of the machine not operating. Most of these causes are attributable to management policy (shortages of equipment, breakdown, shortages of labour, poor scheduling etc.).

The understanding of these paradigms is important if the on-line prediction system to be summarized in Fig. 5.5 is to be properly exploited, and the changes maximized of successfully installing AMT.

4.11 Estimating "Lost Capacity" from the Learning Curve Model

An important application of learning curve models is in the estimation of "lost capacity" during startup. In Chapter 6 will be introduced the concept of "standard cost of learning", which allows us to develop simple formulae for estimating this loss once the learning curve parameters are available (or may be synthesized with confidence). For a delayed time constant model, the operational losses shown in Fig. 4.10 are equal to:

$$\mathrm{OLOSS} = Y_f[D + \tau] \tag{11}$$

Alternatively, this may be expressed as equivalent weeks at full capacity:

$$\mathrm{OWKS} = \frac{Y_f[D + \tau]}{(Y_f + Y_c)} \tag{12}$$

For the model parameters for the FMC of Fig. 4.10, $Y_f = 116$; $Y_c = 8$; $D = 2$ weeks; $\tau = 3$ weeks. Hence OLOSS = 580 hours resource availability and OWKS $\simeq$ 5 weeks loss at a rate of 124 hours per week.

Formulae such as OWKS assist in making more realistic assessments of payback periods (especially when $(D + \tau)$ starts becoming significant fractions of a year). However, this is the "planned" operational loss, which should be independent of the individual company. (In practice, gross mismanagement may give rise to significant difference in OWKS, as defined by equation (12).) However, owing to machine breakdowns, software unavailability, etc. the "abnormals" shown in Fig. 4.10 must be added to equations (11) and (12), to obtain the losses for a company specific application. The sum of the "abnormal" deviations about the trend line is about 233 hours. So the *total lost capacity* is (580 + 233) = 813 hours (or, say, 7 weeks at full planned speed of output).

However, the two sources of operational losses should be viewed differently. There is no reason why the "planned" (or "acceptable") losses as given by the smooth long-term trend line should not be transferable from installation to installation (provided there is not gross mismanagement at startup). However, two companies may well be at different stages of providing an AMT infrastructure (two levels on Fig. 1, for example). Hence an FMC installed in the more "mature" company might well avoid the *additional* loss of 233 hours.

4.12 Recommendations

It is good management practice to install an information system which monitors "industry learning" such as AMT startup, and compares the current rate of learning with the target value. With present knowledge, this target value can only be set in one of three ways:

1. using synthetic learning curve data;
2. from inter-company comparisons available in the open literature;
3. from careful use of a company databank, in which previous performance data has been carefully annotated.

The time-constant learning curve model is frequently adequate for methods 2 and 3. Where it is not, the addition of a simple time delay is usually adequate. If periodic variations due to natural or management-induced causes are suspected then it is suggested that these be allowed for in an additive manner, so that the simplicity of the time-constant model is retained.

We thus advocate the setting up of a learning curve model which represents normal smooth increase in performance, with each significant deviation from the curve being separately accounted for. So the model can become the basis of a management control system with many different applications, including costing.

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5 Forecasting via Learning Curves

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5.1 Introduction

In Chapter 4 we met the family of learning curve models which can be used to describe the dynamics of AMT startup. We now need to develop algorithms which will estimate the parameters for the selected model. If the modelling is to be undertaken on a historical basis, i.e. if the effective steady state has been reached, then simple graphical techniques may prove adequate, especially if the data is smoothed before curve fitting takes place.

The best-known of these methods is the log-transform technique [1]. For example (using the same notation as in Chapter 4), applied to the time constant model, the analysis at each data point would proceed as follows:

$$Y(t) = Y_c + Y_f(1 - e^{-t/\tau}) \tag{1}$$

After transformation, this may be rewritten as

$$e^{-t/\tau} = 1 - \left[\frac{Y - Y_c}{Y_f}\right]$$

Taking logarithms (to base 10, for graphical convenience), we have

$$-\frac{t}{\tau}\log_{10} e = \log_{10}\left[1 - \left(\frac{Y - Y_c}{Y_f}\right)\right] \tag{2}$$

Hence, from equation (2), if we plot $1 - (Y - Y_c)/Y_f$ against t on a log–linear scale, the slope will be $-\log_{10}e/\tau$ where τ can be determined. Thus, provided Y_c and Y_f are known (or in the case of Y_f, may be estimated from capacity calculations) the log transform method is simple, quick and convenient.

An example of the method is shown in Fig. 5.1 for typical AMT startup data. It is arguable whether the system has settled down into "steady-state" behaviour before the estimation of τ is attempted. $\hat{Y}_c$ is assumed to be 58% and $\hat{Y}_f$ is to be 37%. These estimates of initial and final value have required considerable smoothing of the raw data. This will clearly influence the estimate of $\hat{\tau}$.

Some form of least-squaes error is implied in the straight-line curve-fitting of equation (2). However, it is important to note that (by eye) we are attempting to minimize the LSE *for the transformed data*. This is far

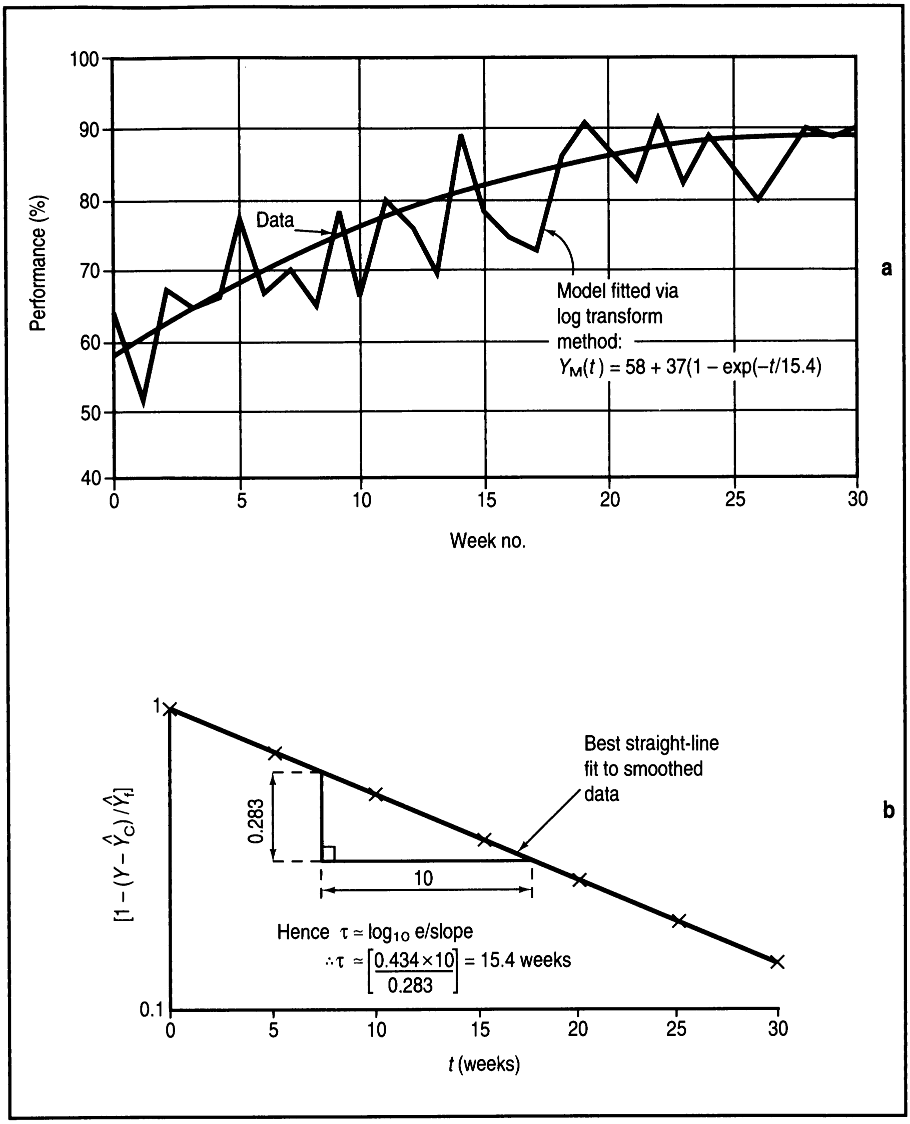

Fig. 5.1. Modelling an FMS startup using a graphical method. **a** Raw data plus model output. **b** Log transform plot.

from the same thing as minimizing the LSE for the original data; for a given startup the differences may or may not be significant. In Fig. 5.1 the resultant time constant model is seen to be a reasonable descriptor for the startup curve.

If the curve-fitting accuracy to the original data using τ estimated in this way is at an unacceptable level then the situation may be improved by trial-and-error. A graphical method also exists for the case where Y_f is completely unknown. However, the method does require differentiation of the learning curve, a hazardous procedure if there is much scatter on the data, so clearly it would be inappropriate for the FMS case considered herein. We assume the slope dY/dt and the learning curve ordinates Y are available at two points on the curve, t_1 and t_2:

$$\begin{aligned} &\text{at point 1} \quad Y_1 = Y_c + Y_f(1 - e^{-t_1/\tau}) \\ &\text{at point 2} \quad Y_2 = Y_c + Y_f(1 - e^{-t_2/\tau}) \end{aligned} \tag{3}$$

Also, by differentiating, we have

$$\begin{aligned} &\text{at point 1} \quad \frac{dY_1}{dt} = \frac{Y_f}{\tau} e^{-t_1/\tau} \\ &\text{at point 2} \quad \frac{dY_2}{dt} = \frac{Y_f}{\tau} e^{-t_2/\tau} \end{aligned} \tag{4}$$

Manipulation yields the simple result for

$$\tau = \frac{Y_2 - Y_1}{\frac{dY_1}{dt} - \frac{dY_2}{dt}} \tag{5}$$

Y_f can then be estimated by substituting in the equation for Y_1, and cross-checking the combined estimates for τ and Y_f in the equation for Y_2. The method can be a useful guide, but only in the case of smooth data. For typical AMT startups, computer algorithms are needed if the forecasting ahead (as distinct from historical modelling) mode is required.

5.2 The Case for Forecasting

From the family of transfer-function-based learning curves previously shown in Fig. 4.7, the general equation for the trend line which we wish to forecast may be written as follows:

$$Y_M(t) = Y_c + Y_f \sum_{i=1}^{i=n} A_i e^{\lambda_i t'} \tag{6}$$

where n is the order of the transfer function and $t' = (t - D)$, D being the pure time delay if one is found to exist. Also, if the learning cuve is an exact inversion of the Laplace transform representation of the transfer function, the residues, A_i, are a known function of the transient modes, λ_i. Since this relationship is determined theoretically, additional information may be built into the curve fitting algorithm. For example, for the general S-model the learning curve equation may be written as follows:

$$\begin{aligned} Y_M(t) = Y_c + Y_f \Bigg\{ 1 &+ \left(\frac{\tau_1}{\tau_2 - \tau_1}\right) e^{-t/\tau_1} \\ &- \left(\frac{\tau_2}{\tau_2 - \tau_1}\right) e^{-t/\tau_2} \Bigg\} \end{aligned} \tag{7}$$

Hence the two residues are directly related to the two time constants, τ_1 and τ_2. However, since we are undertaking empirical curve fitting, A_1 and A_2 could be left to "float" independently of τ_1 and τ_2. While there might be some consequential reduction in curve-fitting error, the convenience of using the transfer function family of learning curve models would be lost. In our experience, where the S-model is found to be the appropriate solution, adequate freedom of curve fit results from using equation (7), and this is the form in which that particular algorithm has been developed [2].

Estimation of learning curve parameters is an important aspect of AMT startup and management control. We have already seen from Fig. 1.3 how a learning curve model may be incorporated within a computer-based management and control system [3]. Note that the critical factor in the MIS is the incorporation of a realistic time-varying learning curve, however crude. Even that shown in Chapter 1 (Fig. 1.2) would be a better starting point than nothing, especially if parameter updating is incorporated, once real live data becomes available.

Many curve-fitting procedures have been developed over the years for modelling learning curves and progress functions. These include:

1. Graphical methods (in addition to those already described) [4,5]
2. LSE algorithm via Taylor series expansion [6–8]
3. Kalman filter [9]
4. Maximum likelihood method [10, 11]
5. LSE search methods [12]

The techniques so far extensively evaluated for on-line industrial forecasting are 1 and 3, which have been widely tested via UK case studies. In the Cardiff directed research, the Kalman filter and the LSE Taylor series expansion have proved roughly comparable in effectiveness. It is therefore proposed to describe only the latter in the next section.

5.3 Development of the Basic LSE Learning Curve Algorithm

We now review the Taylor series LSE estimator applied to the three-parameter time constant learning curve model. The iterative estimation process described in detail in Appendix 1 may be summarized in flow diagram form in Fig. 5.2. The starting point is the time domain equation (1),

$$Y_M(t) = Y_c + Y_f(1 - e^{-t/\tau})$$

where it is assumed that Y_c, Y_f and τ must all be estimated from operating data obtained during AMT startup.

The approach adopted in Appendix 1 is that originally conceived in reference [8]. If we use the notation $Z = 1/\tau$ for ease of manipulation, then the estimated value of Y at time t_i may be written as

$$\overline{Y}_i = f(Y_c, Y_f, Z, t_i) \qquad (8)$$

Using the Taylor series expansion of Appendix 1, a set of linear equations may be determined which are functions of the data points and the parameters

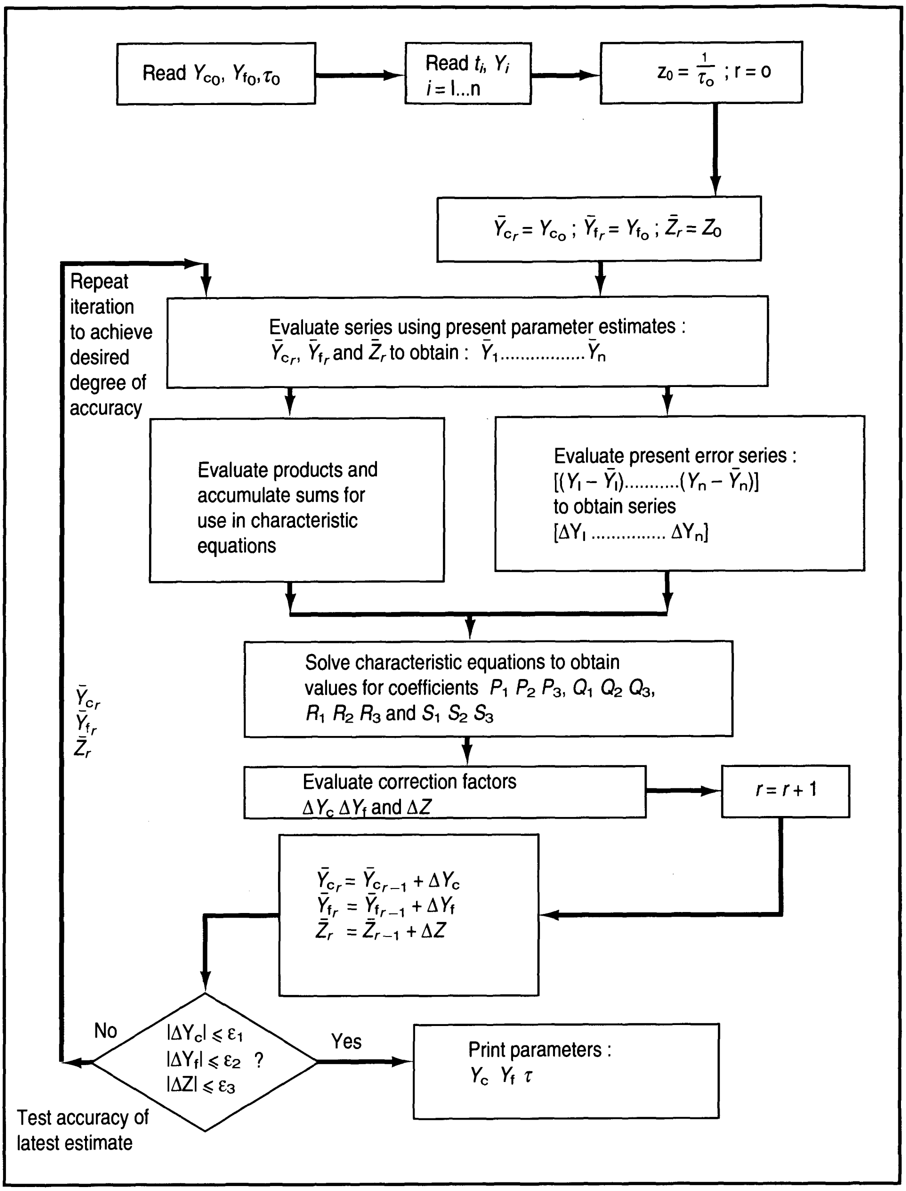

Fig. 5.2. Block diagram summarizing three-parameter LSE algorithm applied to the time constant learning curve model [8].

to be estimated. These equations may easily be solved via Gaussian elimination and the corresponding correction quantities established. Present parameter estimates may then be updated via iteration as long as the correction quantities are considered to be significant. Thus,

$$Y_{cr+1} = Y_{cr} + \Delta Y_c \tag{9}$$

$$Y_{fr+1} = Y_{fr} + \Delta Y_f \tag{10}$$

$$Z_{r+1} = Z_r + \Delta Z \tag{11}$$

Here Y_{cr}, Y_{fr} and Z_r are the estimates available at the rth stage of iteration and ΔY_c, ΔY_f and ΔZ are the correction factors calculated after one further loop of the iteration process. The latter may be controlled by a test for the significance of the present correction quantity for each simultaneously predicted trio of linked model parameters, i.e. the iterations may be terminated when $|\Delta Y_c/Y_{cr}|$ $|\Delta Y_f/Y_{fr}|$, and $|\Delta Z/Z_r| \leq \epsilon$, etc., where ϵ is some small quantity chosen on the basis of experience or by trial and error.

5.4 Some Results Obtained from the Basic LSE Algorithm

Our basic LSE algorithm as applied to the time constant model has been widely tested in reference 1. One such result is shown in Table 5.1 and is typical of industrial case studies covering a wide variety of plant. For the forecast-ahead tests, the estimates of $\hat{Y}_c$, $\hat{Y}_f$ and $\hat{\tau}$ are listed as a ratio of their final values observed on a historical basis when all data is available.

As a test of forecasting accuracy, the expected output at day 70 has been predicted using the model equation

$$\hat{Y}_M(70) \cong \overline{Y}_{cN} + \overline{Y}_{fN}\,[1 - e^{-70/\bar{\tau}_N}]\ . \tag{12}$$

The results show that final performance is estimated to within 13% by day $N = 18$, and within 3% by day $N = 38$. This is without building any additional "intelligence" into the forecasting, which will be the subject of a later section.

The importance of a priori estimates of initial performance is evident from Table 5.1. In the first LSE learning curve algorithm only a two-parameter (Y_f and τ) curve fit was performed. This assumption was made on the basis that a reasonably simple estimate of $\hat{Y}_c$ could be derived using, for example, synthetic data. However, partly because of the absence of good industrial engineering support in the companies where the studies were undertaken, it was found beneficial for long-term forecasting to regard $\hat{Y}_c$ as an uncertain parameter to be estimated as part of the LSE algorithm. Table 5.1 clearly confirms that $\hat{Y}_c$ should be regarded as an uncertain

Table 5.1. LSE algorithmic predictions of learning curve parameters and "look-ahead" to day 70 performance

Day no. on which forecast made	$\hat{Y}_c/Y_{c\infty}$	$\hat{Y}_f/Y_{f\infty}$	$\hat{\tau}/\tau_\infty$	$\hat{Y}_{70}/Y_{70}$
8	0.881	0.754	0.336	0.820
18	0.964	0.962	0.778	0.870
38	0.967	0.978	0.816	0.972
58	1.008	1.001	1.039	1.004
68	1.000	1.000	1.000	1.000

parameter needing separate estimation, hence the development of the three-parameter algorithm described in Appendix 1.

In the same way as estimates for $\hat{Y}_c$ need to be considered carefully (and on-line estimates weighted against a priori values estimated from a databank), it is also helpful to estimate an expected value of $\hat{Y}_f$ from a theoretical analysis of production processes, handling systems, etc. If upper and lower limits can be assigned to a priori estimates for $\hat{Y}_f$, then as data from the actual product line becomes available, the relative weighting to be attached to the on-line estimates can gradually be increased in favour of the latter.

There is much to be said for production management focusing attention on the estimation of $\hat{Y}_c$ and $\hat{\tau}$ during the early startup phase, thus constraining Y_f within the curve-fit algorithm. As production proceeds, the constraints on Y_f may be relaxed since greater confidence will not be placed in Y_c and τ. This implies that at the end of the estimation procedure, we are using relationships of the form

$$\begin{Bmatrix}\text{new estimate of}\\ \text{parameter}\end{Bmatrix} = \begin{Bmatrix}\text{old estimate of}\\ \text{parameter}\end{Bmatrix} + \alpha\begin{Bmatrix}\begin{matrix}\text{new}\\ \text{estimate}\end{matrix} - \begin{matrix}\text{old}\\ \text{estimate}\end{matrix}\end{Bmatrix} \tag{13}$$

where α varies between 0 and 1 according to the amount of data available and the confidence put in individual estimates. The need to disclose the confidence level in this way is similar to making a judgement on the covariance matrices required in the Kalman filter approach [9].

5.5 Zero–One Modelling

We have found intelligent forecasting extremely useful in providing stable estimates from situations where the data is ill-conditioned by an uncertain initial trend or when the signal-to-noise ratio is low. Under these circumstances it is very helpful for the analyst to model the process interactively. This permits smoothing the final estimates as these become available at each stage of the modelling, via equation (13). The latter is one example of "bootstrapping" [12].

Other ways of improving estimates from ill-conditioned data include the provision of "damping" within the LSE iterative loop of Fig. 5.2. Also, given the need to introduce such damping, there is then the opportunity to predict the best value of loop-smoothing constant to be used. Assuming the error function is parabolic makes this selection procedure very simple [2]. Considerable improvements in robustness and rate of convergence then result from these modifications.

However, for on-line modelling and forecasting, feedback and action within the LSE algorithm on the known presence of any significant exogenous operating variables are essential. One method of achieving this goal is via the "zero–one" model [12]. This modulates the trend according to the equation

$$Y_M(t) = Y_R(t) + \sum_{i=1}^{i=q} W_i(t)S_i(t) \tag{14}$$

Here, $Y_R(t)$ is the long-term trend predictor, such as would be obtained from the time constant model of equation (1), $S_i(t)$ is a zero–one switch which will be pulsed during a time period for which the ith exogenous variable is operating and $W_i(t)$ is the performance weighting function to be associated with the variable. In this way we avoid damaging the long-term predictive properties of the forecaster due to known short-term events.

An example of the use of a zero–one approach is shown in Fig. 5.3, which is for one crew involved in a continuous process in the aluminium industry. The deterioration in performance occurs between days 37 and 41 (so that $S_i(t)$ is pulsed for the four-day period), and $W_i(t)$ is 10.1 standard output units for the same period. In this particular case, the exogenous cause noted is temporary drop in crew size. For this case study, four exogenous variables were identified. These were: product mix (at two levels), crew size, and temporary replacement of group leader. Standard statistical techniques were used to evaluate $W_i(t)$ and also to rank these variables in order of importance.

5.6 An FMC Startup: Time Constant Model versus S-Curve

The LSE algorithm learning curve can, of course, be extended to cope with any number of parameters. In reference [2] the S-curve ($\tau_1 \neq \tau_2$) algorithms are presented. Unfortunately, as the number of parameters to be estimated increases, so the probability of convergence of the algorithm decreases, and hence the need to use the simplest model appropriate to the task despite the initial attraction of using additional descriptive parameters.

Figure 5.4 compares the S-curve model with the time constant model as applied to an FMC startup. Unfortunately, the data have only been monitored by management at weekly intervals when daily feedback would

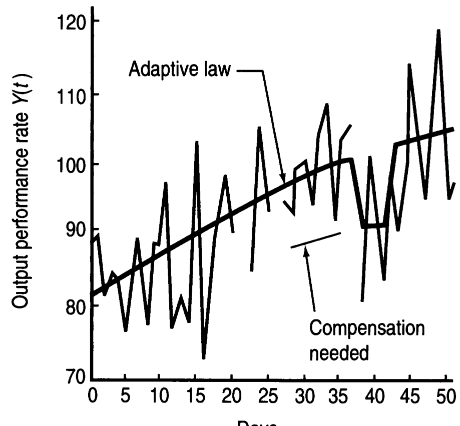

Fig. 5.3. Using the "zero–one" adaptive model to describe aluminium process startup [12].

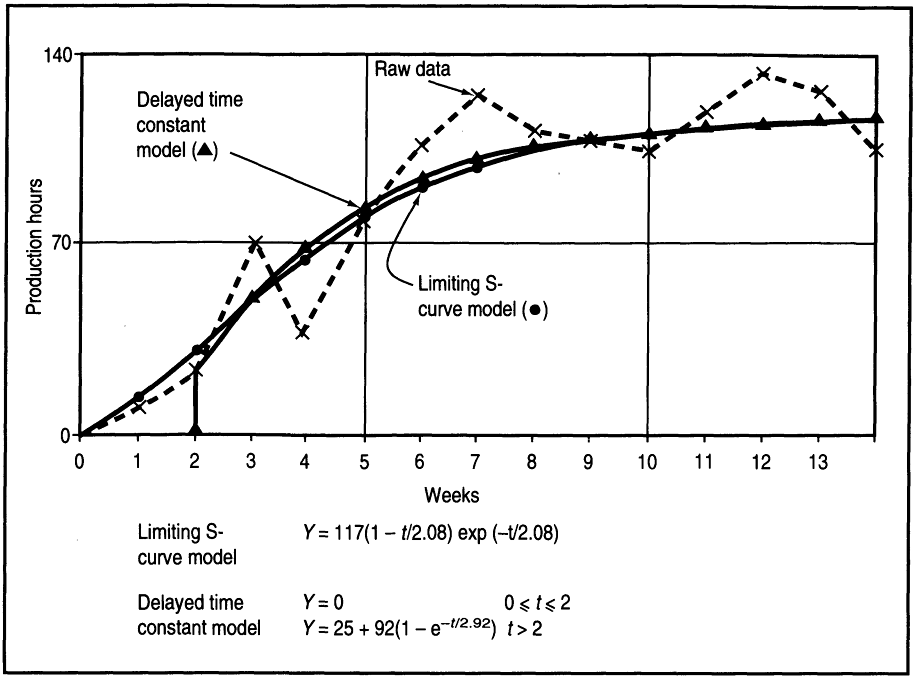

Fig. 5.4. Comparison of fitting delayed time constant model and limiting S-curve model to FMC startup data.

be well justified. Certainly, with these few data points forecasting ahead would be very difficult, especially as the points available are subject to considerable scatter. (Note that the FMS startup model of Fig. 5.1 was for historical curve-fitting only.)

Using the constrained S-curve algorithm (to improve convergence properties) the equation which results is

$$Y = 117.2\,(1 - t/2.08)e^{-t/2.08} \tag{15}$$

whereas for the delayed constant model we have

$$\begin{aligned} Y &= 119(1 - e^{-(t-2)/2.92}) && \text{for } t \geqslant 2 \\ Y &= 0 && \text{for } t < 2 \end{aligned} \tag{16}$$

In this application the S-curve is clearly a better match near the origin; however, if the first two weeks' production is regarded as a pilot phase, then the time constant model is adequate. Note that FMC startup is much quicker (by a factor of about 10 : 1) than the FMS response shown in Fig. 5.1. For the latter the S-curve model is unnecessarily complex.

For the FMS, the corresponding model equation as determined via the LSE algorithm is

$$Y = 60 + 41.3\,[1 - e^{-t/24.3}] \tag{17}$$

which should be contrasted with the values obtained graphically in the introductory section to this chapter. Note that both for the FMC and the FMS the week-to-week variation is high. However, for forecasting purposes the FMC becomes much more difficult because of the relatively few data points per cycle of oscillation.

5.7 Incorporation of LSE Modelling with an On-Line Monitoring System

Without bootstrapping and the availability of a priori estimates, the FMC behaviour would be extremely hazardous to predict. Hence the necessity for the "proper" design of the MIS shown in Fig. 1.3. Also, it must be emphasized that in the cases of both FMC and FMS startup shown there are significant fluctuations about the trend line. The causes are obviously worthy of tracking down via on-site investigation leading to corrective action by management. It is helpful if triggering such action can be done automatically, hence Fig. 5.5. brings together in block diagram the modelling, smoothing and trend prediction aspects of startup management [13]. This includes the provision of feedback of all those exogenous variables known to management, so that long-term performance estimation is not distorted by short-term events. Credibility is hardly enhanced by highlighting the

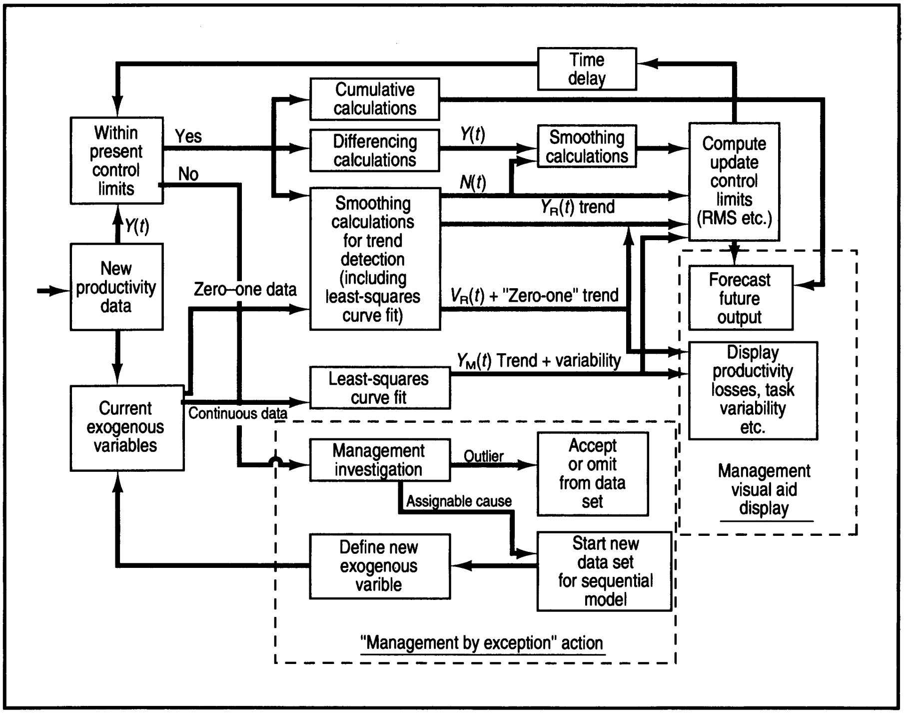

Fig. 5.5. Using modelling, smoothing and trend prediction within an AMT startup control system [13].

obvious! What we have to do is to design the on-line monitoring system to achieve an optimum balance between sending out false alarms and early detection of genuine warning signs. The scheme shown in Fig. 5.5 does this to the limit of our present operating knowledge. A startup databank will eventually prove a very worthy investment.

5.8 Conclusions

A number of algorithms are available for estimating learning curve parameters. Appendix 1 describes in detail the Taylor series LSE algorithm applied to the time constant model and we have shown how it may be used to model both FMS and FMC startup. The extension of the LSE algorithm to other models is straightforward, but can lead to increased problems with convergence. Hence the desirability of including some "intelligence" within the modelling loop. This can be achieved in a variety of ways, including "bootstrapping" and "damping" within the algorithm.

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Appendix 1. Development of the Basic LSE Learning Curve Algorithm

We now review the Taylor series LSE estimator as applied to the three-parameter time constant learning curve model. The starting point is the time domain equation originally encountered in Chapter 4.

$$Y_M(t) = Y_c + Y_f(1 - e^{-t/\tau}) \tag{A.1}$$

where it is assumed that Y_c, Y_f and τ must all be estimated from operating data obtained during AMT startup.

The approach adopted in Appendix 1 is that originally conceived in reference [8]. If we use the notation $Z = 1/\tau$ for ease of manipulation then the estimated value of Y at time t_i may be written as

$$\overline{Y}_i = f(Y_c, Y_f, Z, t_i) \tag{A.2}$$

This equation may be expanded using the present best estimates for Y_c, Y_f and Z ($\hat{Y}_c$, $\hat{Y}_f$ and $\hat{Z}$ respectively). If terms above the first order are neglected, then we may write via the Taylor series expansion:

$$\overline{Y}_i \simeq f(\overline{Y}_c, \overline{Y}_f, \overline{Z}, t_i) + \frac{\partial f}{\partial Y_f}\Delta Y_t + \frac{\partial f}{\partial Z}\Delta Z + \frac{\partial f}{\partial Y_c}\Delta Y_c \tag{A.3}$$

in which

$$\frac{\partial f}{\partial Y_c} = 1 \tag{A.4}$$

$$\frac{\partial f}{\partial Y_t} = [1 - \exp(-t_i\overline{Z})] \tag{A.5}$$

$$\frac{\partial f}{\partial Z} = \overline{Y}_f t_i \exp(-t_i\overline{Z}) \tag{A.6}$$

Substituting equations (A.4) to (A.6) into (A.3), the current estimate becomes

$$\begin{aligned} \overline{Y}_{ir} \simeq\ & \overline{Y}_{cr} + \overline{Y}_{fr}[1 - \exp(-t_i\overline{Z}_r)] \\ & + \Delta Y_c + [1 - \exp(-t_i\overline{Z}_r)]\,\Delta Y_f \\ & + [t_i\overline{Y}_{fr}\exp(-t_i\overline{Z}_r)]\,\Delta Z\ , \end{aligned} \tag{A.7}$$

where the suffix r denotes the appropriate values of the parameters after r iterations.

Following q iterations, the "best" estimates are obtained for the model parameters Y_c, Y_f and Z. The correction factors, ΔY_c, ΔY_f and ΔZ will then become insignificant and equation (A.7) reduces to

$$\overline{Y}_{iq} \simeq \overline{Y}_{cq} + \overline{Y}_{fq}[1 - \exp(-t_i\overline{Z}_q)]\ , \tag{A.8}$$

where the parameters are the best currently available.

Returning to equation (A.7), we see that after r iterations the current estimate of the sum of errors squared is given as

$$\begin{aligned} E^2 = \sum_{i=1}^{n} \{ & Y_i - \overline{Y}_{cr} - \overline{Y}_{fr}[1 - \exp(-t_i\overline{Z}_r)] - \Delta Y_c \\ & - [1 - \exp(-t_i\overline{Z}_r)]\,\Delta Y_f \\ & - \overline{Y}_{fr}t_i\exp(-t_i\overline{Z}_r)\,\Delta Z\}^2 \end{aligned} \tag{A.9}$$

Letting

$$\Delta Y_i = Y_i - \overline{Y}_{cr} - \overline{Y}_{fr}[1 - \exp(-t_i\overline{Z}_r)] \ ,$$

equation (A.9) can be written as

$$E^2 = \sum_{i=1}^{n} \{\Delta Y_i - \Delta Y_c - [1 - \exp(-t_i\overline{Z}_r)]\,\Delta Y_f - \overline{Y}_{fr}t_i \exp(-t_i\overline{Z}_r)\,\Delta Z\}^2 \qquad (A.10)$$

Since equation (A.10) is now linear in ΔY_c, ΔY_f and ΔZ, the traditional minimum sum of errors squared approach may be employed. Hence for

$$\frac{\partial E^2}{\partial \Delta Y_c} = 0, \quad \frac{\partial E^2}{\partial \Delta Y_f} = 0, \quad \frac{\partial E^2}{\partial \Delta Z} = 0$$

we have

$$S_1 = R_1\,\Delta Y_c + Q_1\,\Delta Y_f + P_1\,\Delta Z \ , \qquad (A.11)$$

$$S_2 = R_2\,\Delta Y_c + Q_2\,\Delta Y_f + P_2\,\Delta Z \ , \qquad (A.12)$$

$$S_3 = R_3\,\Delta Y_c + Q_3\,\Delta Y_f + P_3\,\Delta Z \ , \qquad (A.13)$$

where

$$\begin{aligned}
S_1 &= \sum \Delta Y_i \\
S_2 &= \sum \Delta Y_i[1 - \exp(-t_i\overline{Z}_r)] \\
S_3 &= \overline{Y}_{fr} \sum \Delta Y_i t_i \exp(-t_i\overline{Z}_r) \\
R_1 &= n \\
R_2 &= \sum[1 - \exp(-t_i\overline{Z}_r)] \\
R_3 &= \overline{Y}_{fr} \sum t_i \exp(-t_i\overline{Z}_r) \\
Q_1 &= \sum [1 - \exp(-t_i\overline{Z}_r)] \\
Q_2 &= \sum [1 - \exp(-t_i\overline{Z}_r)]^2 \\
Q_3 &= \overline{Y}_{fr} \sum [1 - \exp(-t_i\overline{Z}_r)]t_i \exp(-t_i\overline{Z}_r) \\
P_1 &= \overline{Y}_{fr} \sum [t_i \exp(-t_i\overline{Z}_r)] \\
P_2 &= \overline{Y}_{fr} \sum [1 - \exp(-t_i\overline{Z}_r)]t_i \exp(-t_i\overline{Z}_r) \\
P_3 &= \overline{Y}_{fr}^2 \sum [t_i \exp(-t_i\overline{Z}_r)]^2
\end{aligned}$$

Equations (A.11) to (A.13) are the characteristic equations, all linear in ΔY_c, ΔY_f and ΔZ respectively.

These equations may easily be solved via Gaussian elimination and the corresponding correction quantities established. Present parameter estimates may then be updated via iteration as long as the correction quantities are considered to be significant. Thus,

$$Y_{cr+i} = Y_{cr} + \Delta Y_c \qquad (A.14)$$

$$Y_{fr+i} = Y_{fr} + \Delta Y_f \qquad (A.15)$$

$$Z_{r+i} = Z_r + \Delta Z \qquad (A.16)$$

The iteration process may be controlled by a test for the significance of the present correction quantity for each simultaneously predicted trio of linked model parameters, i.e. the iterations may be terminated when

$$|\Delta Y_c/Y_{cr}|\ |\Delta Y_f/\overline{Y}_{fr}| \quad \text{and} \quad |\Delta Z/Z_r| \leqslant \epsilon$$

where ϵ is some small quantity chosen on the basis of experience using LSE algorithms in flow diagram form.

6 Dynamics of AMT Capacity Planning

A. Davies and H. Lewis

6.1 Introduction

The introduction of advanced manufacturing technology (AMT) to an industrial concern can result in a protracted startup period. This may well extend into the anticipated operating phase of a new installation and thereby limit the productive capacity of the plant. In assessing the dynamics of capacity planning we need to understand the significance of any estimate made of $\hat{Y}_c$ (the initial productivity), $\hat{Y}_f$ (the productivity gain) and $\hat{\tau}$ (the rate at which the improvement in productivity is gained). "^" means the best estimate available at the time a forecast is to be made.

Within the startup period the equipment may not achieve its desired rate of utilization owing to three interacting factors. These are as follows:

1. Difficulties with making the *technology* work in a reliable manner. This imposes a limit on the availability of the AMT equipment and consequently reduces its utilization, which results in a loss of production.
2. Difficulties with making the AMT support *organization* work properly. This directly restricts the utilization of the AMT equipment rather than its availability and results in a loss of production through the inadequacy of logistic control. For example, the equipment may be operational but have no work owing to the poor scheduling of resources.
3. Difficulties with the *attitude* of management and/or shop-floor personnel within the company towards the introduction of AMT systems. This factor can also curtail the utilization of an AMT installation and result in a loss of production as a consequence of what is essentially a management failure either to lead or to follow up.

All of these problems are normally present and indeed are interactive during AMT startup. Depending upon their degree of severity, they can deny to a manufacturing system a significant portion of its planned capacity.

This chapter illustrates how the productivity losses which arise as a consequence of these factors, as typically met in flexible manufacturing system startup, can be assessed through the analysis of industrial data. We conclude that the use of the modelling techniques shown herein can provide production managers with an accurate indication of likely system capacity during the startup phase. Consequently, the financial implications for the company if no corrective action is taken to curb excess productivity losses are also calculable.

6.2 System Utilization

One of the principal criteria normally used to establish the performance of a manufacturing system is that of overall utilization. The precise definition of this term and also of equipment availability are important considerations when attempting to establish the extent of production losses. Thus the following definitions of these two terms, taking machining as a baseline example, are used subsequently throughout this chapter when referring to the utilization or availability of AMT equipment.

Both utilization and availability are ratios and are normally expressed as a percentage of planned working time, thus:

> *Utilization* is the ratio of productive machining time to planned working time.

(*Note*: Planned working time is defined as the theoretical maximum production hours available for a given shift pattern.)

> *Availability* is the ratio of planned working time minus system downtime to planned working time.

(*Note*: System downtime is defined as the time in which the equipment is not in an operational state during the planned working time.)

As a consequence of these definitions, several points arise which need clarification before they can be applied to manufacturing systems. This is to allow for the precise interpretation of production data and the correct evaluation of "utilization", together with the subsequent calculations on the cost of lost production.

As we have already seen in Chapter 1, in any practical situation, unmanned machining for 24 hours, 7 days a week is not a sensible proposition. This is because time will be required to be subtracted from the theoretical maximum available hours for preventive system maintenance, aggregated unforeseen events and perhaps the accommodation of a particular shift pattern within a company, leaving a net realistic number of planned hours. In addition, the definition of planned working time presupposes that the production schedule for the equipment will utilize all the available shift time. This is true only if the shift pattern exactly correlates with cumulative machining cycle times. In the main this is unlikely, and some loss of production can be expected as a result of mal-fit on this account.

The availability of AMT equipment is also critical to its utilization. Thus, in addition to the immediate effect of breakdowns and the consequent loss of production, the repair time needed to make the system operational and the point in time at which it becomes available may seriously affect the production schedule. The knock-on effects of failure can be severe in terms of lost production, as illustrated by the data obtained in respect of the FMS case studies to be outlined in Chapter 8. Losses are not simply limited to the time the equipment is down. Manufacturing logistics may be thrown completely out of kilter by a system failure, and, depending upon its recovery time, operational priorities may well have changed. This results in a further loss of production while the system is reset to meet a revised schedule (which in itself may be a time-consuming activity). Thus the "reliability and maintainability" of AMT equipment upon which its "availability" depends are critical factors in the design and operation of these systems.

In practice the causes of lost utilization are many and varied. They include several items which may properly be set under the heading of organizational, logistical or attitudinal delays and are for the most part a function of the system's environment within a company rather than errors in the equipment design. Figure 6.1 indicates the variety of the reasons established for lost utilization and productivity during the industrial study known as FMS B [1]. The diagram shows the wealth of problems which can attend the introduction of complex AMT equipment. Similar studies conducted outside the UK tend to pinpoint the existence of these difficulties during the startup phase [2] and, in addition, confirm the potential increase in utilization afforded by AMT over conventional equipment when such problems are resolved and the targeted steady-state position is reached.

6.3 Learning Costs and Lost Productivity Costs

The modelling of system startup is thus an important activity which can help to minimize the effect of productivity losses during AMT introduction, firstly by providing an early indication of their existence, and then by forecasting the likely consequences. As this chapter will show, the modelling and data analysis of startup quickly helps to identify productivity losses and allows corrective action to be taken with the minimum of delay using such monitoring techniques as those shown in block diagram form in Fig. 5.5.

The use of learning, experience or startup curves in manufacturing industry is now well established, and their utility has been noted for many applications. Originally they were used in the aerospace industry as a means of estimating significant increases in direct labour productivity which occurred following the introduction of new airframe models [3]. More recently they have been applied in various other industrial situations, and in the literature there are several models which can be used to describe the phenomenon of learning [4].

To some degree each of these models can provide a useful fit to the data in question, although as shown in Chapters 4 and 5 the time constant model is to be preferred owing to its curve-fitting accuracy, its convergence properties and the fact that the model parameters can be easily related to many industrial processes [4–7]. It is also easily extended to cope with sequential models and and to cover the case of plateaux phenomena which are frequently met in AMT startup [8].

For convenience we repeat the analysis in Chapter 4; we have the equation

$$Y(t) = Y_{\mathrm{M}}(t) + N(t) \tag{1}$$

where $Y_{\mathrm{M}}(t)$ is the model trend and $N(t)$ is the scatter, or variance from the trend (which is usually at zero mean and frequently random in nature).

For the time constant model the trend line for a single startup is defined as:

$$Y_{\mathrm{M}}(t) = Y_{\mathrm{c}} + Y_{\mathrm{f}}\,(1 - e^{-t/\tau}) \tag{2}$$

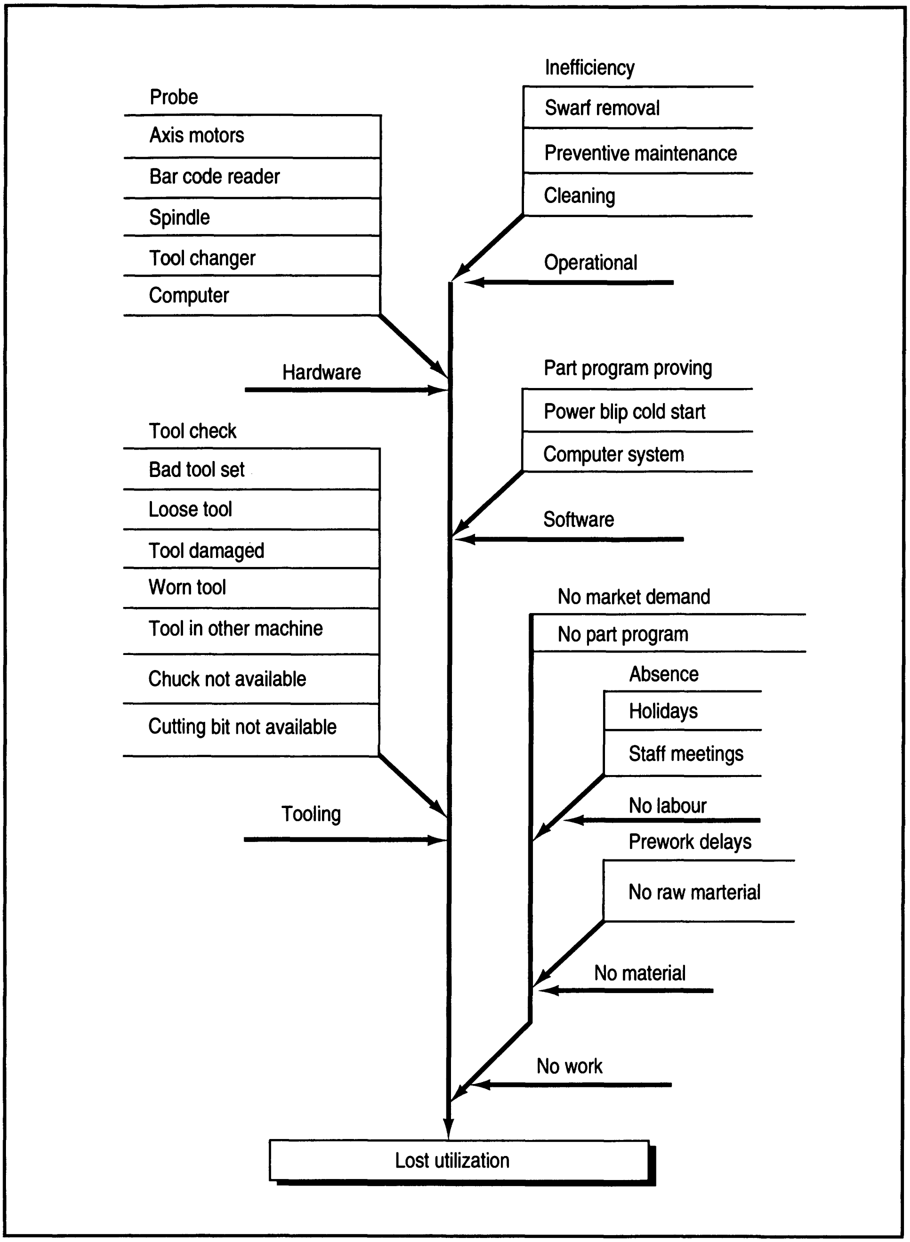

Fig. 6.1. Cause and effect diagram (lost utilization).

where Y_c is the initial output value, Y_f is the final value of increase in output rate, τ is the time constant and t is the time.

The "time constant model" as represented above is one of the family of industrial dynamics of transfer-function-based learning curve models. It is in our experience the simplest model in the group which adequately describes AMT "learning" [8–10]. To establish the model, the AMT equipment must be regarded as a time-varying system in respect of its output. Then equation (2) will provide the trend effect for the model, while $N(t)$ is a measure of uncertainty due to random effects, modelling errors and, in some cases, periodic variation for which there is usually an explanation forthcoming if management digs deeply enough.

As already seen in Fig. 5.5 it is the trend part of equation (1) that is used as the target for management purposes, such as forecasting future output, estimating productivity losses, and, if so required, to take action to improve performance. It should be noted that the ability to predict the true trend line generally proves to be more difficult (a) the further away we are from the original targeted output in the startup phase; (b) the greater the scatter of the raw output data about the trend line (known in communications engineering as the problem of a poor signal-to-noise ratio (SNR).

Both these factors are usually indicative of poor startup performance due to bad managerial control of AMT introduction. Good control is reflected in the raw production data by (a) a relatively small range of data point oscillation or scatter about the target curve as learning proceeds and sometimes by (b) a decrease in the frequency or an increase in the time period of data point oscillation about the target as learning proceeds.

6.4 Standard Cost of Learning

Having established that the model is a suitable and adequate representation of the experience gained during AMT introduction, it is important to relate the curve generated to the actual loss of production which occurs in startup. One technique which is often used as a goal in a learning curve context is the so-called standard cost of learning (SCL). Here the loss in production can be visualized as shown in Fig. 6.2. The assumption made using this criterion is that

> a manufacturing system will perform at its designed output rate from the commencement of startup until the final asymptotic value is reached.

By inspection of Fig. 6.2, we see that for this case

$$\mathrm{SCL} = \int_0^\infty \hat{Y}_\mathrm{f}(1 - \mathrm{e}^{-t/\hat{\tau}})\,\mathrm{d}t \tag{3}$$

which on solution and substitution gives the following delightfully simple result:

$$\mathrm{SCL} = \hat{Y}_\mathrm{f} \cdot \hat{\tau} \tag{4}$$

Hence, if we assume that Y_c, Y_f and τ are realistically assessed then $Y_\mathrm{f}\tau$ is a measure of the loss in productivity due to startup dynamics. Obviously, if the curve fit to obtain Y_c and Y_f is undertaken historically (i.e. startup is to all intents and purposes over) then SCL will be estimated fairly accurately and will consequently form part of the company data base.

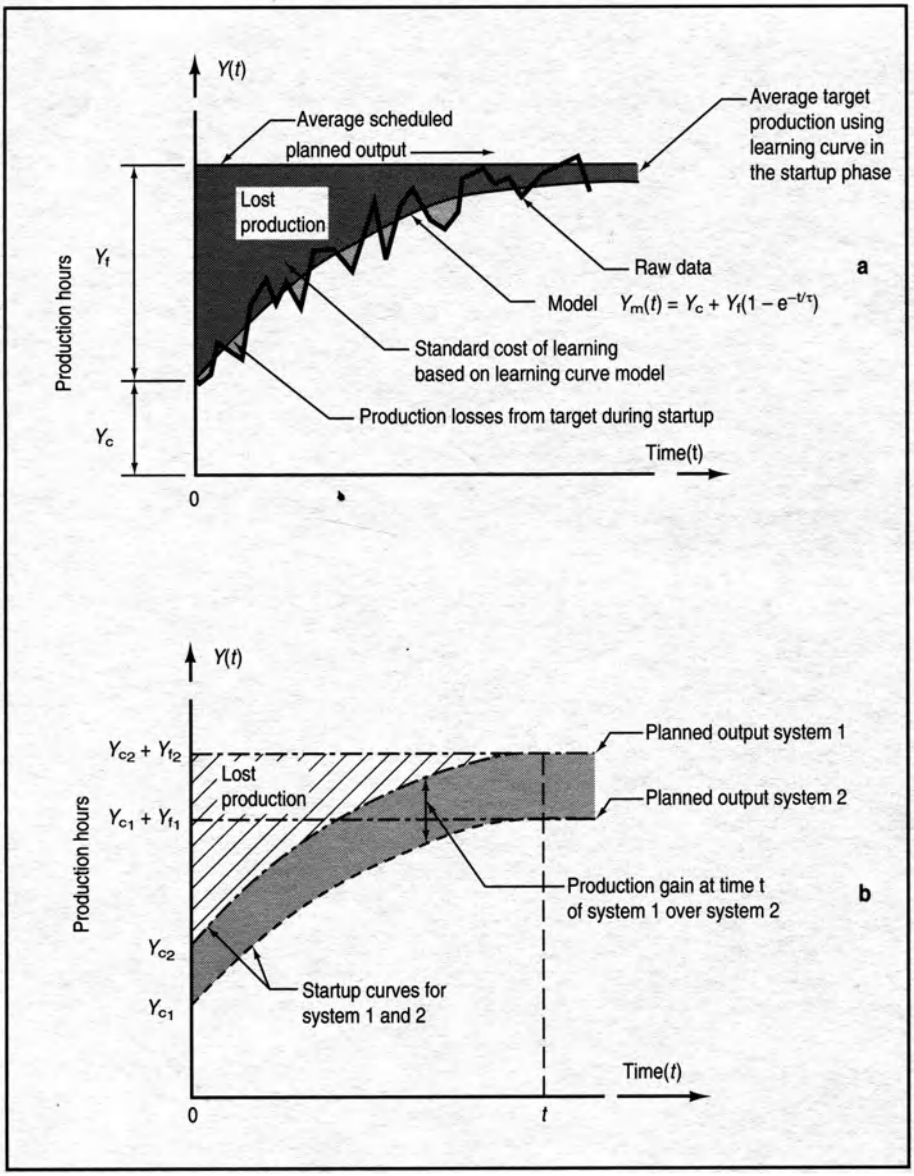

Fig. 6.2. Cost of startup. **a** Standard cost of learning. **b** The evaluation of alternate systems – effect of both Y_c and Y_f changing.

In practice, even if Y_c is identical for two installations [5], Y_f and τ may vary. It makes it even more imperative to assess the trend time as soon as possible during startup. Otherwise we may find that payback periods are not met, deliveries are missed and excess costs build up. Differences may occur due to any of the attitudinal, technological, or organizational factors defined in Chapter 2.

Figure 6.2b shows the effect of Y_c and Y_f changing from target. Obviously, such changes can be deleterious, or (occasionally) lead to the enhanced performance provided new and improved operational methods have been developed. Note also, as discussed in Chapter 4, that fluctuations about the trend are also significant "carriers" of information concerning possible routes for improved controls. This fluctuation should be monitored by management as a source of excess costs. Indeed in reference [6] two ostensibly similar factory outputs were compared, and the learning curves shown to be significantly different. The consequence was the closing down of the less efficient factory coupled with the transfer of work to the better-managed plant.

6.5 Costing the Effect of Discontinuities in Operating Conditions

In Chapter 5 we saw that changes in operating conditions could be categorized as exogenous or endogenous. We therefore need to account for these as far as practicable during the trend detection phase, either by zero–one modifications (e.g. strikes) or by multiple startups (e.g. capacity changes). To omit to do so would throw away intelligence concerning our operations. In particular, two common expansionist situations may be met:

1. *Plant capacity is increased, with no changes in the management structure nor in the production techniques and processes.* (In this case we can assume that there is no preplanned effort to change the support organization and learning place by evolution.) In effect, for FMS A the organization gains experience on the first two machines prior to the step increase in capacity, which results in the system becoming four machines. The technology is also assumed to be static; i.e. all machines are identical and the support organization remains unchanged.
2. *Plant capacity is increased alongside other changes in structure, production techniques and/or processes.* (In this case there may well be a planned organizational change in the support system owing to learning on the first pair of machines.)

In case (1), the time constants for different phases may well be about equal. However, the steady state may not be reached for phase 1 before phase 2 is introduced, which means equation (4) is modified. Suppose phase 1 lasts for a time T_1 weeks; then the lost production in phase 1 is

$$\mathrm{LP}(1) = \hat{Y}_{f1} \cdot \hat{\tau}_1(1 - e^{-T_1/\hat{\tau}_1}) \tag{5}$$

Similarly, the lost production in the second phase lasting T_2 weeks is:

$$\mathrm{LP}(2) = \hat{Y}_{f2} \cdot \hat{\tau}_2(1 - e^{-T_2/\hat{\tau}_2}) \tag{6}$$

and so on. Note that the final value used in the trend line for phase 1 need not be the same as the initial value for phase 2. It just depends on the operating conditions at the time.

6.6 Estimating Utilization of FMS A

A typical installation is the introduction of FMS A, which occurs in two stages. Phase 1 occupies a period of approximately one year during which two machines are tracked after installation and commissioning through their production startup. Phase 2 sees a stepchange take place in the productive capacity of the system with the addition of two extra machines, and constitutes the final arrangement with its main communication links to all four machines.

Figure 6.3 shows the data recorded for this system and the discontinuities that occur in productive capacity and in actual production. Week 52 sees the start of the second phase of the FMS implementation, while in week 110 one machine is decommissioned for repair. Also, a major industrial dispute occurs at week 75 and lasts until week 85, when production eventually restarts. However, during the dispute extensive modifications are made to the system in the light of previous operational experience, so that the performance at week 85 is as though no break had occurred!

The maximum number of hours theoretically available for production manifestly depends on the number of machines in commission. This is shown in Fig. 6.3 by the enveloping solid line, which in systems engineering terms can be seen as a sequence of positive/negative steps.

For this case the productivity losses (up to week 110) are best evaluated graphically. If a single long-term time constant model is used to represent company learning (which is our choice) then the areas give us the following:

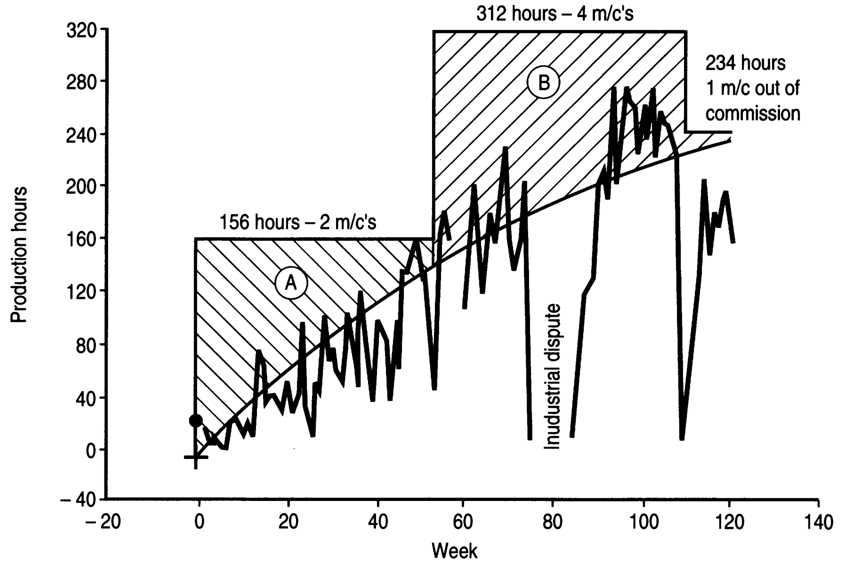

Fig. 6.3. Raw production data fitted historically with single long-range startup curve.

$$\begin{bmatrix}\text{productivity}\\ \text{losses}\end{bmatrix}_{\text{week }0}^{\text{week }110} = \begin{bmatrix}\text{area A} + \text{area B}\\ + \text{(exogenous losses due to strike)}\end{bmatrix} \qquad (7)$$

By direct graphical evaluation (which can be checked mathematically if required) we have area A = 3900 hours and area B = 7192 hours. Hence

$$\begin{bmatrix}\text{productivity}\\ \text{losses}\end{bmatrix}_{\text{week }0}^{\text{week }110} = \begin{bmatrix}11\,092\text{ hours}\\ + \text{(exogenous losses due to strike)}\end{bmatrix} \qquad (8)$$

Therefore on this basis during phase 1 the AMT has been operating at an average utilization of $\{1 - [3900/(156 \times 52)]\} = 52\%$ and during phase 2 the AMT has been operating at an average utilization of $\{1 - [7192/(312 \times 58)]\} = 60\%$. The exogenous causes (the strike and the much later machine decommissioning) reduce these utilizations yet further but they are known about and should be accounted for separately.

6.7 A Multiple Learning Curve Representation

Alternatively, instead of a single-company time constant model, a multiple time constant model format may be used, as shown in Fig. 6.4. Three sequential models are now defined with time spans of 52 weeks and 23 weeks respectively. Again, neglecting exogenous losses, the utilizations may be found graphically or mathematically, and give the following results:

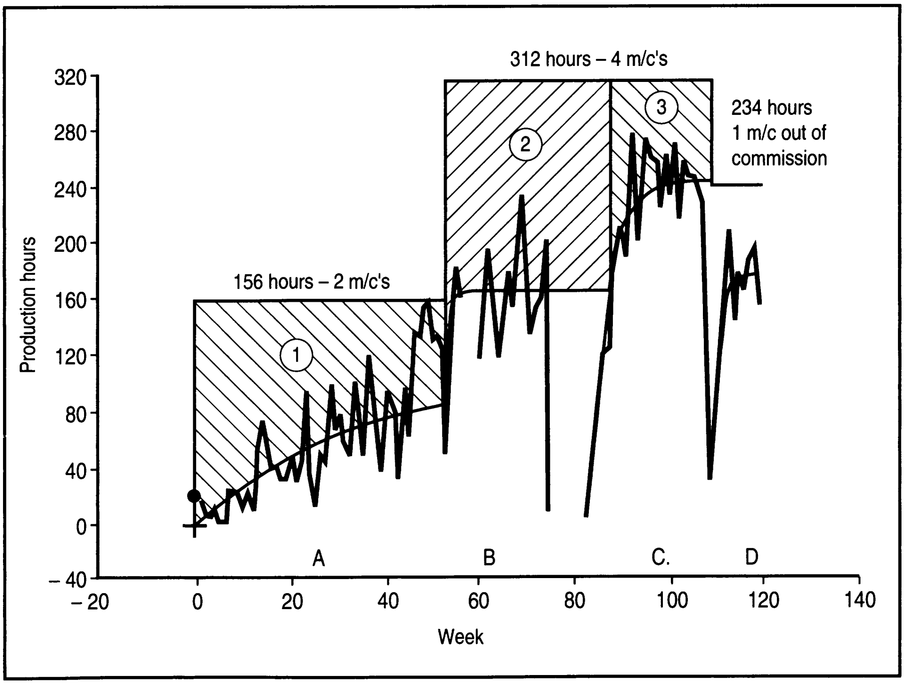

Fig. 6.4. Multiple startup learning curve.

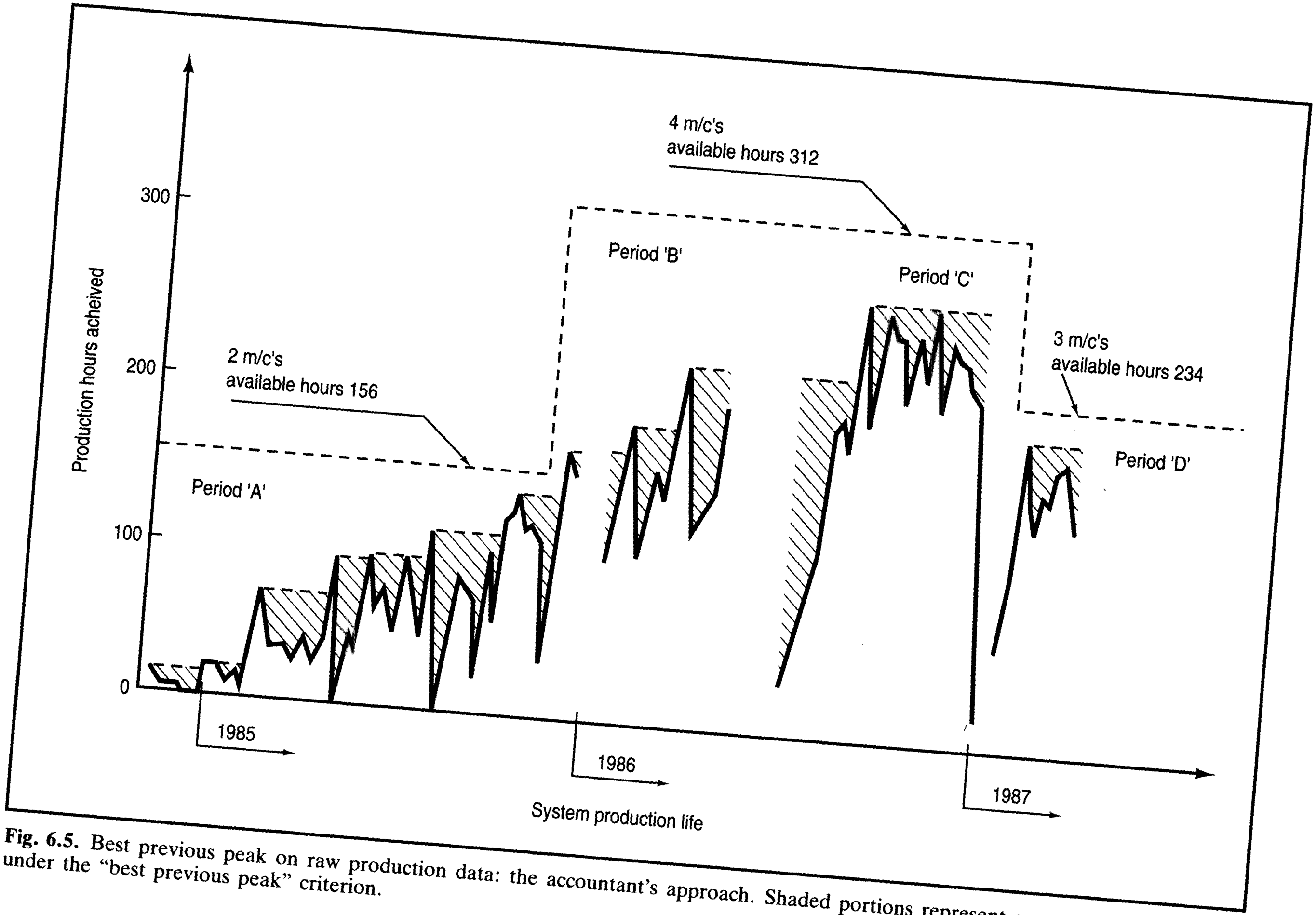

Fig. 6.5. Best previous peak on raw production data: the accountant's approach. Shaded portions represent areas of lost production under the "best previous peak" criterion.

$$\begin{array}{lll} \text{utilization} & \text{phase } 1 = 27\% & \text{(weeks 0 to 52)} \\ \text{utilization} & \text{phase } 2 = 50\% & \text{(weeks 53 to 87)} \\ \text{utilization} & \text{phase } 3 = 74\% & \text{(weeks 88 to 110)} \end{array} \qquad (9)$$

In this case, the advantage of using three phases instead of two may be the higher visibility of the improved rate of recovery after the industrial dispute, but this choice of model is largely within the remit of the production manager. The single time constant model also considerably overestimates utilization during the first 52 weeks.

6.8 The "Accounting" View of Best Previous Peak Performance as a Means of Estimating Productivity Losses

A simple technique frequently used by management accountants to estimate productivity losses is that of the "best previous peak" (BPP) approach [8]. It is based on the premise that the best previous peak performance ever recorded by the AMT can be maintained at all times by the manufacturing system, i.e. there should be no slippage whatsoever. The area lying below the series of steps thus generated and the actual performance values recorded is then accepted as a measure of the loss in production for the system.

Figure 6.5 illustrates the use of the technique on the production data for FMS A. Unfortunately the method, which is very simple to apply because no modelling or curve-fitting is required, offers very limited information about the startup process and is quite unsuitable for prediction or forecasting purposes.

However, the existence of the peak performance draws attention to possible best practice. Studies of peak performance and peak performers have consistently shown the importance of targeting goals that demand our best compared with using historical averages which tend to mark our improvement potential [9].

The method does, however, permit accountants to query why any dropback in production is allowed. It also provides them with one means of estimating their beloved cost variances! Furthermore, it provides manufacturing managers with a "rough cut" estimate of their production losses and a minimum target for which they should aim in order to ensure that the learning process in respect of the plant is continuing (in the sense of not dropping back too far). We suspect also that with sophisticated performance-monitoring techniques the method can also be refined in several ways to overcome its lack of predictive capability, and thereby effectively allow the data available via the BPP to be modelled.

Thus the following refinements to the BPP technique generate target curves for production, which additionally imply the use of the time constant learning curve model and which may be considered more realistic than losses calculated from the BPP method alone. One such possible modification is to curve-fit to the previous peak performance (PPP) values, where the production target shifts to the previous peak as the raw output data

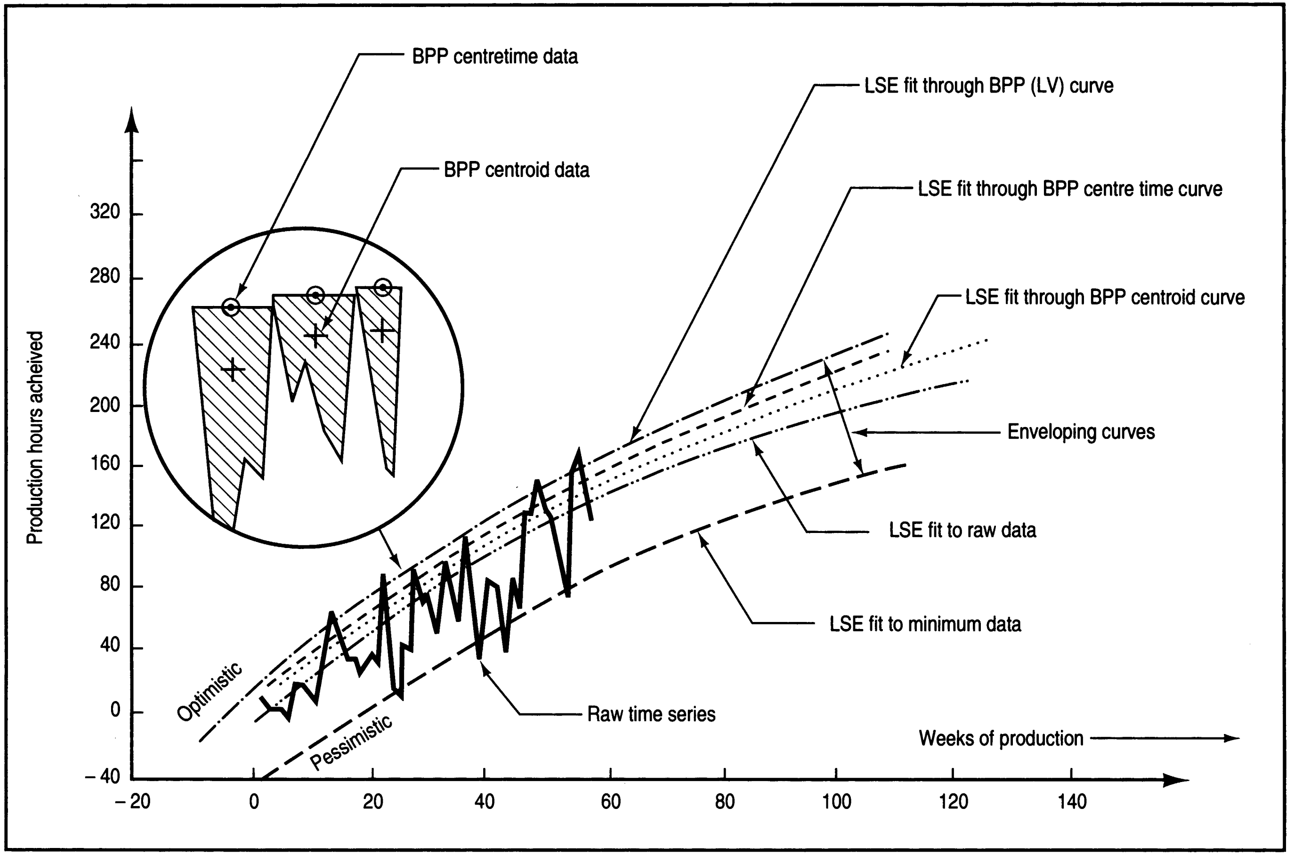

Fig. 6.6. Possible modifications to the BPP technique to allow prediction using the time constant model and LSE fit to the data.

progresses with time. The main effect of this policy is that peak values lower than the best ever previously reached (but still regarded as significant) can be included in our estimation procedure. Similarly, abnormally low values of peaks can also be ignored [10,11]. We are, of course, discarding data as compared with determining the *average* trend line via the LSE curve-fitting techniques of Chapter 5. This is the classic situation where better smoothing may be achieved, but at the expense of working with sparse figures.

Two further options for the generation of production targets/data points from the raw output data are the use of time centre (TC) and centroid (C) values, also shown in Fig. 6.6. Put simply, the time centre value is the centre point on the best previous peak line and the alternative centroid value is found for those areas which lie below the BPP line. Assuming we have enough data points, production target curves can be fitted to these points, using for example the LSE time constant model, or any other suitable model, to provide an AMT learning curve. Figure 6.6 shows a rough comparison. The advantages of one method over another have to be determined, and their use depends in general upon what is best for a particular set of circumstances. Because both these simple modifications (although not the accurate curve-fitting) can be made on shop floor visual displays, and are arguably more realistic for target setting than the BPP, they may have a use in performance monitoring at operator level.

6.9 Las Vegas Modelling

The LSE curve-fitting technique discussed in Chapter 5 predicts the average long-term trend. If we wish instead to attempt to estimate the likely maximum loss in production during startup, using "expected best practice" as a target, then the so-called Las Vegas (LV) curve may be used [12]. As shown in Fig. 6.7, the approach uses the outliers (maximum data points) to optimistically model system performance and thus calculate the extreme production losses experienced during startup. The loss in production is taken as the area between the LV curve and the actual production data. In Fig. 6.7 the time constant model is used and fitted (again at the expense of sparsity of data) to the outlier points in the time series, although any other model which reasonably fits the data could be used equally well.

The technique is similar to the BPP method in that the outlying data points are used as the target for performance improvement. However, it does have the added advantage of being able to estimate future production losses based on an established learning curve for the system and to forecast the likely maximum production capacity. The LV equations for the data shown in Fig. 6.7 are based on a least-squares error fit of the "time constant model" and are given in Table 6.1.

The LV curve is intuitively appealing, combining as it does the targeting aspect of the BPP approach with the trend detection capability of the least-squares-error curve-fitting. However, a problem which may frequently arise is the occurrence of ill-conditioned data, where extreme fluctuations may be encountered (i.e. we have too little data available because there are relatively few outliers). This can result in the generation of totally false

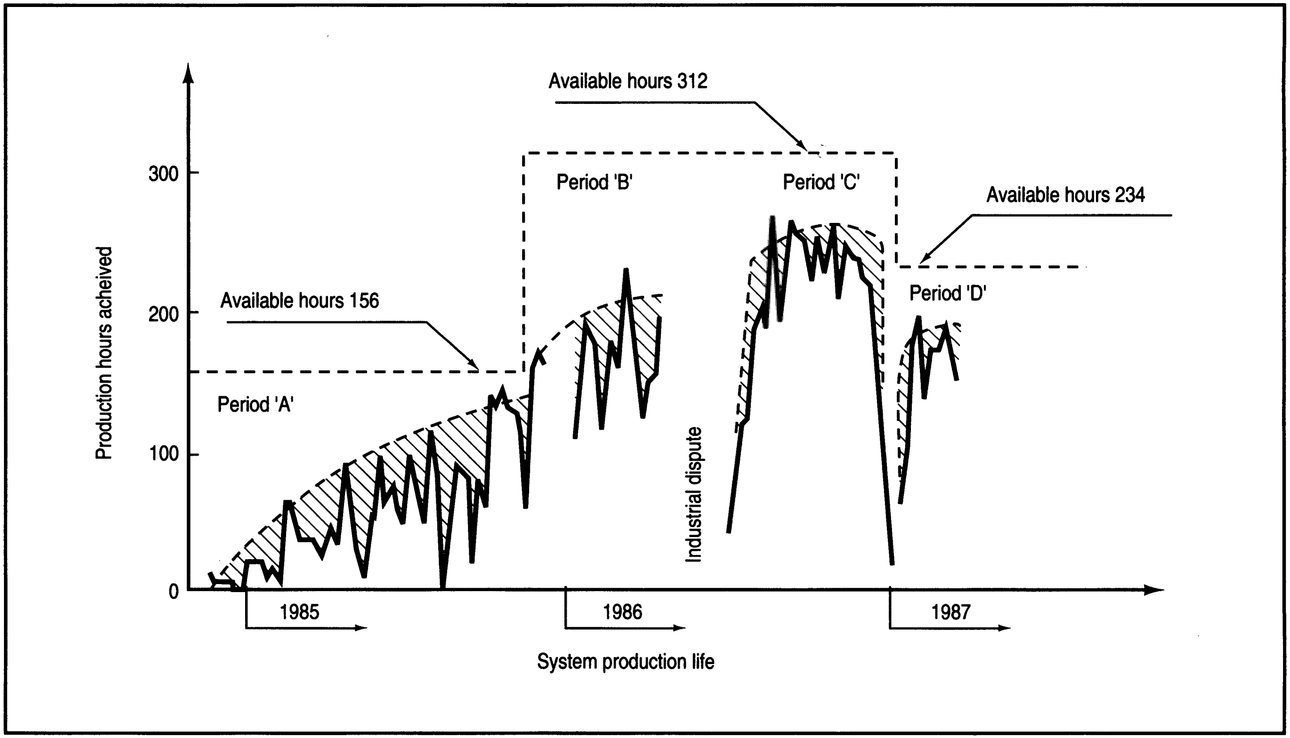

Fig. 6.7. Las Vegas curves for raw production data fitted through outliers. Shaded portions represent areas of lost production under the "best previous peak" criterion.

Table 6.1. Las Vegas multiple startup curve equations

Period	Learning curve equations
A	$Y = 159(1 - e^{-t/28.33})$
B	$Y = 152 + 61(1 - e^{-t/5.9})$
C	$Y = 119 + 139.5(1 - e^{-t/3.25})$
D	$Y = 132 + 53.5(1 - e^{-t/0.92})$

For convenience, *t* in each case is measured from the new startup time datum.

target curves. If violent scatter occurs in the raw data and only a few points can be used to fit the curve then even very sophisticated modelling techniques may fail to generate a suitable LV model.

6.10 An Alternative Approach to Las Vegas Modelling

Because the LV-based targets should actually be obtainable with time, there is a need to determine a standard (and better) method for evaluating such a curve. This is especially so if the technique is to be used for forecasting and management control actions which involve comparing the results of different AMT startups. Such a curve can be generated, via the use of digital computer software, to derive a target curve which statistically envelops the majority of data points but where LSE modelling is based on the average trend line [13]. This can be achieved, as shown in Fig. 6.8 and Table 6.2, by adjusting the curve to a set distance from the trend line. The distance at which the curve is placed is thus related, as is clearly illustrated in the figure, to the observed scatter about the line.

On a subjective basis only, and by comparing a number of simulations based on industrial curves, it was established that the target curve passing through 1.66 standard deviations best represented the trend of the maximum peak performance. The probability of a point lying outside this curve is 5%, and although such outlier points do exist they are few and far between. Thus the outliers may well represent exceptional cases which are irregular, unstable or unpredictable (rather than individual attainable targets). Accordingly, they should not be used for the establishment of production targets (as happens in the true LV curve) but instead should be investigated in an attempt to identify and benefit from correcting their causes [13].

6.11 Conclusions

The dynamic modelling techniques outlined above allow production managers to assess in a fairly simple way the following important aspects of AMT startup:

1. The likely rate of learning during AMT introduction, and as a consequence the probable plant capacity during the startup phase, realistic payback

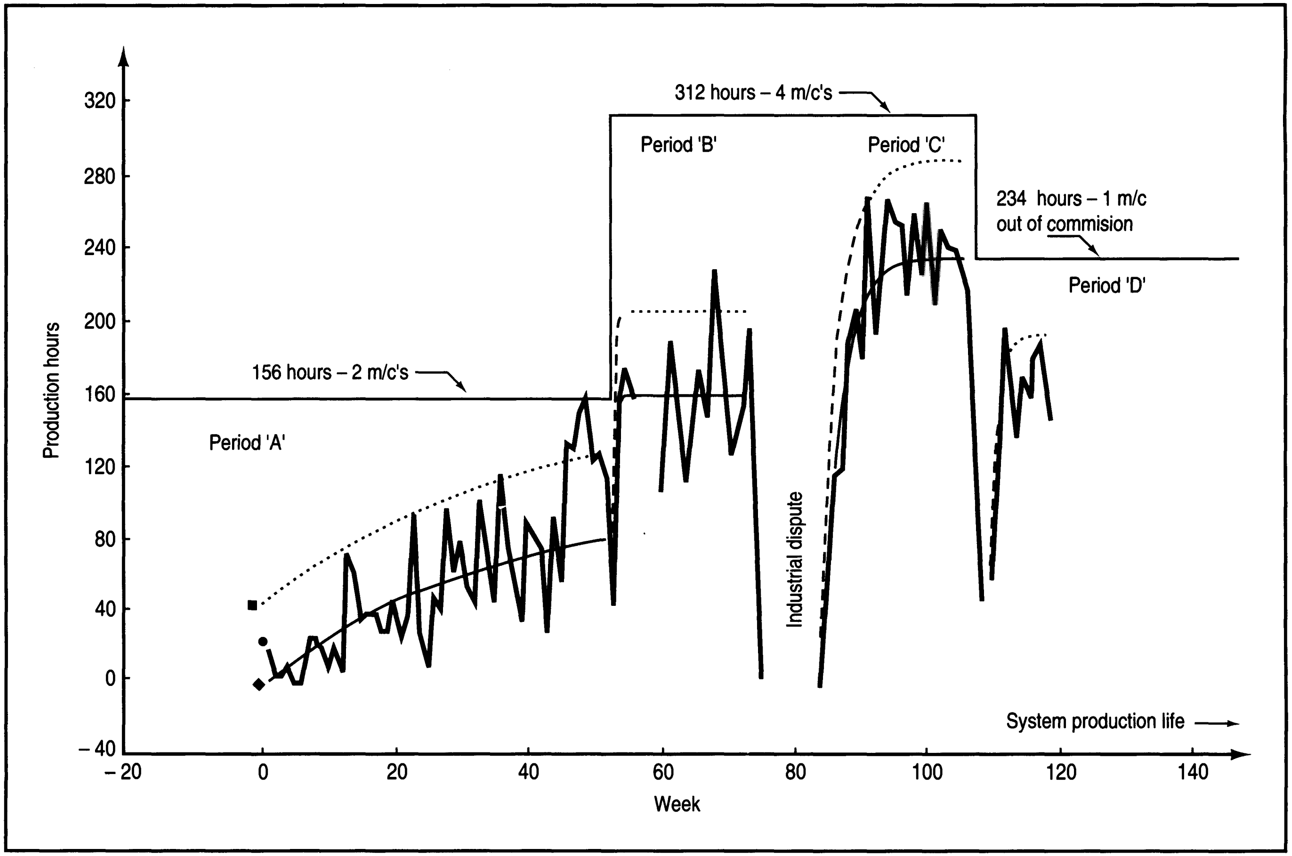

Fig. 6.8. 95% confident "alternative" Las Vegas curves for raw production data. ●, raw data; ◆, learning curve; ■, Las Vegas.

Table 6.2. 95% confident Las Vegas multiple startup equations

Period	Learning curve equations
A	$Y = 145.7(1 - e^{-t/34.1})$
B	$Y = 83.1 + 157.7(1 - e^{-t/0.35})$
C	$Y = 88.5 + 247.7(1 - e^{-t/3.16})$
D	$Y = 89.1 + 142.3(1 - e^{-t/1.20})$

For convenience, t in each case is measured from the new startup time datum.

periods, and delivery times for various products. (These are *not* matters to be left to chance!)

2. The likely production losses which are to be expected from the introduction of particular AMT equipment can be estimated. In each case the lost productivity value is obviously dependent upon the chosen target curve, and this can lie, as shown, within an envelope of possible models. The "alternative Las Vegas" curves look good for this purpose.
3. The startup performance of the AMT equipment and of the manufacturing logistics system within the company can be modelled. Good and poor startup performance indicators have been explained, and, used with the time constant and similar models, can monitor the AMT introduction process and alert production managers to the need for corrective action.
4. To achieve international standards of performance, the data must not merely be collected; they must be exploited by modelling, trend prediction and dynamic variance estimation. Management has to be able to forecast the best possible as well as the most likely performance.

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7 Use of Discrete Event Simulation in Evaluating FMS Performance

M.M. Naim and S.M. Hoh

7.1 Introduction

Discrete event simulation (DES) is a well-recognized technique in evaluating the performance of flexible manufacturing systems (FMS). FMSs lend themselves to such a method because of the inherent complex element interactions, the queueing principles involved and the changes of state that occur within them. In particular, to attempt to rely on intuition, experience or static optimization alone can lead only to a limited FMS design solution. DES allows the analyst to recognize the dynamics of FMS while also allowing him to interact with the system model in such a way that changes in, say, layout, system design and operation strategies (scheduling, routing, etc.) may be assessed. Hence, "what if?" scenarios are orchestrated [1]. The analyst not only is able to make changes to the simulation rules but also is capable of altering data records and displays.

Although DES is widely used in the design and development (D & D) stages of FMS, its application in the subsequent management monitoring and control of such a system does not seem to have been fully appreciated. In particular, goals and aspirations set out early on in the life of an FMS project inevitably have to be updated in light of an extensive startup period during which the environment that the D & D studies were carried out have considerably changed. In one respect, this chapter is different from the rest of the book. Here we are concerned mainly with simulation procedures which will ensure that there are no capacity bottlenecks imposed by wrong choice of the numbers of AGVs installed, etc. The problem solved is therefore basically technological in origin, although organizational considerations (especially scheduling procedures) will influence the outcome.

7.2 Modelling Techniques

Simulation modelling has come onto the scene as an effective design and management tool only since the early 1980s. Its proliferation has resulted as computing (and in particular, software) costs have diminished.

Extensive work has been undertaken analytically on the design and analysis of FMS [2]. This has resulted in mathematical models of such systems that, although they give some insight into possible problems, fail to realize the dynamic behaviour of FMS, that is, the changes that occur within it.

Mathematical models *had* the advantage of being simple in nature. Once a suitable model has been derived they are easy to use, due to the speed in changing parameter values, they are data-driven and they require no software modification. Their main disadvantage is that they are based on long-term averages (for example, on the number of parts, average yields, etc.) with the system being in a state of equilibrium.

7.2.1 Simulation Modelling

Simulation may be regarded as the technique of building an abstract, logical model of a system, which describes the internal behaviour of its components and their complex interactions, including stochastic variability [1].

Simulation further allows the user to validate the effect of any changes (for example, with regards to decision and policy changes) that may occur in the system itself, due to both internal and external sources. At the same time, the pattern of change in system behaviour may be observed as opposed to just the resultant effects. This leads to greater understanding of how a system works, and possible areas of improvement may be recognized. Inferences may be drawn even before a new system is built, thereby accelerating the rate of improvement up the learning curve; that is, possible problems are foreseen prior to actually encountering them in the real system. The chances of successfully progressing along the learning curve are therefore improved.

Simulation modelling is therefore a means of studying the behaviour of a system as a whole by defining in detail how its various components interact. The more complex the system, the more appropriate is the use of simulation as opposed to analytical means.

7.3 The Case Study FMS

FMS in this particular context relates to an "FMS module" installed into a British company in the mid-1980s. The system is of a turnkey design and manufacture, although implementation and commissioning was shared by both vendor and customer. The vendor is an American corporation with extensive FMS experience, with well over fifty such installations (see Chapter 11).

The physical system, a schematic of which is shown in Fig. 7.1, consists of four machining centres (milling), two automatically guided vehicles (AGVs), four load–unload stations and a computer control room. The system is manned by four operators (a systems manager, two setters and a loader–unloader) during any one shift. Overall system control is via a PDP-11 host computer that manages the system to randomly manufacture the required product mix and volume. The host's eight basic software tasks are router, scheduler, mover, traffic, management information, logger, operations and file transfer.

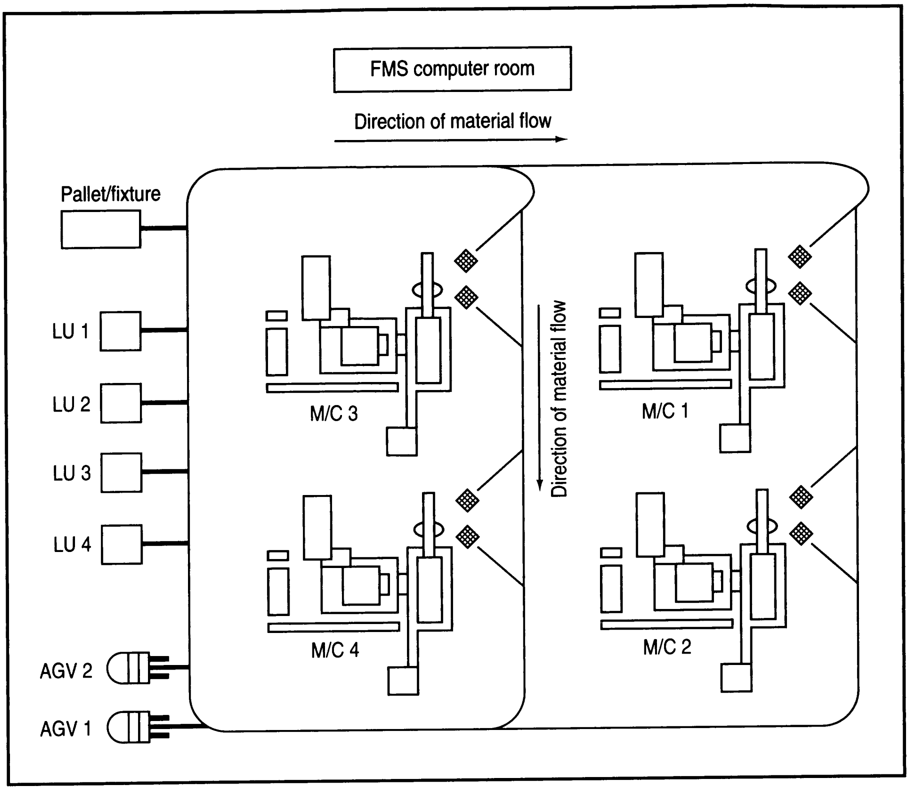

Fig. 7.1. Schematic layout of the FMS.

7.4 The Case Study DES

The D & D simulation model of the FMS was constructed using Fortran 77. Such a high-level, general-purpose language was used (as opposed to a simulation specific package, such as Siman, Hocus or Witness) according to reasons set out at the time of study. This was mainly in consideration of its maintainability by the FMS personnel and the greater flexibility it offered in model construction [3,4]; that is, the simulation was not limited by the capabilities of any one package.

Nevertheless, the system has subsequently been modelled via Witness [5], which when compared with the "bespoke" simulation has the advantage of being generic in nature. This allows a wide variety of systems to be modelled. However, the results of the overall simulation project presented here are applicable as much to the Witness package as they are to the "bespoke" simulation.

7.4.1 The DES Design

The process interaction approach was employed in the DES. This method has a high face validity, allowing the system users, who are knowledgeable about the real world system, to fully understand its workings. The users are thus able to view, via a graphics interface, the dynamic behaviour of the various components, or entities, that make up the FMS. They literally visualize the movement of the AGVs and parts, and the state of the various entities; for example, whether a milling machine is awaiting a part and is idle, whether it has broken down and awaiting maintenance, or whether it is busy carrying out a function.

The entities considered in the model were as follows:

12 component families
4 manual load–unload stations
4 machining centres
2 AGVs
11 pallets
1 pallet changeover station
2 battery-charging areas for AGVs
1 load–unload operator

A simplified simulation flow chart for the system is shown in Fig. 7.2. The simplest functions of the software control system involves the selection and scheduling of "workpieces" (that is, the components fixed onto the pallets), directing the AGVs to transport the workpieces and coordinating available resources to produce the "finished" goods. Figures 7.3 and 7.4 show typical decision-making algorithms that have to be input into the simulation model so as to ensure the adequate movement and loading of AGVs.

The DES is of a data-driven type, that is, the data input directly specifies most of the characteristics of the FMS. The data required by the simulator include:

FMS layout
AGV travel time table
Part/fixture data
Part/tooling data
Work schedule
FMS operation schedule
Part routing and process times
Tooling on machines
Resource data, including numbers of entities, machine breakdown data and initial conditions

In this way the system manager may treat the DES as a "black box" and concentrate on preparing appropriate input data and analysing the output results. The latter is presented in terms of:

Equipment utilization statistics
Part-produced statistics
Machine downtime statistics
Worker utilization statistics
Time-related histograms

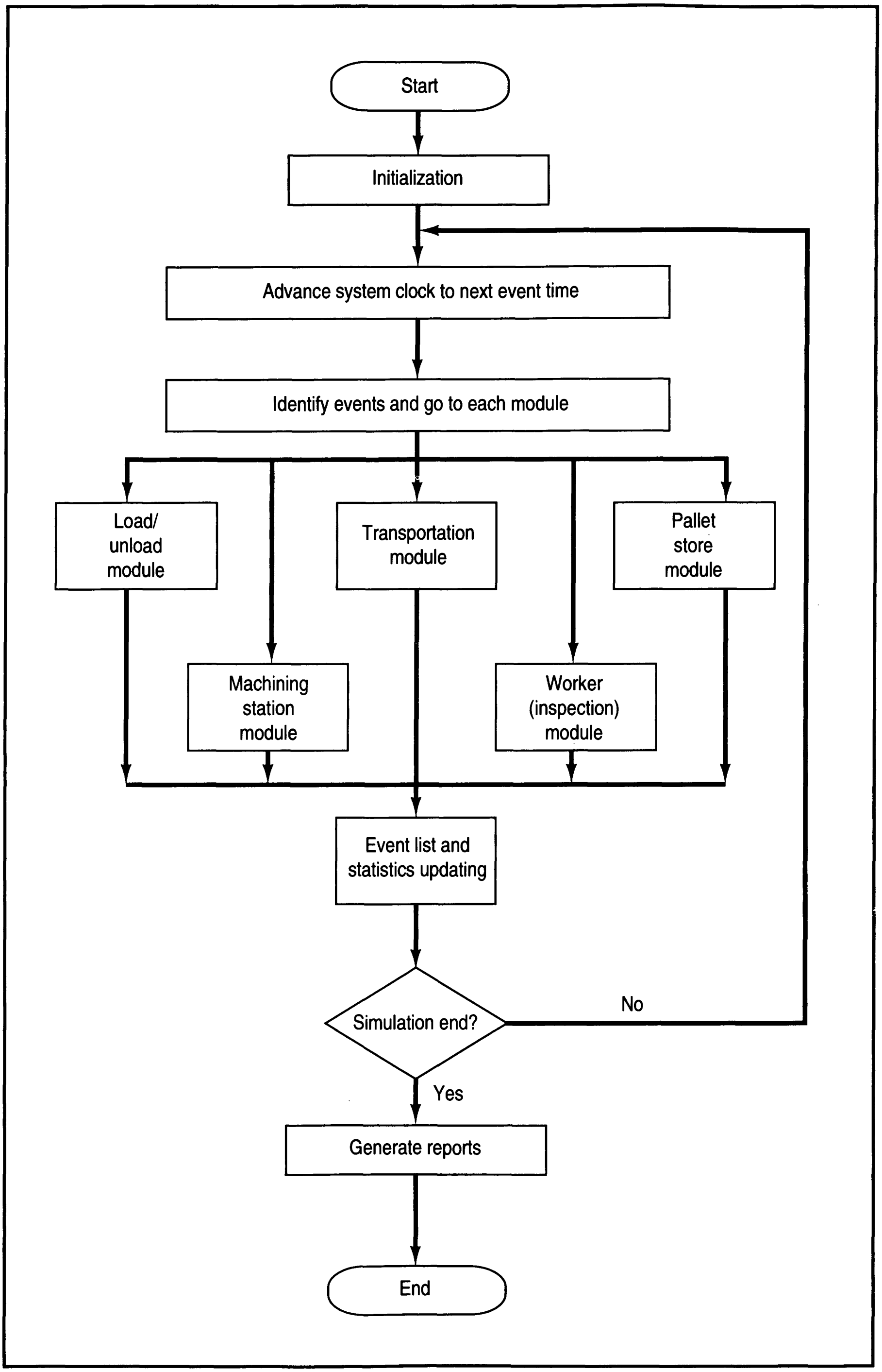

Fig. 7.2. FMS DES flow chart.

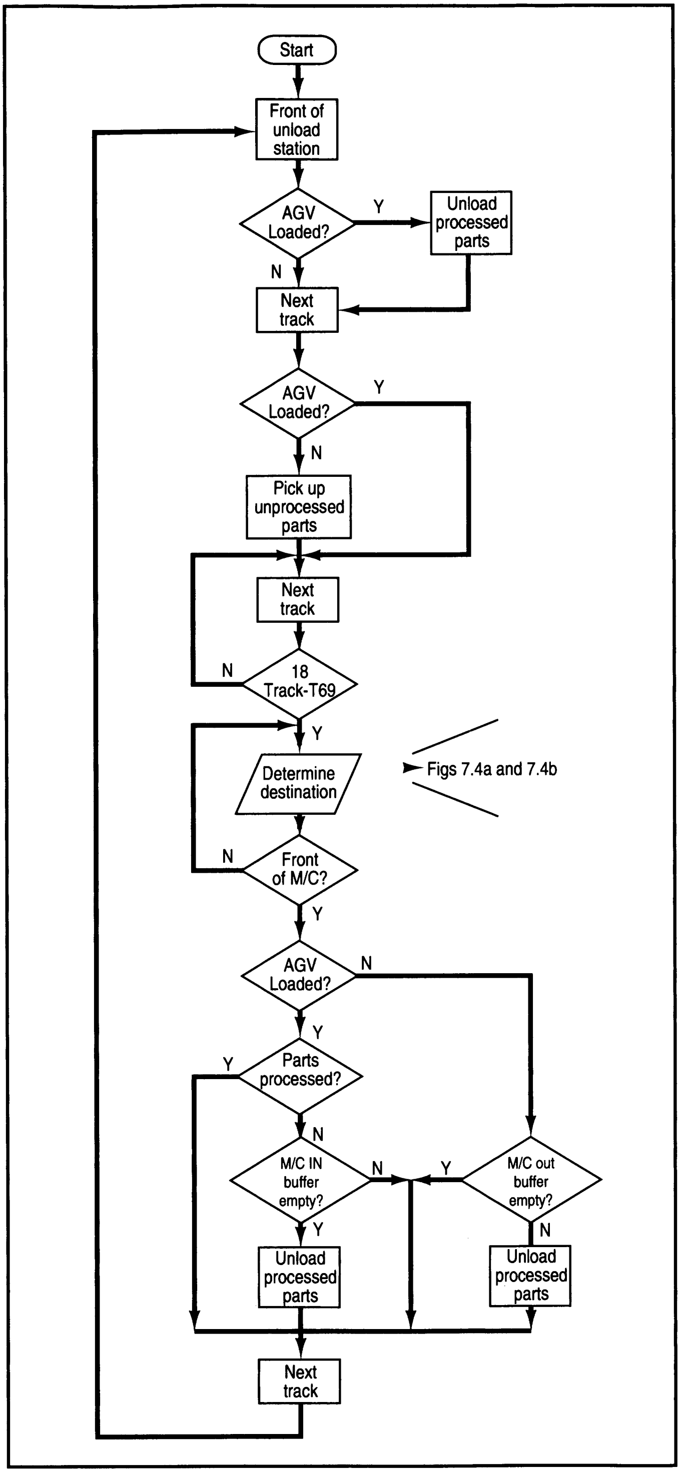

Fig. 7.3. Movement of AGVs.

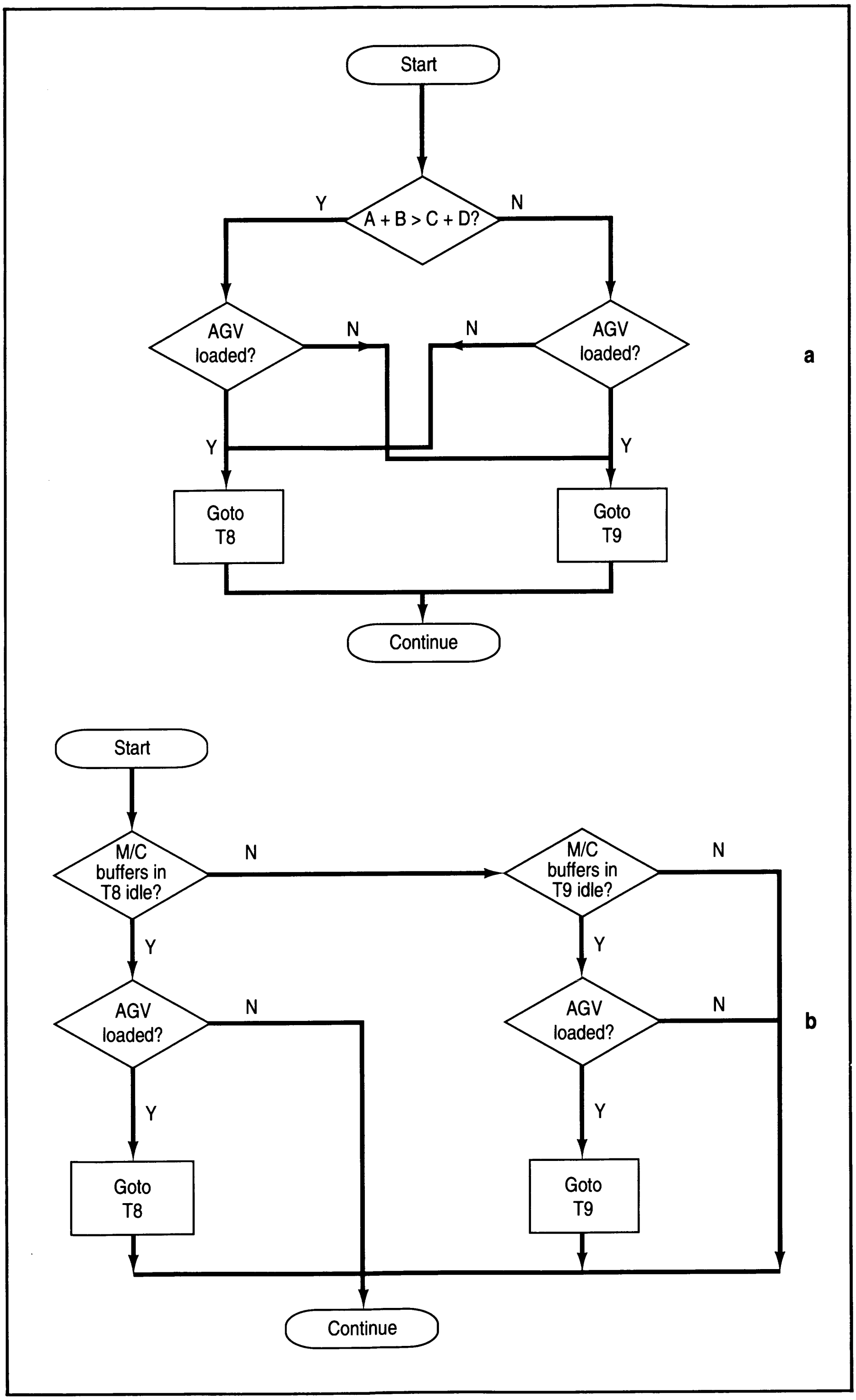

Fig. 7.4. Loading flow charts. **a** Processed parts. **b** Unprocessed parts

Typical output results are as shown in Figs 7.5 and 7.6. Figure 7.5 highlights the effect of machining cycle times for varying numbers of parts within the system. Figure 7.6 shows how lot sizing (that is, the number of pallets being processed at any one time) influences FMS performance.

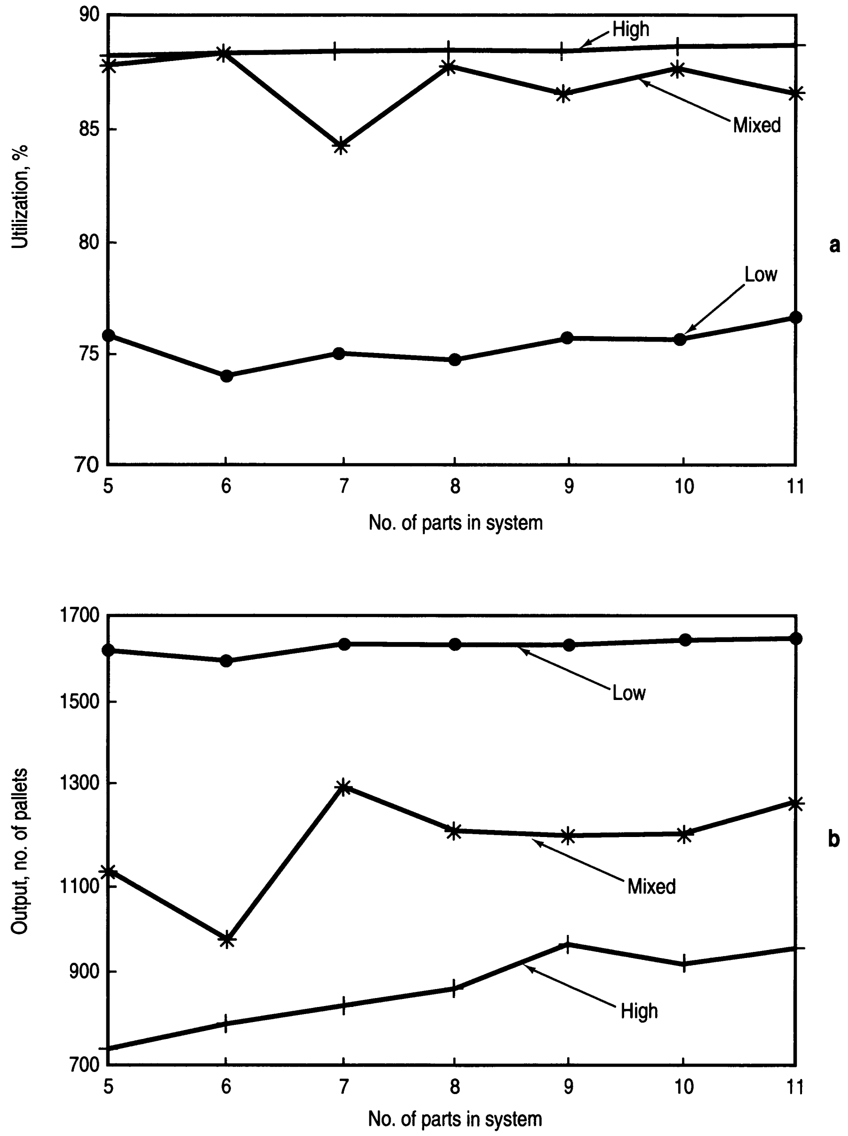

Fig. 7.5. Simulation results. **a** Machine utilization. **b** Production output.

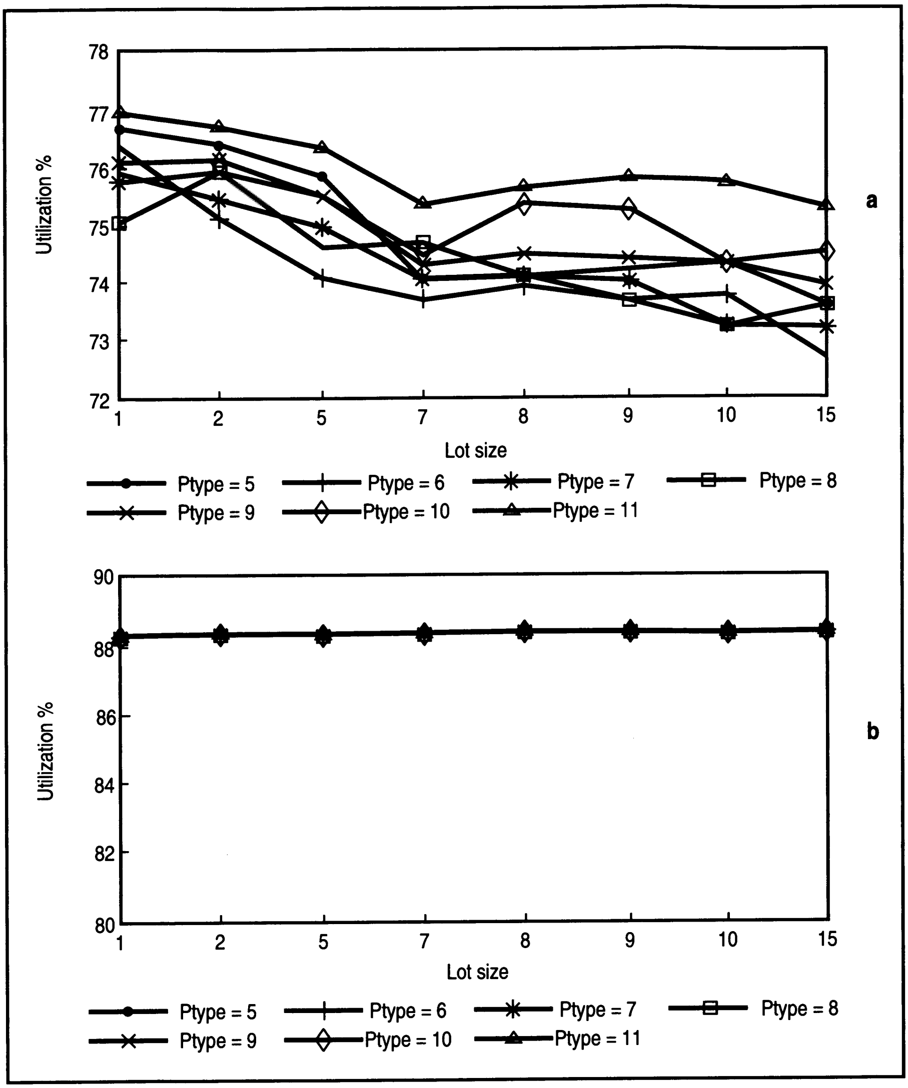

Fig. 7.6. Machine utilization predictions. **a** Low cycle times. **b** High cycle times.

7.4.2 The D & D results

The simulation results revealed the following:

1. The FMS was capable of steady-state operations at well over 90% utilization. This result was not surprising considering that the FMS actually replaced old machines that had a higher annual throughput.
2. There exists an optimum number of pallet stands in the system for a given product mix. Compromise must be made between the amount of

work-in-progress and machine idling time. As the number of pallets in the system approaches a certain limit the probability increases of a deadlock occurring. The shuffling of pallets to release them merely increases unwanted AGV utilization.

3. Short machine cycle time components reduce machine utilization while increasing unwanted AGV utilization. The materials handling system begins to show signs of strain when the ratio of the average component machining time to the average AGV travel time approaches unity.
4. Two AGVs can cope with the system adequately.
5. A single operator is capable of handling load–unload operations.

These results aided management in developing their FMS requirements and operating strategies. An important feature to be highlighted was the distribution of component (pallet) processing times. As new components became available to the system there was a tendency to try to increase their processing times so as to keep machines fully loaded at all times. However, the simulation results revealed that this could in fact be detrimental to the system performance. As the range of component processing times increases the risk of machine idle time increases. This applies when the maximum processing time becomes far greater than the minimum processing time. Increasing the number of pallets within the system beyond the optimum further aggravates the situation.

7.5 The FMS Startup

A considerable amount of data regarding FMS performance was made available by the company. This was mainly in the form of the host computer weekly reports, which included utilization statistics, product output rates, scrap rates, product mix and causal (downtime) information [6]. The latter reports were categorized into unscheduled events (such as breakdowns), scheduled events (routine maintenance), shortages of raw material for the FMS, tooling problems (breakages and missing tools), new product part proveout, and miscellaneous (including swarf clearance and idle time waiting loading/unloading). In addition, in-depth investigations were made to back up the data obtained (see Chapter 6) as well as to ascertain the organizational and attitudinal influences on the FMS (see Chapter 10). Such comprehensive data, although faithfully recorded, were seldom used for ongoing improvements, and never in a structured manner.

7.5.1 Modelling and Forecasting the FMS Startup

The utilization figures for the FMS are shown in Fig. 7.7. There is a clear period of learning encountered over the first 30 weeks, at which time a discontinuity occurs. These figures revealed similarities to those analysed from another FMS investigation and which has been modelled via the time constant learning curve (see Chapter 6).

This model, via least-square-error algorithms, has been applied to the FMS startup data as a means of ascertaining its dynamic performance. This

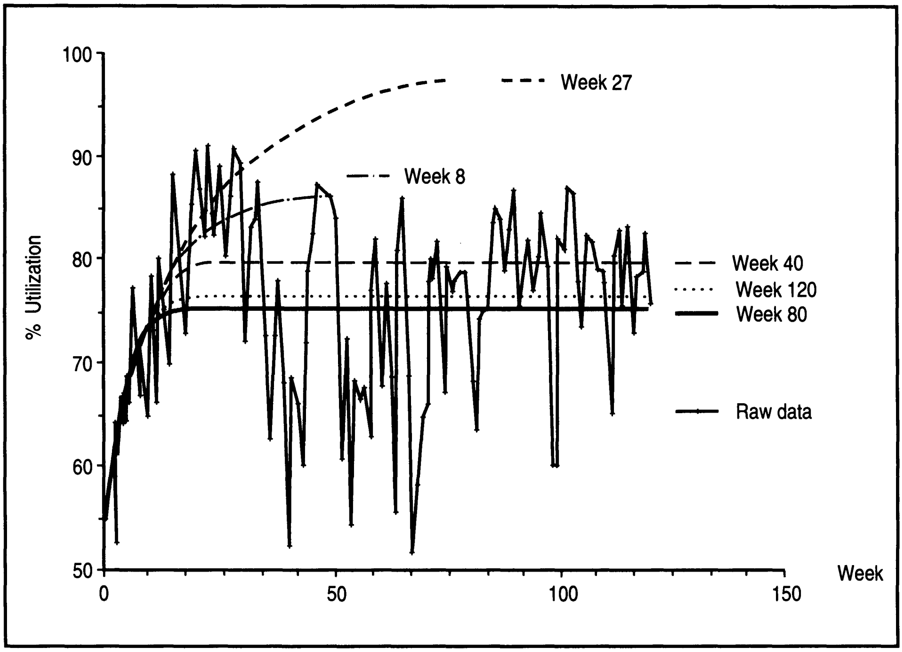

Fig. 7.7. FMS startup modelling.

is best illustrated with reference to Fig. 7.7 and Table 7.1. As early as week 8 the model predicts a final level of utilization of 86.6% and consistently between weeks 8 and 30 a final level of utilization of over 85% is forecast, with a time constant value in the region of 15 to 24 weeks. Of course, as with any quantitative model-fitting exercise, erroneous results may be encountered and any results should be viewed in parallel with other information (including qualitative) sources.

The dynamic nature of the startup is highlighted by the time series of the data itself and by the changing nature of the time constant model parameters. In conjunction with other statistical techniques, such as CUSUM analysis, control charting, range analysis, etc., significant events may be identified and perhaps sequential models applied [7] so that effective system control may be achieved.

Table 7.1. Learning curve equations for Fig. 7.7

Time at which model estimated (week no.)	Learning curve equation
8	$Y = 59.3 + 27.3\,(1 - e^{-t/41.2})$
27	$Y = 59.9 + 37.8\,(1 - e^{-t/35.9})$
40	$Y = 56.4 + 21.9\,(1 - e^{-t/5.5})$
80	$Y = 55.2 + 19.5\,(1 - e^{-t/3.4})$
120	$Y = 56.0 + 19.9\,(1 - e^{-t/3.9})$

7.5.2 Causal Information for the FMS Startup

Figure 7.8 indicates the contributory event for major downturns in FMS performance. Cause-and-effect analysis is an important ingredient in the effective use of any management control aids. The study of the FMS has revealed a considerable variance between pre-startup expectations and final steady-state operation. The reasons for these variances are organizational, attitudinal and technological factors, which translate themselves into poor performance figures. It is the first two factor categories which have been revealed as causing the major disruptions in startup production, accounting for over 70% of the problems associated with the FMS. These are also the most difficult to overcome (see Chapter 10).

The major contributory factor to FMS downtime has been the business decision to introduce a greater product mix (the number of parts programmes available increased from 6 to 170 over the 120-week period), with ever-decreasing batch sizes, one-off batch sizes becoming increasingly common. In conjunction with the lack of investment in computer-aided simulation part proving (CASPP) this has meant that individual machining centres are taken out of production for considerable periods of time. The assignable fault types may be categorized as major/frequent (part proving), major/infrequent (tool changer) or minor/frequent (swarf clearance).

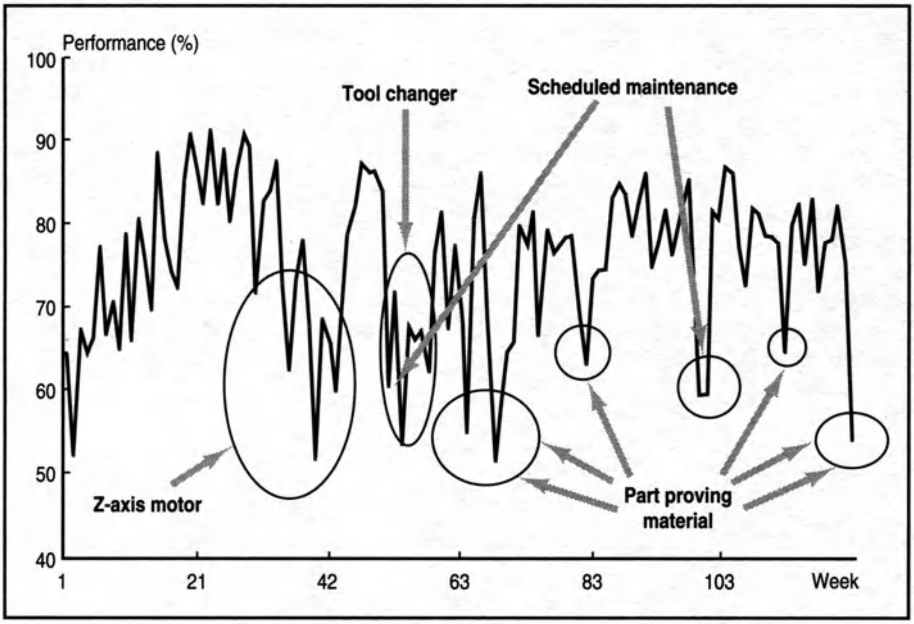

Fig. 7.8. FMS causal information.

7.6 Comparing the D & D DES with Actual FMS Performance

The D & D DES was based on only limited data on the perceived system requirements. A number of assumptions had to be made regarding the following:

1. Individual FMS elements, such as machine utilization, the behaviour of which may be better quantified when assessed under actual system working conditions.
2. Tool availability, which proved to be a frequent problem during startup as the investment in equipment for tool maintenance had not been made.
3. Material availability; the D & D DES assumed that all required raw material was at hand.
4. Product mix; the D & D DES assumed a maximum of 12 part families and made no allowance to machine downtime for part proving.
5. Process dedication; this increased during the startup period as more and more parts became dedicated to certain machines in order to increase production. This seemed to contradict the increase in product mix.

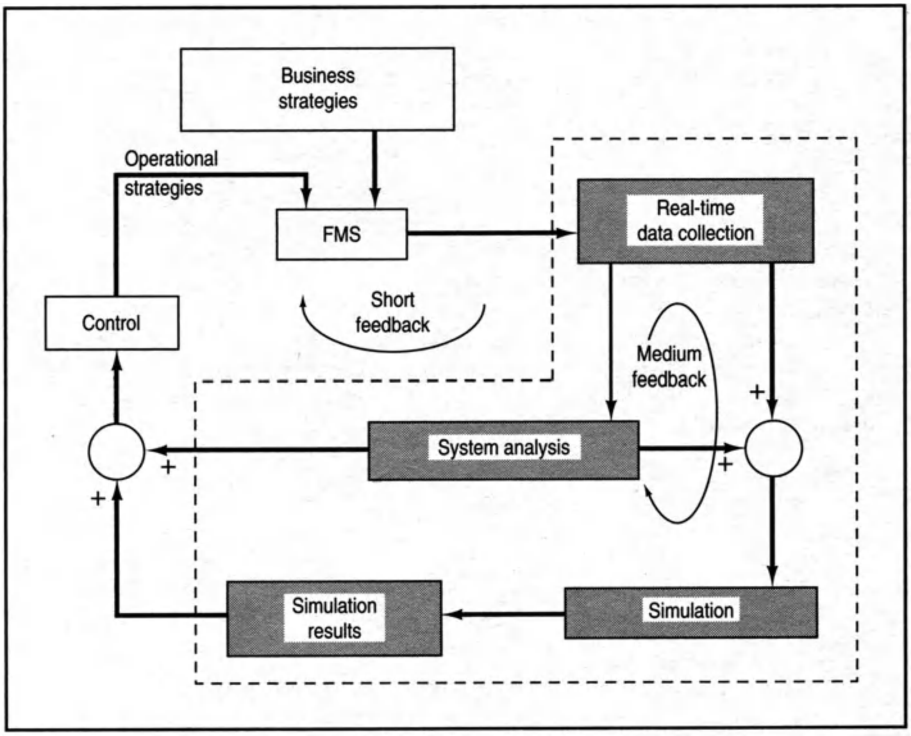

Fig. 7.9. Conceptual framework for simulation modelling.

The learning curve analysis has revealed that the FMS was "potentially" capable of attaining the 90% utilization target. At the same time, a considerable lead time to steady-state operation has been revealed, during which the environment has considerably changed, which invalidates much of the initial DES studies. Therefore operational strategies need to be updated in light of the information fed back from the real system and input to a dynamic DES.

7.7 Conclusion

The application of DES in the design and development of an FMS aids management and operators alike in realizing potential pitfalls prior to the system coming into on-line production. This greatly improves the likelihood of a steep learning curve.

This chapter has outlined the use of DES in the development of an actual FMS; its central theme has been the need for adequate monitoring and control during FMS startup and steady-state operation. In particular, to be able to model the startup phase, forecast likely operational performance, and, from there, to interact with a DES to update control strategies is a vital prerequisite for the efficient running of an FMS. This is especially true considering the relatively long lead times associated with FMS.

Such a management aid should not be employed in an operational vacuum, but should be seen as one element in a management monitoring and control system, which should include an efficient data collection system (DCS), which the FMS under study has, an effective information feedback system and a dynamic discrete event simulation (DDES). Figure 7.9 outlines this conceptual model.

Research is already being done in the field of the use of DDESs as schedulers and short-range planners with the aim of developing expert systems by combining a DDES with a knowledge base [8]. But clearly the potential already exists with most FMSs, which have as standard a monitoring and diagnostics system, and a purpose-built simulation package on their host computers, to use such a managerial structure of Fig. 7.8 without the need for automation but with the concept of simplicity in mind. It is simplicity which aids in understanding the process and improves responsiveness to changing circumstances.

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8 FMS Shop-Floor Experience

A. Davies and M.M. Naim

8.1 Introduction

The all-embracing definition of AMT referred to in Chapter 1 may well be valid; in practice, however, advanced manufacturing technology is often thought of as being synonymous with flexible manufacturing systems (FMS). These systems are typified by the use of computer-controlled production equipment, and, depending upon the level of sophistication, can form an extensive automated and integrated machining/assembly plant.

Information technology (IT) forms the link between these items of manufacturing hardware and thus makes the system work as a complete entity. The ability to accurately encode manufacturing information/instructions for computer processing is crucial to the successful operation of this type of equipment. Hence familiarity with the system software is essential, and, depending upon the equipment used, this may range from simple computer numerical control (CNC) programming to computer-aided manufacture (CAM) using computer-aided design (CAD) and computer-aided production management (CAPM).

The level of expertise available to implement these techniques can vary from company to company. This limits the employment of higher-level AMT in manufacturing industry and has ensured that companies adopt a step-by-step approach to the use of flexible automation. To ensure a smooth startup, a good in-house knowledge of the equipment installation is essential; otherwise, when the commissioning trials are over and the suppliers expertise is withdrawn, an excessive delay will occur in obtaining the required production performance.

The main objective of such systems is to achieve an ever-increasing amount of unmanned running via the management of the controlled movement of process materials and tools. This objective may follow from a policy of workforce reduction. Accordingly, care must be taken to plan for and negotiate the staff reductions required during the planning stage of AMT implementation. Not surprisingly, the transition to these higher levels of AMT integration is fraught with industrial relations problems. Hence the preference of management for greenfield sites.

In order to ensure that the additional features of advanced manufacturing design function automatically, extra communication and hardware links have to be established. As described later on in this chapter, the reliability of these complex systems is sometimes very poor.

8.2 Skill Development and the Reliability of FMSs

The unreliability of these systems means that the total elimination of labour is not yet possible.

The major changes in skill and responsibility coupled with the actions and attitude of outside specialists are likely to lead to tensions and insecurity among existing personnel at all levels within the company. Consequently, one prerequisite of successful company reorganization around AMT is the issue of adequate training. Otherwise there will be insufficient internal skills to fully grasp highly complex and computerized new technology. Not only is an increase in the level of skill needed, but we also require further breadths and kinds of skill. Experience and integrated skills allow for flexibility and the ability to anticipate where problems are likely to occur. Thus the importance of information flow, teamwork and training on workforce attitudes should not be underestimated; each can be critical to the acceptance and smooth introduction of AMT systems [1–3].

The key to manufacturing success in any modern competitive industry is production performance. A company that wishes to retain or expand its share of the marketplace must have the ability to respond to any customer order with flexibility, providing good product quality and short delivery times. As a consequence, many firms are investing heavily in AMT, which employs precision machinery in an environment of continuous-production to provide the output required.

Machine utilization in such a manufacturing system must be high in order to justify the equipment cost and to achieve the desired output level. A badly designed system which is characterized by repeated equipment failure, poor availability and high repair costs can sometimes lead to a serious situation, owing to lost production. In this type of manufacturing environment it is of paramount importance to minimize, if not eliminate, machine downtime. In the case of flexible manufacturing systems this means improving machine tool reliability and maintainability [4].

In this respect, various projects have been carried out to evaluate the performance of machine tools and to investigate the nature and cause of machine breakdown [5,6]. Such studies have attempted to provide a basis for an improvement in machine tool design and have shown that there is a particular need to improve the reliability of electrical electronic components and the maintainability of mechanical items. The financial effects of poor equipment design are shown in Fig. 8.1. This outlines a typical AMT service profile and how excessive costs may be incurred during acquisition, installation and operation of these systems.

In view of the high capital cost of AMT, extreme care and attention to detail must be exercised throughout the acquisition process. The feasibility study/justification analysis in particular must be unbiased and if AMT is not warranted then the project should not proceed. If an AMT system is justified by the analysis for a given application, then the system specification phase should be conducted with circumspection. The final specification must spell out in detail the performance requirements of the system and should include the reliability, maintainability and availability values expected of the system when in service.

The selection of an equipment supplier should also be undertaken with

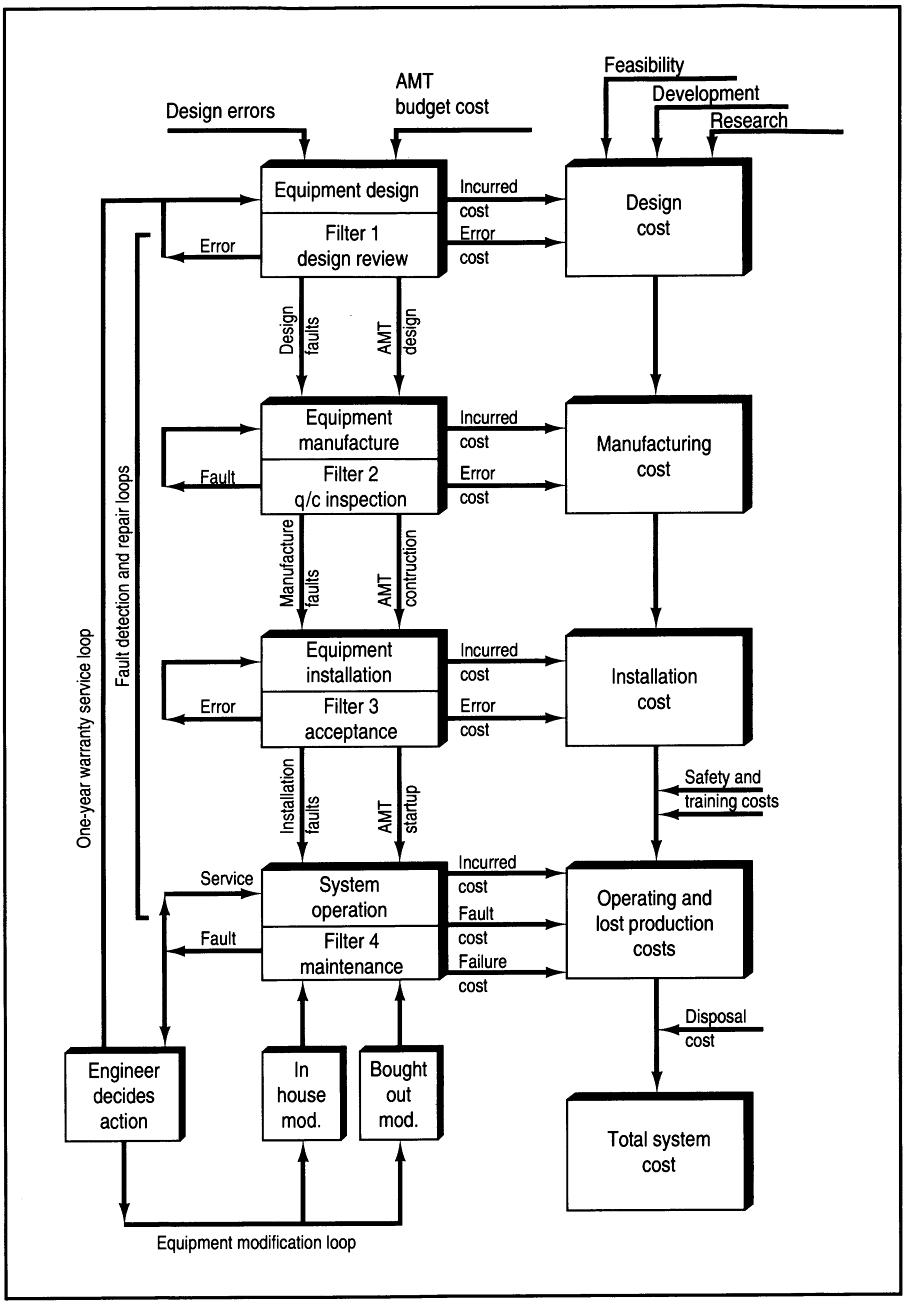

Fig. 8.1. Typical AMT service profile illustrating the financial effects of poor equipment design.

care. A vendor with a proven track record in supplying reliable and effective AMT with extensive backup support to the customer may look a safe bet, but this is not always the case. Several alternative suppliers should be evaluated. As soon as the vendor is selected, a project monitoring and review procedure should be agreed. This procedure should include the methods by which system performance can be measured against the values contained in the final specification, and the right to request engineering design changes on the grounds of improving reliability and maintenance.

An active and conscientious project review team is an essential customer safeguard against the possibility of technical difficulties arising with the system. The interaction of the customer and supplier engineering/management staff is necessary to ensure that any potential problems are quickly identified and resolved at each stage of the acquisition procedure. The review team should be multi-disciplinary in nature and capable of acting as the check filters shown in Fig. 8.1, identifying the problems/faults as they occur and instigating corrective action as soon as possible in the acquisition/operation of the system. If it is conducted correctly, this approach minimizes the problems of production startup and subsequent system operation by monitoring the project from conception to completion [7].

The "turnkey" alternative, wherein the supplier provides the complete installation with only limited customer consultation, is a doubtful procedure to follow in the purchase of anything other than a fairly simple AMT system. Consumer companies must realize that to operate AMT successfully they need to have an intimate understanding of the technology. The best way to achieve this is to be involved not only in the system operation but also in its design, manufacture and installation. AMT systems do fail in service – a fact which has been outlined in several recent studies, and which emphasizes the point that reliability of operation is not an automatic attribute of any AMT system [8–10].

The results quoted in references [8] and [9] cover a complete product range, and refer to the service callouts experienced by a single equipment supplier over a period of one year. Each system is used under a variety of different conditions, in a number of different industrial concerns; hence they can be reasonably considered as reflecting the approximate level of current "in-service" CNC machine tool failures. Accordingly, these studies have some important implications for prospective AMT users. The mean repair time (MRT) for machining centres for example, as shown in Fig. 8.2 and Table 8.1, is reported as roughly 5.5 hours per event. This is a significant amount of downtime for a production system, especially when coupled with technician travelling time and perhaps other logistic delays before the equipment again becomes operational. Thus if the failure frequency is high then the maintenance costs combined with the lost production costs may render a system uneconomic. This is a scenario which should be considered at the planning stage when simulating system operation. It may be a critical factor in deciding whether to go ahead or not.

8.3 System Startup

In the foregoing sections, the problems outlined are those which may arise as a consequence either of the initial adoption of AMT by a company or

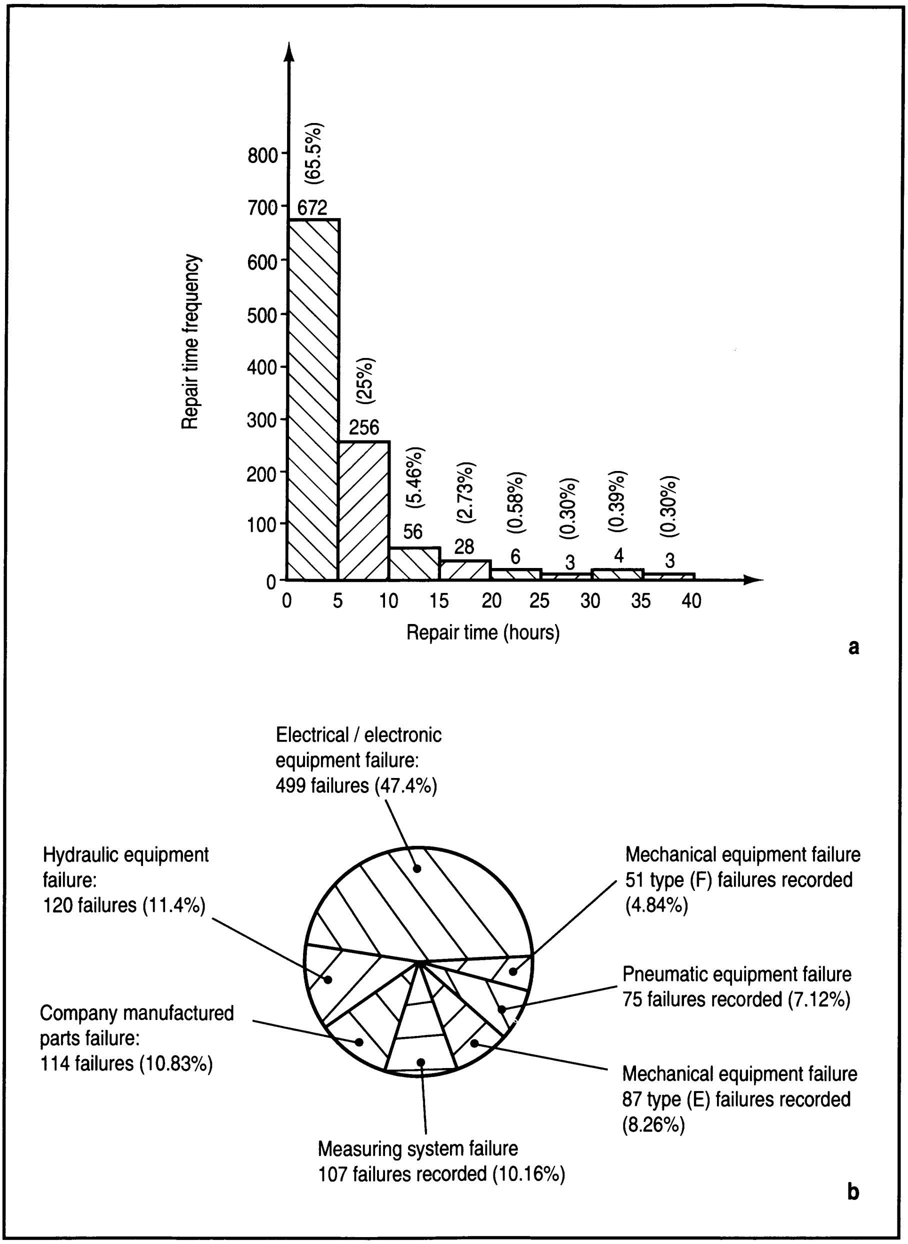

Fig. 8.2. Breakdown and repair statistics for a sample of 216 CNC machine tools. **a** Histogram analysis of repair time frequency. **b** Pie chart analysis of failure areas.

Table 8.1. Repair time statistics for a sample of 216 CNC machine tools of seven different types

Repair time (h)	Machine type							Total
	H1	V1	V2	V3	V4	V5	V6	
0–5	24	179	234	9	132	61	33	672
5–10	15	57	100	3	39	24	18	256
10–15	8	10	23	1	8	3	3	56
15–20	2	5	13	0	1	5	2	28
20–25	2	1	1	0	0	2	0	6
25–30	0	1	2	0	0	0	0	3
30–35	1	1	2	0	0	0	0	4
35–40	0	0	0	0	0	1	0	1
Total	52	254	375	13	180	96	56	1026
MRT (h)	7.39	4.96	5.43	4.85	4.20	6.08	5.30	5.46

Repair hours range: 0.25 hours minimum, 38.25 hours maximum

of an attempt to increase the level of AMT within a company. They are not insurmountable, and many of the difficulties associated with AMT can be resolved quite easily by intelligent management anticipation and good technical expertise. The importance of identifying and solving problem areas well in advance of production startup can be illustrated by reference to a case study [11].

Figure 8.3 shows the actual startup profile for flexible manufacturing system A and an analysis of its non-operational hours. The system shown represents an expansion of production facilities in a company which has a high degree of technical expertise and which has previously introduced several successful AMT systems. The introduction of this system occurred in two stages. The first stage occupied a period of approximately one year during which only two machines were available for production. Then at week 48 (1985) two additional machines were brought on-line and began their production startup. In week 1 of 1987 a machine was decommissioned for repair and this reduced the system to three effective machines.

The maximum available hours for production depends upon the number of machines in commission and this is shown in Fig. 8.3 by the dashed profile line. Actual achieved production hours are indicated by the histogram format, together with a least-squares-error (LSE) fitted curve which represents company learning, in this case according to the time constant model of Chapter 4. Although this learning or experience curve indicates approximately the overall trend of the complete data set, it does not satisfy accurately the trend in several localized areas of the raw data [12].

Several mathematical techniques have therefore been used on the data in an attempt to improve the analysis and thereby increase effective management control. These include regression analysis, Las Vegas modelling and least-squares-error fitting to identify the "best" predictive learning curve, plus a cusum analysis to locate discontinuities in the data. The cusum may indicate the possibility of a multiple startup. Such analyses allow

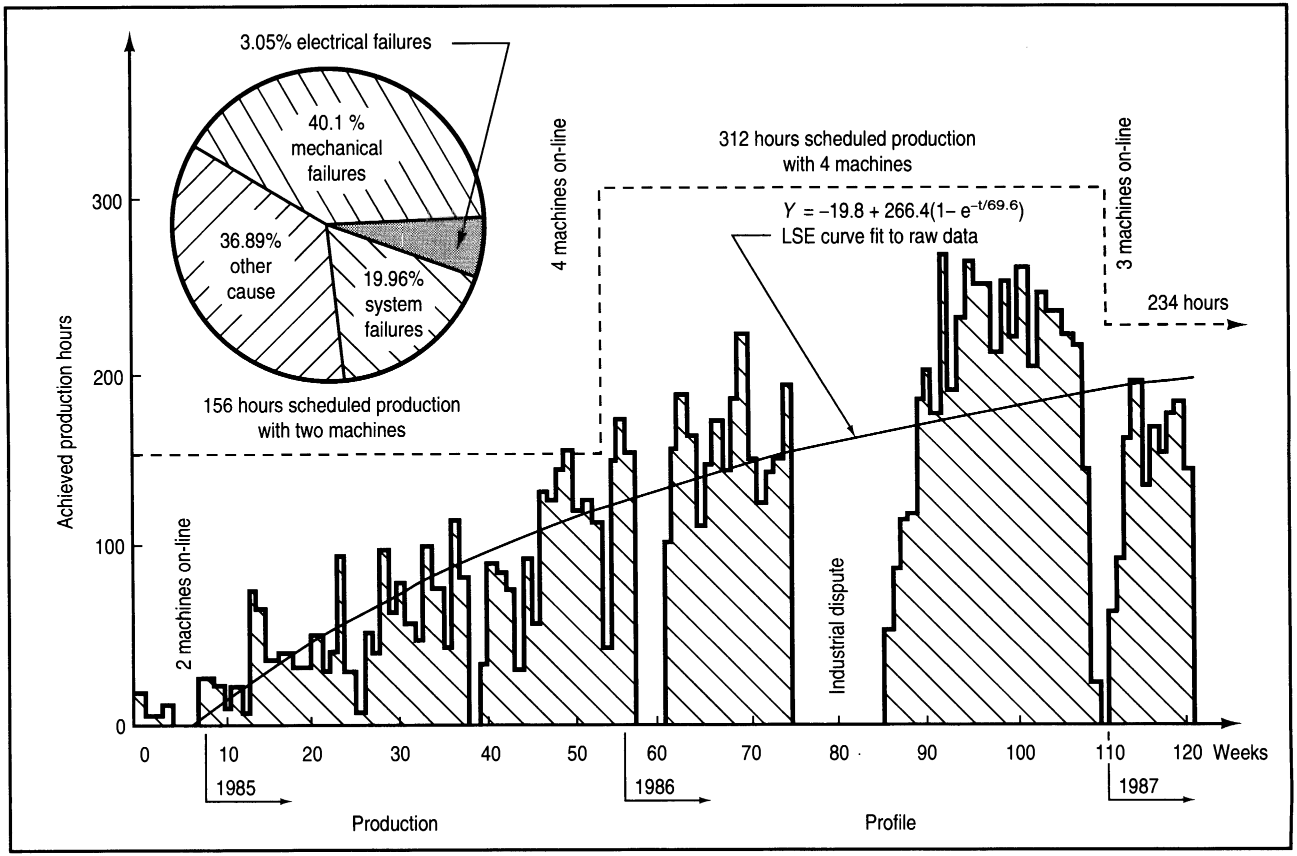

Fig. 8.3. FMS A: startup profile and analysis of non-operational hours.

management an insight whereby they can exercise more effective control over a given startup situation [11, 13].

A useful modification to the standard analysis is the translation of the raw production data as shown in Fig. 8.3 to cumulative percentage utilization. The effect of this conversion superimposed on the instantaneous percentage utilization is shown in Fig. 8.4. Performing the translation confers several benefits, including non-artificial smoothing of the data, the use of every data point including zero production, a startup profile upon which each significant emotive event can be identified, and a superior data set which exhibits minimal scatter. This information allows the fitting of a precise least-squares-error learning curve, which on inverse translation yields (as shown in Fig. 8.5) an accurate estimate of the recorded cumulative production.

The importance of this type of modelling is well portrayed in Fig. 8.5. The difference between the theoretical cumulative production and the actual illustrates the impact of organizational, attitudinal and technological problems and represents important lost production. Because AMT is intended to replace conventional facilities including standby capacity, difficulties with the system during startup may cause discontinuous output. This in turn could lead to serious financial problems for the company [4].

The slow and ragged startup depicted in Fig. 8.3 has all the attributes of a situation which involves many of the difficulties discussed previously. This caused grave concern to senior management, especially in respect of the large fluctuations in productive performance which arose as a consequence of these failings. Technical difficulties in particular restricted the availability of the system for production. Coupled with logistic delays and attitudinal problems, this conspired to extend the startup phase for the system to virtually two years [14].

Clearly, this is unacceptable for a system which represents a large financial investment and which should start to show an early return on the capital employed. The inability of the system to meet the required production target probably resulted in an immediate financial loss, owing to the lack of manufactured product and to the incurred costs of plant unavailability. These can include staff salaries, material/tooling costs, overheads, repair and maintenance costs and possibly a loss of future orders due to poor product delivery times.

8.4 System Utilization

In comparison with the poor startup of FMS A, a more reasonable case study performance is recorded in Fig. 8.6, which illustrates the startup profile of FMS B. This equipment represents a major investment of more than £3m by an engineering equipment manufacturing company with an estimated current annual turnover in excess of £60m. The FMS now forms a major part of a valve manufacturing process, and consists of four horizontal machining centres and two automated guided vehicles, plus associated material load–unload stations. "It covers the most critical production area in terms of quality and cost", i..e. the formation of the various holes required to turn a component blank into a valve block, and therefore can

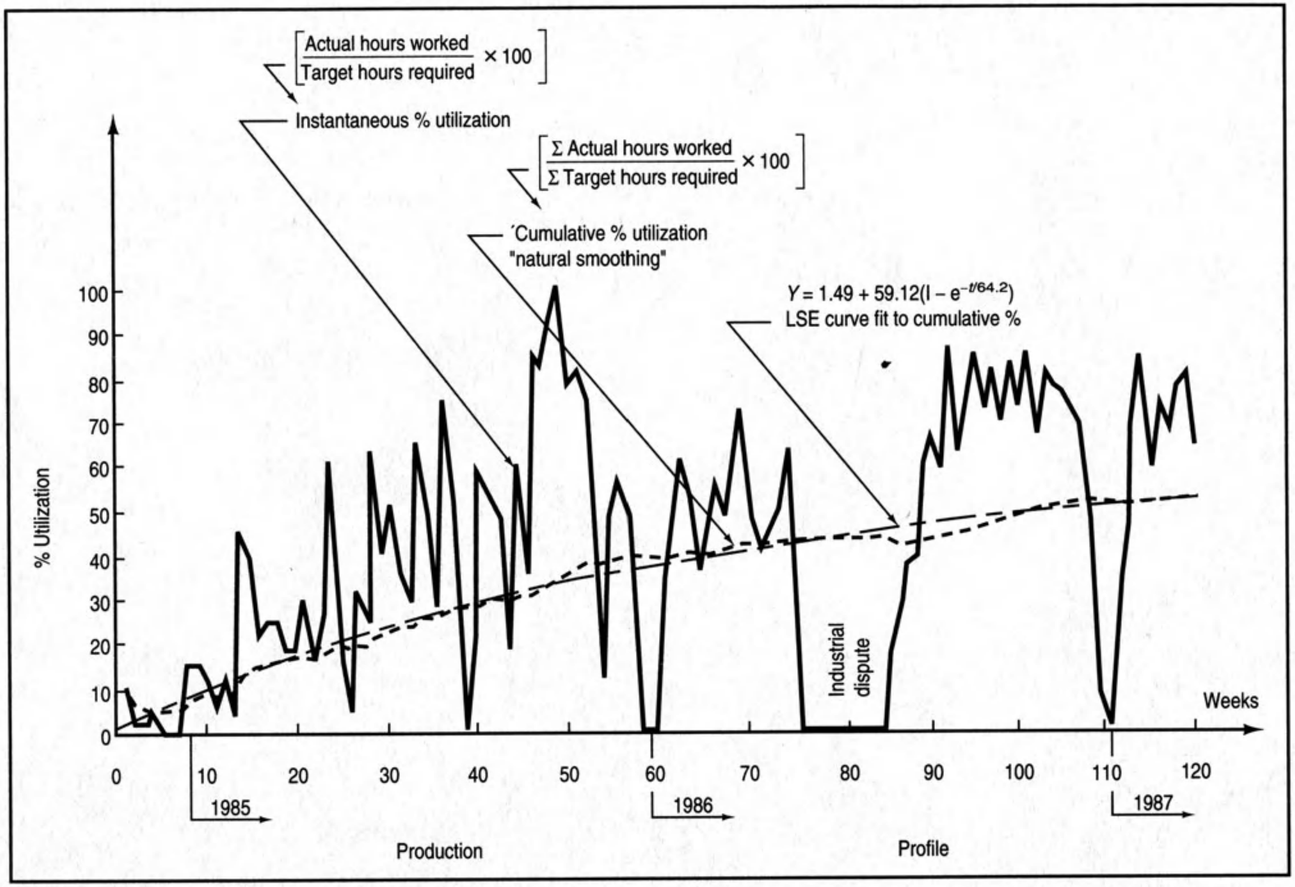

Fig. 6.4. Startup profile showing instantaneous and cumulative utilization. FMS A: LC parameters are $Y_c = 1.49$; $Y_f = 59.12$; $\tau = 64.20$.

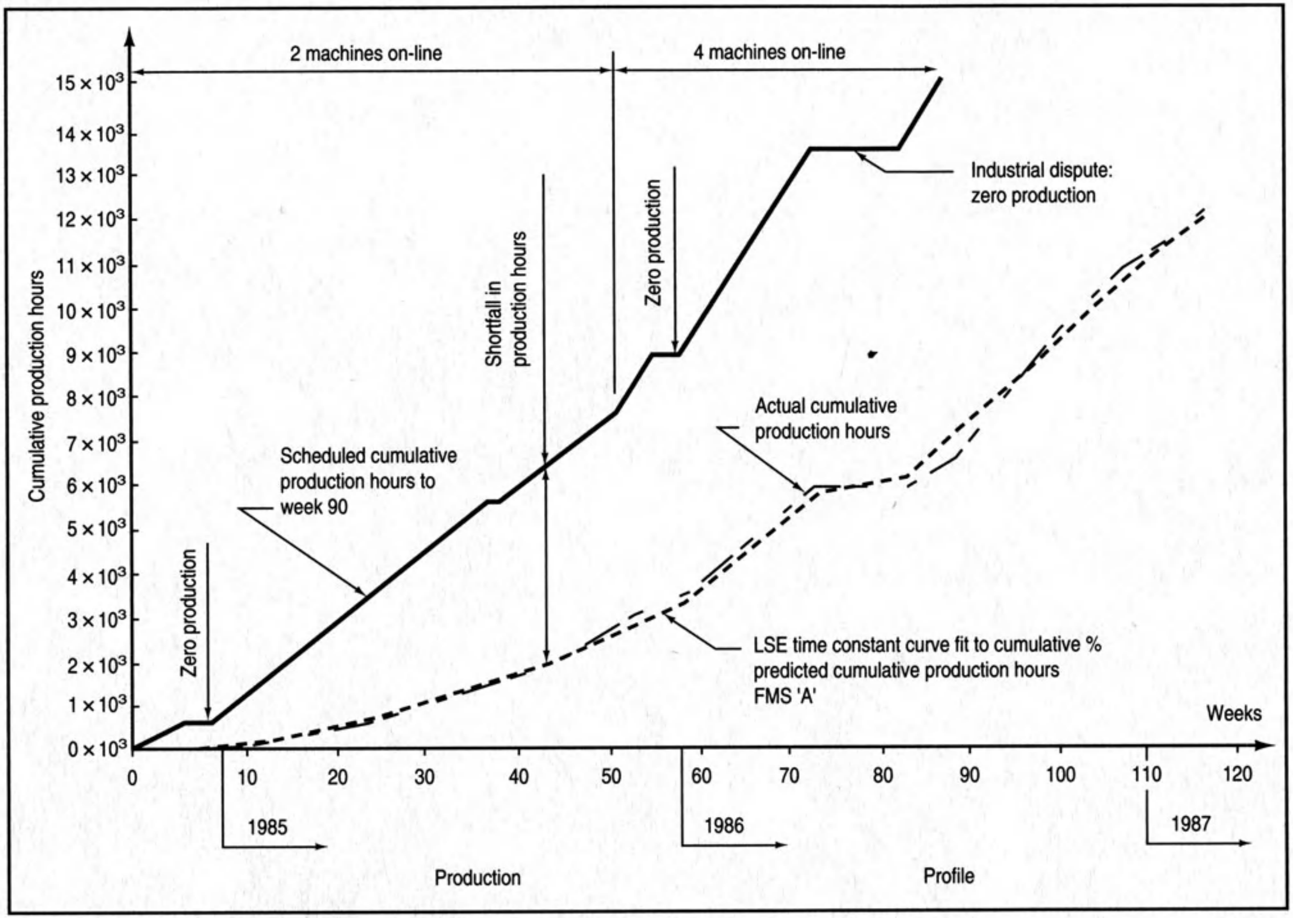

Fig. 8.5. Startup profile showing actual and predicted production hours.

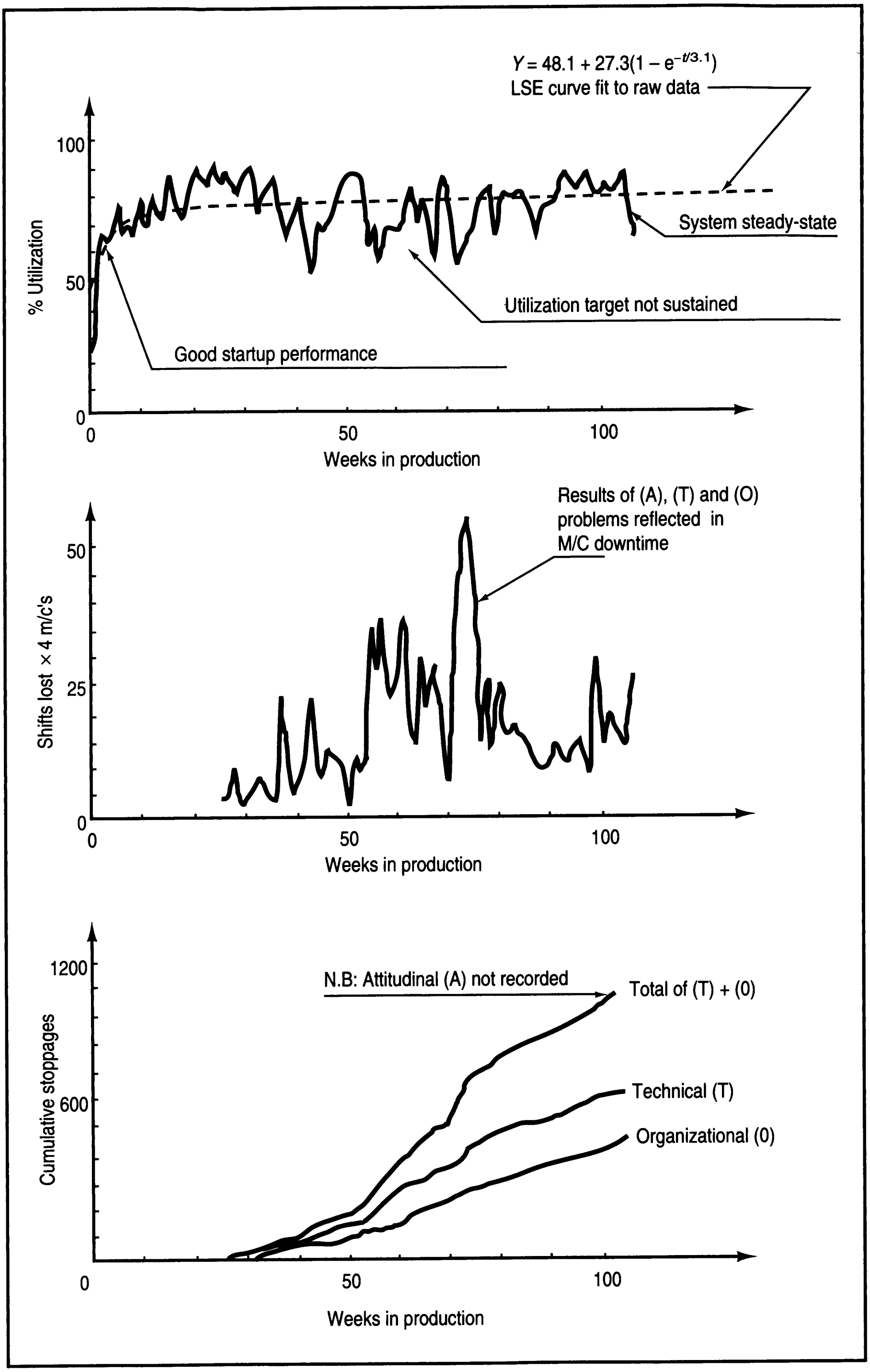

Fig. 8.6. FMS B: system performance (first 97 weeks of production).

be regarded as a "bottleneck" in the manufacturing system. In general, the methodology behind the implementation of this FMS can be regarded as an example of good practice in respect of the introduction of AMT and as such it is outlined briefly below [15, 16].

Because of the diverse nature of the company's product range, no buffer stock of completed or partially finished components is held. Thus all items are manufactured on the basis of confirmed orders only. Material requirement schedules are generated via a computer-based system and these, together with purchase and production schedules, are passed to the relevant manufacturing section. The FMS is run continuously via four operating teams. Quality control in respect of the system is stringent, with each operating team being responsible for its production quality and sample, independent inspection of valve blocks being frequently undertaken by quality control personnel. Cutting-tool quality is automatically monitored during production against time-based estimation of tool life, power consumption at the spindle, and direct measurement via a probe system. Production information is automatically recorded by the FMS software, as are the locations of tools and fixtures. Performance reports can be generated on demand, and different production schedules simulated.

System utilization was the main criterion by which the company measured FMS manufacturing performance. A target of 80% utilization was initially specified by the company, and this was guaranteed by the system manufacturer subject to the availability of a suitable workload on the FMS. The utilization is logged automatically by the control system, which deducts idle periods such as breakdown, cleaning or part program development from the record. Variations in this output indicator are shown in Fig. 8.6, which illustrates both the startup and the steady-state performance of the system. It is apparent that although a good startup was achieved, the original 80% target utilization has not been met consistently. Periodic downturns are due to a wide variety of causes such as initial learning, maintenance, machine cleaning, breakdown, part proving and the non-availability of work for the system.

The deteriorating performance of existing machining methods, taken together with a need to increase quality standards and to improve manufacturing flexibility, demanded that some, if not all, of the old production facilities be replaced. Thus when a technical analysis of the options available to the company revealed six alternatives as outlined in Table 8.2, a detailed financial study was undertaken which reduced this choice to that of a flexible manufacturing system. The principal financial criteria involved a return on investment of 16% and this was predicted for

Table 8.2. Alternative options available to the company

1. Do nothing.
2. Replace with like for like.
3. Replace with stand alone CNC.
4. Replace with a multi-pallet FMC.
5. Replace with an FMS.
6. Subcontract.

the FMS via the use of discounted cash flow (DCF) on quantified direct, indirect and intangible benefits plus the award of a 26% government grant. The FMS project planning and implementation was carried out by a specially formed project team. Several different suppliers were approached. After an extensive study into company requirements versus vendor capability, a complete system was bought from a leading American supplier. Via the project team, the company actively participated in the development and installation of the FMS, which took 25 months to complete.

This figure indicates the importance of monitoring system performance beyond the point where the installation and startup phases are complete. There is no guarantee that once satisfactory performance is achieved, it will be maintained without ongoing management effort. In this case, an increase in system flexibility was evident from a close analysis of the production records. Batch size showed a decreasing trend, with one-off batches becoming increasingly common. The number of different parts made each week tended to rise over the period analysed, finally levelling off at around 30 parts per week. Initially only 12 part programs were available for the system, but this rose to 170 at the end of the study.

The installation of the FMS has undoubtedly improved the world-class manufacturing ratios for the company, although they are still poor in comparison with those for Japanese manufacturers. Lead-time to work-content is 60 : 1, process-speed to sales-rate is 9 : 1, and number-of-workpieces to workstations is approximately 108 : 1. In Japan single-figure ratios are quoted as the norm for all three statistics in similar manufacturing industries.

During FMS operation, tooling problems were experienced in respect of the quality of new tooling, resharpened tools and the availability of complete tool assemblies. Conventional machining tools were found to be inadequate for unmanned machining and the amount of "sister" tooling required by the FMS was underestimated at the planning stage. Inadequate quality was also experienced in respect of the metal cutting coolant. This resulted in poor thread definition and thus questionable quality. A change of coolant resulted in improved accuracy and a minimization of corrosion on the FMS. The information flow between the FMS operating teams and production management is limited by the shift pattern worked in the company. Although not a major problem, it could be improved. Job flexibility is practised within the FMS teams and accepted, albeit with some reservation. Production planning problems have been reduced through the use of the FMS and the development of a design for manufacture culture noted during the study.

In this application, FMS implementation was resisted by the union and resentment and/or antagonism towards the system carried over into the initial production phase. It is still slightly evident within the company and there is very little integration between the FMS operating teams and the rest of the company workforce. The FMS is now regarded as a successful and productive area within the company, although no further development is envisaged at present. Neutral support for the system is forthcoming from the administrative and technical personnel, who are torn between accepting new technology and the fear of redundancy. An improvement in external company image, via the implementation of the FMS, is accepted by all personnel within the company, particularly in obtaining new product orders.

8.5 Summary

The introduction of advanced manufacturing technology or the progression of a company to a higher level of AMT usage, may result in an extended equipment startup time. The delay in achieving system operation is usually caused by problems arising in three distinct areas of the human activity system embodied within a company. These are the attitude of company personnel to AMT introduction, the reorganization of the company around AMT, and the effective operation of the technology itself. In each case, the solution to the difficulties of AMT startup rests with the management of the company.

Foresight, together with the effective monitoring and control of a project, must be exercised by senior management to ensure successful implementation. To assist in this task, learning curve theory can provide managers with a useful insight into the consequences of complex decision interactions which occur during AMT startup. As a management tool, such experience curves are visually effective, and can prompt action more quickly than other project monitoring techniques. With a better understanding of the problems encountered during startup, via case studies and experience reporting, their easier resolution or avoidance may be possible. As a consequence, the analysis of production data can be seen to be useful in the smooth implementation of AMT.

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9 Case Studies Based on Three AMT Users

D.G. Coward and J.E. Cherrington

9.1 AMT Productivity Losses Described

The analysis of productivity losses during startup requires management to determine the time when, in their view, commissioning finishes and production startup commences. In larger companies this is relatively straightforward because system engineers record the time of handover of the AMT to production personnel. Unfortunately, with smaller companies it is not always possible to identify this change so precisely.

Two examples of this problem occurred with the firms identified later in this chapter as Company A and Company B. The reason in both these cases was that the firms insisted that good-quality output in the form of qualification test samples be produced during the commissioning stage. Now commissioning is typically a protracted activity beset with productivity losses, so in order to determine the point where good-quality products were produced in greatly increasing quantities we used the four-parameter, first-order delayed time constant model, as was shown in Fig. 4.10.

In addition, Fig. 4.10 also separated lost productivity into organizational and operational losses. The causes of these losses may be analysed in a roughly chronological order of decisions relating to the sources listed on pp. 72–3. Table 9.1 shows the order in which these decisions and hence their associated productivity losses occur before actual machining takes place.

Losses due to type 1, 2 and 3 decisions are usually accepted and built into costing and delivery forecasts. The startup described on pp. 71–2 for Company A may be further analysed to identify the nature of these decisions and the losses due to them. The average asymptotic level of 124 hours per

Table 9.1. Decision classification

Type	Description
Type 1	Strategic organizational decisions
Type 2	Strategic planning decisions
Type 3	Operational planning decisions
Type 4	Operational control decisions
Type 5	Operational programming decisions

week in Fig. 4.10 compensates for abnormal events such as holidays and unavoidable breakdowns.

When peak values are examined following the work of Chapter 6 it would appear that there is a maximum steady-state level of 129 hours per week. This results from an organizational decision not to achieve unmanned running on this machine but to limit maximum working hours to those scheduled elsewhere in the factory. On social grounds this was a sound decision. The effects of major equipment breakdowns which involved the visit of a service engineer from the supplier were also caused by an organizational decision regarding in-house maintenance capability.

During the startup period extensive warranty claims were made for both major and minor productivity losses because of equipment failure. Management felt that cash recovered by this means more than compensated for the productive output lost from the pallet changer machining centre. A design fault eventually discovered in a voltage regulator was the main cause of these problems.

If the availability of all resources is seen as being controlled by long-term strategic decisions then the transient effects of such resources as trained operators, in-house maintenance and supervisory expertise may be said to represent strategic planning decisions. Reference is made on pp. 71–2 to a delay of 11 weeks before the startup curve settles down. This delay could be said to be due to these strategic planning decisions. Weeks 1 to 3 in Fig. 4.10 showed the effect of the company initially working for a single shift, with time being subsequently allocated for the training of an operator for the second shift.

Examples of type 3 operational planning decisions were conveniently identified as those allowing for minor equipment faults, incomplete tooling support, software unreliability and the unavailability of production material. Although mainly consisting of transient elements, these faults did persist into the steady state and were satisfactorily modelled in total as a continuous exogenous variable.

Type 4 operational control decisions were related to the way the available resources were used. Particular examples were the utilization of tooling and transport facilities, the removal of swarf, and, more importantly, deviations from the planned working methods.

In the second example of a flexible manufacturing cell in Company B, where products were produced in reasonable size batches and the variety of work was relatively limited, different aspects of startup and operational control decisions were evaluated. Owing to the arrangement of machines within the cell, various alternative working patterns could be employed. For example, additional labour could be introduced into the cell to support the two AMT operators. This labour would then be employed on ancillary operations such as frazing. Hence, although the startup of the new AMT was modelled in isolation, its effect on the total AMT usage in the cell was of even more interest. Total product output was of particular significance because of the co-operation required between the operator in charge of the new AMT and the operator looking after the existing AMT. Figure 9.1 shows the productive AMT hours per week for the new machining centre on its own for the first twenty weeks of the startup, week 39 being the Christmas holiday week. The finite and time constant delays for the new

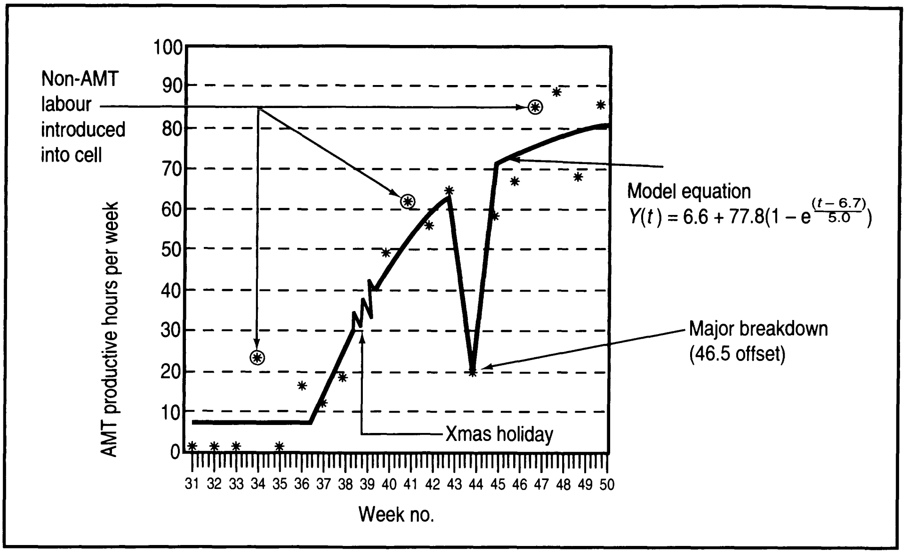


Fig. 9.1. Company B – AMT hours/week.

machine were of 7 and 5 weeks respectively. Further analysis using exogenous variables described the effect of different working methods adopted following operational planning decisions. Extra unskilled-labour hours, when employed, contributed 110% to the AMT productive hours, because the AMT operators were able to concentrate on the AMT part of the production cycle. The replanned working arrangements in the cell produced a significant amount of unmanned running, so that the temporary absence of the AMT operators produced less than directly proportional losses in AMT usage hours.

In Fig. 9.1 values above 74 hours a week represent unmanned running. Hence efficiencies greater than 85% were achieved. This implementation was also successful in cost terms, with payback being achieved in 18 months. The most significant feature of the implementation was the large amount of detailed planning achieved by the project team, followed by close monitoring of performance compared to plan. In contrast to implementations observed in other companies, AMT specifications were matched exactly to the product requirements. As the components produced were to their own design and the forecast of production requirements was reasonably accurate, the latter because they intended to make some products in house that would previously have been subcontracted, the company were able to justify the purchase of a new machine. They thus had these two powerful advantages over Company A when contemplating the AMT procurement.

The main conclusion to be drawn from these two examples is that although technological feasibility was not really a dominant issue, expensive productivity losses still occurred. In learning curve terms, both the time constant and pure time delays could have been reduced. In particular, monitoring and controlling to a plan should not be seen as an academic exercise but as genuine management activities which aim to better guarantee satisfactory cash flows and profit margins.

In this section we have described the startups of machines introduced into two companies, A and B. The rest of the chapter describes the steady-state running of such machines and the implementation of another form of AMT, namely shop-floor data collection systems, into these firms and a further one labelled Company C.

9.2 Automatic Shop-Floor Data Collection

Information regarding the first three types of decisions was relatively easily obtained from our normal top-down approach via questionnaires, structured interviews and analysis of company records. From this approach we were able to confirm that strategic decisions caused the majority of the productivity losses, provided 100% productivity is based on 168 hours' productive time per week being available.

Obtaining information regarding operational control decisions was another matter entirely. Investigations soon revealed doubts regarding the integrity of shop floor data. Consequently, we decided to implement our own data collection systems as part of a "bottom-up" approach. Machine sensors were constructed and installed by the authors relatively painlessly. They transmitted data regarding the "lights-on" performance of the programmed machine movements and cutting time. Having knowledge of the effects of type 1, 2 and 3 categories of decisions and also of full machine running time meant that when the total of these values was subtracted from the full resource availability time then the remainder corresponded to the losses due to operational control decisions.

The objective of this data collection exercise was to separate operational times into those which involved (a) the operator and machine working together, (b) the machine running independently of the operator, and (c) the operator working independently of the machine. Monitoring the operator was, as expected, an interesting exercise. A full description of the pitfalls encountered when introducing the SFDCs into three companies follows in later sections.

Although the equipment was extremely basic in nature, acting primarily as an event recorder, when used in conjunction with data analysis and summary programs the system provided an opportunity to analyse machine and operator performance in terms of the following:

1. Distribution of cycle times for the same job
2. Distribution of cycle times for the same job but with different operators; specifically "highlighting" different shifts
3. Distribution of adjustment and setting times
4. The disruption of machine running by excessive manual intervention
5. Comparative results of actual and planned cycle, setting, load, unload and availability times

Selected software output included simple listings of sequential event times, frequency plots of activity times and utilization diagrams. These outputs yielded information on such features as the following:

1. Effects of tea, lunch, weekend and holiday breaks
2. Patterns of shift working
3. Utilization of machines on a selected time basis, e.g. seconds to months

9.2.1 Degree of Monitoring

Computer recording of signals received from the machine sensors measured such features as the following:

1. Cycle light on – automatic mode
2. Manual data input mode
3. Machine door open/shut
4. Pallet access door open/shut
5. Swarf disposal system on/off
6. Machine spindle rotating/stationary

The choice of signals monitored depended upon the characteristics of each machine, e.g. if "cycle light on" operated only when the machine was operational then it was regarded as a single useful piece of information. However, if the light stayed on when the machine was being set and the slides were manipulated by the inching button then only by comparing the condition of both the "cycle light on" and the "manual data input" modes could it be ascertained which actually was being carried out, i.e. running or setting.

The signals thus recorded could be analysed from the source sensors into three main areas:

1. Machine operating cycle
2. Machine undergoing setting/resetting
3. Machine idle

Generally speaking, while something was actually happening it was possible to detect whether or not the action was useful. However, "all signals off" could tell us only that no work was being done on the machine. The reason why had to be found out by other means, e.g. by operating a keypad. Hence a simple keypad was added, with 10 coded inputs available which were activated by the operator. Such action writes onto a computer program data file a digit that signifies the reason for the condition of the machine's status. This feature was developed by the authors to improve the quality of the information available.

Status codes included:

0 = normal running
1 = setting
2 = breakdown
3 = swarf removal
4 = rectification
5 = CNC Program Prove Out
6 = shift over

Table 9.2. Company A – Extract from 45-day sample of time spent on three main classification states (no keypad used)

Period analysed: 9-hours shift – 45 days

Day	Machine running	Setting	Machine idle
M	7.240	0.034	1.671
T	2.050	4.280	2.910
W	7.560	0.420	1.260
T	4.060	2.760	2.420
F	6.070	2.120	1.050
S	3.800	0.009	0.030
M	7.400	0.960	0.936
T	2.700	4.310	2.268
W	4.600	2.010	2.560
T	7.100	0.330	1.770
F	6.500	1.730	1.038
S	2.230	1.420	0.601
Total	200.076	60.453	129.723
Average	4.446	1.343	2.76
% of shift	51	18	31

7 = tooling changes
8 = spare/available
9 = spare/available

Results confirmed that satisfactory usage depends on the operator's acceptance of the monitoring equipment, different success rates being achieved with different shift operators.

A printout of a typical analysis without the keypad is given in Table 9.2 and a typical analysis sheet with the keypad is shown in Table 9.3. These

Table 9.3. Results from machine sensors and keypad

Analysis of time period 03–18–1989 07:45:00 to 03–18–1989 12:00:00.
Length of time period scanned: 0 d 4 h 15 min 0 s (15 300 s) – 3113 events logged
Time accounted for 15 300 s
Running: 8033 s Setting: 5101 s Idle: 2166 s

Total time cycle ON: 8424 s (55% of total time)
Total time cycle OFF: 6876 s (44% of total time)

Key 0:	8401 s	Normal OK	54%	::::::::::::::::::::::::::::
Key 1:	6899 s	Setting	45%	:::::::::::::::::::::::
Key 2:	0 s	Breakdown	0%	
Key 3:	0 s	Swarf/oil	0%	
Key 4:	0 s	Rectification	0%	
Key 5:	0 s	NC program	0%	
Key 6:	0 s	Shift over	0%	
Key 7:	0 s	Tooling	0%	. . . .
				Percentage of time ⟶

CYCLE ON – keypad runtime routine: 23 s (Keypad runtime = 8401 s)
CYCLE OFF – keypad downtime: −23 s (Keypad downtime = 6899 s)

utilization figures are very powerful. Because they point to any performance variances they can also be used in summary form or analysed as a function of time over any shift.

Two of the companies studied normally had small to medium-sized batches processed (1 to 50), while the third one had long production runs of days or weeks with the same job being machined. These gave us the opportunity to study the output of a range of operating conditions which exist in general production on this type of AMT.

Confidence in the results obtained was high. The pattern of operation records obtained was a reasonably reliable description of the operation of AMT at three different companies. The commonality observed means that important lessons have still to be learned and consequential action taken to improve performance on these machines.

9.3 Introduction to Case Studies

This chapter is constructed around case studies from three different companies designated as A, B and C who were operating broadly similar AMT systems involving pallet-changing machines. Distinct differences in management and shop-floor attitudes were observed by the authors. Also, the companies' starting positions with regard to AMT implementation were quite different.

Pallet-changing machines consist of a control system capable of being programmed to change tools, set speeds, and select cutting rates to carry out a variety of operations such as milling, boring, drilling, tapping and countersinking, in the production of flat, circular and more complex shapes. To aid the production of parts and increase the actual cutting time of the machine relative to the floor-to-floor time the pallet-changing system is added. This allows single and multiple job loading and unloading to be carried out at a duplicate non-operational pallet position so that the machine can keep working. Cutting is not then delayed by waiting for operator activities connected with component changing. As an example, it is possible to change a pallet in seconds when the individual components could take anything from 20 to 40 minutes to load. This feature can increase potential AMT usage by as much as 50%. Hence, pallet-changing machines are seen as a critical expensive step change in technology and are rightfully considered to be in the forefront of AMT, although they have been in use in other areas of manufacture for over a quarter of a century. Pallet-changing machines present particular problems to management:

1. High potential AMT output which alone can justify their cost can only be effected by close management involvement with the installation and by changes in operator working practices.
2. Operational control is essential to ensure that fixtures, tooling and loading sequences used are incorporated into the pallet changing sequence. This ensures that the computer control system is fully operational and the manual element of control is but a small part of the time cycle.
3. Any problems arising need immediate action to show management interest and concern. This means that real-time monitoring is essential

to prevent prolonged delays and ensure dynamic feedback, as already outlined on pp. 86–7. Otherwise, conventional slow reporting systems may cause output activity to be depressed and give control to the operator rather than management, thus allowing bad habits to creep in.

The authors have visited several companies which had very successfully integrated pallet-changing machining centres into existing cells and departments. These companies had achieved very high utilizations and had appreciable periods of unmanned running. Some of these companies were near-neighbours of those described in this chapter. However, A, B and C may be regarded as three totally different companies who collaborated with the authors to establish the extent of their efficiency.

Pallet changers can add an additional £20 000 or so to the cost of a machining centre, and the controlling computer systems cost many multiples of this sum. Hence, the question to be answered is: How do operational managers ensure they get value for money for both of these elements when an AMT system is installed? The investigations were planned to answer this question based upon a combination of information made available by the company, supplemented by auxiliary data collected by the authors in new areas of study. In this way a reasonable judgement could be made concerning the present position within the companies and also give indications of changes that might be required to enhance management control if this was found to be slack.

In all three cases, our preliminary studies followed the classic top-down methodology of questionnaires and structured interviews followed by an analysis of company records. Early on in the studies doubts concerning the integrity of the existing shop data collection systems were raised in the authors' minds. To find out the extent of the problem, company management and workers were pursuaded to co-operate or even participate in on-line data collection using our equipment specially designed for the purpose. The main idea behind this latter very detailed, "bottom up" monitoring process was to provide reliable information regarding the operation of this expensive AMT. In parallel, we expected to identify causes for the productivity losses incurred during both startup and steady-state stages.

To fully understand and compare the results for each company, knowledge of the status of the businesses of A, B and C has to be acquired in terms of the following four elements of their manufacturing strategies:

1. Attitude to change
2. Levels of trust
3. Training support
4. Shop culture

It was thus necessary to appreciate as much of the manufacturing picture as possible in order to identify the problems facing AMT introduction before a successful implementation could be executed.

Many top-down investigators (Chapter 1) have identified the symptoms, but it was realized that only by a bottom-up process could root causes be exposed. Our experience is that this dual methodology is essential, and indeed it was shown to be inevitable when the investigation kept getting stalled by the availability of only *inadequate or incorrect information typically used in management control of operations.*

Frequently we have found that detailed analysis of an official record reveals massive inconsistencies and leaves doubts concerning its usefulness and adequacy concerning AMT installations. At all three companies, job cards were studied to try to draw conclusions concerning shop-floor activities, especially those causing delays. This proved to be difficult because of the quality of the data collected. The following examples of these were all too frequently seen:

1. "Clocked" times were crossed out and amended; written times were substituted either to lengthen the time on booked jobs or to shorten it.
2. Machine delays were not recorded for production purposes, although unofficial logs kept by maintenance engineers proved invaluable for our analysis.
3. The night shift cards were always completed by the day shift so that "consistency" was achieved. Thus the night shift results were possibly pure fiction on occasions.
4. Quantities produced were overbooked in order to increase bonus payments independent of true performance.

These problems confirmed that on-line monitoring of plant was essential and consequently we designed our own recording system based on simple sensors.

Because it is important to understand each company scenario, an outline description of the businesses now follows. This permits the merits of the bottom-up analysis to be judged against the company background existing at the time.

AMT is not only installed in greenfield sites with detailed planning and clear objectives and with total employee and management commitment; it is also introduced into the kind of situations outlined in the following section, and so any methodology adopted must take these factors into account.

9.4 Descriptions of Companies Involved

9.4.1 Company A

This is basically a subcontracting machine shop operating in a large valve body market. It produces parts in alloy steels with batch sizes from 1 to about 200, with the average being around 20 items.

The company employs 40 people and operates on two or three shifts, depending upon workload. The company have moved upmarket over a number of years by *replacing* smaller conventional machines *with larger CNC* and conventional equipment as part of an overall strategy. The latter includes obtaining BS5750 recognition and trebling the rate per hour charged for machining. The computer-aided production management (CAPM) system installed relies upon obtaining estimates for machining times from a company data base. Some special jobs are not forecast; the time actually taken is subsequently recorded and accepted as correct for databank purposes.

The firm does not have its own product range, so marketing and forecasting is difficult. They therefore adopt flexible strategies in terms of product size, shifts worked, and the number of machines available compared with the number and type of skilled operatives employed. 25 machine operators normally cover 16 machines via multi-shift operation. The capacity available for sales purposes was thus flexible and wide-ranging. About half of the workshop machines could be graded CNC (or better) in terms of control. Maintenance was not considered to be a critical problem because of the spare machine capacity and the flexibility of the workforce. However, when real breakdown problems occurred on one particular machine the data-recording system used was not suitable for identifying what was happening so an informal one had to be set up weeks after it was really needed. As soon as the breakdown problem was reduced to manageable proportions, the informal data recording system was abandoned.

The official data-collection system was based upon planning cards and job cards which were issued for each operation, the men clocking on and off each operation. No bonus or incentive payments based upon performance existed, but management did monitor such information. However, no observable corrective action was taken.

To enable the computer to be loaded with "correct" information the supervisor checked each job card for acceptability. He sometimes changed the time taken after discussion with the operator if this was outside his expectations. This often occurred because delays had been incorrectly logged, such as when they were booked to a code that management did not like to see identified.

The information system software was designed to print out operator performance data, not machine performance. For example, if a machine broke down it would be recorded only (and indirectly at that) if the operator did no work during this period. However, if the operator was moved to another machine, his performance continued by logging on to another machine number but no record was kept of the *unavailability* of the previous machine. Sometime later, as convenient, and when the repair was completed, the operator moved back, e.g. when a reallocated job was finished.

In terms of strategy, Company A required flexible capacity to respond to market demands and a planning and costing system which would ensure that sufficient margins were estimated for each job, irrespective of shape, size and precision. The system was thus required to estimate total productivity losses without attempting to analyse them as part of a continuous policy of improvement.

The managing director liked this system but knew it was limited by the number of job cards that the supervisor could screen ready for the database. It was considered that he had reached saturation level under the present conditions. The company was constrained from further expansion until this situation was de-bottlenecked. It was to this end that monitoring machine performance was perceived by the management of Company A as a useful experiment.

9.4.2. Company B

This is a manufacturing company with their own product range, employing 1000 people and forming part of an international group. The machine shop employed 60 people and used only a few CNC machine tools.

The confidence level of the company management concerning future demand for their products is high. They understand their market, are well established and have the edge on most of their competitors. Because of the success of the business over 50% of the products reviewed were subcontracted. Any future changes in manufacturing strategy had this buffer in demand, thus ensuring further AMT investment would not fail for lack of throughput. The ability of Company B to sell all that was made had an effect on shop-floor culture. It was mainly centred on output, which put accurate information needed for operational decision-making low on the list of priorities.

Raw material for the product range was to a special specification which resulted, for reasons of economy, in large quantities being purchased. Consequently, large batch quantities would typically be ordered to match material availability and market demand. This situation creates a rigid throughput regime, which was easily disrupted by demands for 50 or so products on urgent delivery. This occurred regularly, leading to split batches with duplicated paperwork and hence a loss of control. If this sequence of events is repeated until all data become questionable then only measurable physical output is real; the rest rapidly becomes arbitrary.

The AMT installation consisted of a special flexible manufacturing cell set up to produce large quantities of a wide range of aluminium components used as part of electronic assemblies. Future expansion was anticipated in this area and basic data concerning the cell's effectiveness was required. The *present* company information system consisted of three software packages each purchased from different suppliers loaded onto two computers with no computing links between them. The necessary links were sometimes obtained by manual input of data after "selective" modifications between stages in the hope of improving "accuracy". Large batches of work were issued to the cell and these were then split by supervisory staff to suit demand and spread over a period of time. A bonus system also operated and people attempted to overbook. These two activities helped to confuse the monitoring of workflow.

The cell consisted of a number of machine tools grouped around a CNC machining centre. The single operator worked each machine in turn while the CNC machining centre was on automatic cycle. Two shifts were worked for five days per week. However, a reasonable proportion of demand was subcontracted out. It was this work that formed some of the output being considered for investment in a second machining centre.

The cell had become the secret world of the two operators trained to work the machining centre, and management knew little about its operational effectiveness. The whole cell was plagued by difficulties with tooling, fixtures, swarf conveyors, split batches, high levels of work-in-progress, quality problems, breakdowns and occasional absenteeism. The pay rates were low, so that pressurizing workers for details of productivity losses was not considered a good policy when they already produced near the "expected" levels, however badly these were defined.

Because of all the above delays and problems the "expected" output targets were established on the basic operating experience and used by the company's management as standard data. A continuous improvement strategy was not used. Unlike the other two companies, however, Company B employed a group of production engineers, whose function was to write programs and to develop a range of support tooling which increased the "on-time" proportion of the CNC production cycle time. In effect they were able to divert ancillary operations to other machines in the cell, thus ensuring that the machining centre was interrupted only for unload–load activities and for emergencies.

9.4.3 Company C

This business recently became part of an international company. It remains reasonably autonomous and makes its own product range of commercial and catering food-processing equipment.

Although the company have their own product range, demand forecasting was still not easy. The lead time to manufacture was high (3 months on average), while the customer demand period was low (1 week). Company C also make a wide range of equipment in both type and size. Matching production to demand at around 80% was therefore considered excellent. This still leaves plenty of room for urgent rush jobs, which obviously can disrupt work schedules for the "planned" 80%. Large stocks are one answer to the problem of satisfying the customer, but these are expensive and not part of the company's strategy.

A number of attempts to reduce lead time and work-in-progress have been made, but all available data relate to past performance and the "efficiency" behind these figures is difficult to quantify. For example, if 6 main bodies take 72 machine-hours including setting allowances and the standard in the past has been 60 hours, what can be done by management? Reasons and excuses can be offered, but as it may be 6 or 12 months before that same job is done again, not necessarily by the same person, how can senior management gain control? After this time period other important issues are also likely to dominate the scene, so that such isolated events do not appear to matter. However, if this example is typical then fundamental management control problems exist in Company C.

Batch sizes are small (about 5 or 6) and a conventional machine shop employing 20 people has 4 CNC machines, one of which is a pallet-changing machining centre. The staff operate on two shifts and work overtime only occasionally to obtain extra output.

A wide variety of jobs are produced over a typical week. The operators are provided with route and job cards with minimal information on them. They are not used for clocking in and out, but used to record the total time taken by each machine. If the expected time is exceeded to any large degree on any operation then verbal excuses can be put forward to "explain" why this occurred. It is very easy to find such a reason when using supposedly complicated equipment which the supervisor has not been trained to use and is therefore in a weak position to dispute the time taken.

The main company thrust is to reduce both work-in-progress and stocks and to increase throughput rates. CNC machining centres are part of this strategy owing to their enhanced theoretical output rate, due to many operations being carried out at one setup.

One of the few involvements of the parent company is to set performance criteria in which all the above three factors play a part. This is also why the batch sizes are small. However, the company allow standard setting times between batches, and these are generously set at 2 hours or 4 hours for CNC machining centres. This is a neglected part of throughput philosophy and on some days the workload has more than one setting allowance, which makes potential utilization very poor. Incentives of a general nature are paid to operators. However, changes to the system have not achieved the objectives of reducing work-in-progress to any degree.

9.5 Strategic Decision-Making for AMT

Each of these three companies manifestly had their own reasons for purchasing an AMT pallet-changing machine. The measure of their success in meeting these objectives comes from (a) an analysis of the level of achievement of each objective and (b) the degree of effort put into startup and steady-state running to monitor these objectives. Attention will now be focused on point [a] and the second point will be fully discussed later.

9.5.1 Achievement of AMT Objectives in Company A

This company did not have their own product range and relied upon subcontracting from known customers. The objectives were based upon extending the range and flexibility of machining capacity on offer to customers, increasing metal removal rates so as to indirectly generate extra cashflow, and the ability to machine tough materials at competitive rates. Their particular machine had a torque meter fitted to warn of potential overloads, but this was ignored on some jobs when metal removal rate was considered more important. Yet breakdowns of the machine were not then related by management to this activity. Justification for using a pallet changer was a little remote from shop-floor practice because a full-time operator was allocated to the machine and the second pallet was used only occasionally. Unmanned running of this facility was never an objective of management because production quantities were too small. To conclude, newly introduced AMT was thus treated like all the other CNC machines and similar results were expected by management from the very basic control system used.

9.5.2 Achievement of AMT Objectives in Company B

Far more attention was focused on the necessary specification because a small range of large-volume products were to be manufactured, all of which were the company's own products. This necessitated expenditure on fixture design and operation plus the provision of suitable datum faces prior to introduction of AMT machining of these products. The main objective was minimization of total costs. This necessitated unmanned running through tea breaks, lunch hours, and between each shift, via use of the second pallet facility. Other objectives previously associated with CNC machines such as consistency of quality were also expected from the AMT.

All the foregoing objectives were achieved by constantly monitoring the output obtained against set targets and taking managerial action when problems were identified.

9.5.3 Achievement of AMT Objectives in Company C

This business has a wide range of both large and small products of their own design. Demand is often high but is very variable. The original objectives for purchasing AMT pallet changers have been overtaken by company strategy moving towards OPT (optimum production technology). This action change led to small batch sizes but without the corresponding reduction in setup times. In an attempt to reduce work-in-progress and speed up throughput some of the advantages normally expected from pallet changers were lost. An example was the use of only one pallet for loading and unloading operations because, owing to excessive cost, the fixtures were not always available. A surprising omission from this company's strategy was accurate datum face preparation. Each casting had to be carefully positioned using unmachined surfaces, even though they possessed complicated, three-dimensional features. This contrasted with Company B which despite having a simpler product, provided machined datum faces to speed loading and accuracy.

Some success was achieved in reducing work-in-progress and speeding throughput of small batches, but the underlying constraints mentioned above prevented any further gains. A step change in culture concerning these productive machines is necessary.

Summarizing, each company had different reasons for purchasing pallet changers. Without the detailed planning and control necessary to monitor performance at all times it is hard to see how management can be confident or sure that their aims are achieved.

9.6 Management Attitude to Informing Operatives about the Monitoring Exercise

As previously demonstrated, the top-down analysis identified a shortfall in the usefulness of the information system, hence the bottom-up approach was adopted to increase the value of the data. This shortfall identified itself in other ways, namely how management credibility is perceived when a move is made towards implementing new technology. It is interesting to observe (or note the absence as the case may be) the efforts made to make the shop-floor aware of the management's wish to record the detailed actions of the AMT installation.

An outline of how this activity is accomplished may therefore help the reader understand more of the background to effective and inefficient AMT *utilizations*.

We must again emphasize that utilization of equipment is *not* the main driving force in most situations where AMT is implemented. Competitive advantages, as described in Chapter 1, are more often quoted as the criterion of performance against which progress is measured. In such cases, however, the AMT is extremely expensive and is introduced to overcome bottlenecks in material flow. High utilization and an associated reduction in floor-to-floor time is then a primary objective.

9.6.1 Installing Monitoring Equipment in Company A

Here the managing director was certain there would be no difficulties encountered in installing and using the monitoring system. After pressure from the authors he said he would personally arrange for implementation to be carried out. Eventually a message was received, stating that if the supervisor of the production department was contacted the installation could proceed. A telephone call by the authors to the supervisor established a time and date. When the team arrived to install the equipment the supervisor asked for a full explanation. A little later it was established that the only communication received by the supervisor from the managing director was that he was to co-operate with the authors. What was to be installed, and why, he did not know. He then became worried and requested us to talk to the operators involved so as to get their approval.

This was done, and a slightly uneasy situation developed, enabling installation to start but with the computer situated in the supervisor's office. The system worked well on the two machines involved for a number of weeks but eventually the CNC turning machine suffered data "breakdown", with wiring removed from the control panel on three separate occasions. The shift operators did not know why. Fortunately, enough results had already been obtained by the time this happened to ensure that these "induced" failures did not cloud our conclusions.

The other machine suffered no such ill effects and a reliable set of data was obtained. After about three months it was agreed to install a pushbutton pad on the remaining machine to enable the operator to press a code number signifying the reason for any non-operation.

The managing director was fully involved in this plan. He wanted the 17 codes of Table 9.4 to be available so as to detail every eventuality. Reminding him (yet again!) of the past history of changes to their system, the authors asked for explicit management involvement in the discussions with the two operators concerned. He was now willing to provide this, but in practice failed to obtain clearance. This was because of a disagreement over a wage demand, non-co-operation with management being one of the sanctions used. Eventually, after another 3 months we requested the removal of the equipment to install elsewhere. In the event the keypad was not used at this company.

The managing director was very pleased to see removal of the equipment based on the authors' action rather than on his own directive. The existing company information gap was rapidly reinstituted. Both sides of this industry

Table 9.4. Company A – Analysis of productivity losses as applied to manpower

Code no.		Classification for machine*
1.	Rectification of defects	S
2.	Replacement of scrap	S
3.	Making tools	S
4.	CNC tape proving	S
5.	Machine breakdown	B
6.	Waiting work	W
7.	Waiting tools	W
8.	Machine repairs	B
9.	Waiting material	W
10.	Waiting inspection	W
11.	On-job training	S
12.	Off-job training	S/W
13.	Job machine reset	S
14.	Wait CNC program	W
15.	Swarfing out machine	S
16.	Tool/job development	S
17.	Waiting crane	W

* S = setting; B = breakdown; W = waiting.

appeared pleased that the investigation was over. However, 18 months later the Company successfully installed a commercial data-logging keypad system.

9.6.2 Installing Monitoring Equipment in Company B

Permission to install the equipment was first given by the senior production engineer for the department concerned. The authors pointed out, in a friendly way, that someone from direct line management should consult with the labour force. This was reluctantly agreed to by the company. Later a message was received that the works manager was in agreement but the shopfloor supervisor was against it. This situation seemed ominous, but we were subsequently invited down to meet the company union convenor and his colleagues, from the shop stewards' committee, to discuss the data collection system.

No management personnel attended the meeting, which lasted for a full two hours. A compromise was eventually reached in which the authors had the full co-operation of the workers provided we did not inform the management of the results obtained.

The installation of data recording equipment then proceeded. Full co-operation was obtained from the operators involved. When approached by the author they were quite willing to fill in the gaps the monitoring computer could not record. The authors were obviously put in a difficult position by this agreement, but the management said they were not particularly interested in our results because it was such a successful manufacturing cell (but how did they really know?).

After a few months the management told us that they were considering purchasing a second machine and asked if the authors would assist in establishing the economic case for a new system. This resulted in a justification being put forward using some of the information thus obtained and adding suggestions for different working practices for the proposed unit. This was incorporated into the feasibility study in such a way as to mask from management the information regarded by us as essential yet confidential by the operators. We used the data to justify an expansion of the production unit, thus creating three new jobs, rather than let the new work be subcontracted out. The plan was approved and the second AMT installation was purchased.

The new system was rated a success and the cash flows generated using new monitoring and control methods created a favourable impression.

9.6.3 Installing Monitoring Equipment in Company C

This installation procedure followed a classic UK industrial relations pattern, with the management playing a leading role throughout. They acknowledged their responsibility from the beginning and after internal discussions at the appropriate level the authors were brought in to be introduced to the workers' representatives and to answer questions. In this study management would have access to all the results and action could follow in the elimination of any particular delays or problems identified. For this project, the monitoring equipment was set up on a machine considered to be a critical bottleneck.

During the data-gathering phase various questions were raised by operators. These concerned the reasons for the data collection and were asked mainly because, as usual, even in better-managed environments, the last line of communication is always the weakest. In all three case studies the success of the monitoring equipment installation manifestly depended upon the credibility that existed at the operators–data collector interface.

With good and trusting relationships it is possible to negotiate and arrange for data collection keypads to be fitted and used for a reasonable time span. The particular problems of operator involvement encountered are discussed in the next section.

9.6.4 Summary

Each firm started the AMT implementation which formed the basis of these case studies from a different position, and this was graphically demonstrated by the negotiation histories outlined above. A quite surprising range of different *modi operandi* was employed for such a small sample, yet each company had similarly expensive AMT installations. It is manifest that the management-to-shopfloor communication links varied considerably between companies. This highlights the problems of feedback of information likely to be encountered when the reverse, but even more problematical, shop-floor-to-management link is considered.

9.7 Audits of Data Collection Systems Analysed

The authors initially started their industrial studies with the traditional top-down analysis of performance of companies using AMT. This method used interviews to ascertain delivery date assessment, stocks, factory targets, schedules, forecasting, the utilization of equipment, and ways and means of company data collection and analysis.

We then came to studying the database of each company, sometimes needing to jump quickly from one information system to another. Occasionally we were fortunate enough to meet a person working between the system interfaces or whose job was to interpret and sometimes update the data using local knowledge. Such encounters would greatly assist our investigations.

All companies concerned allowed us to study their systems in detail. As a first step, an audit of the accuracy of the manufacturing data was carried out. These audits established beyond any doubt that in all cases company information was incomplete. Under these circumstances the only way forward was a bottom-up approach to establish how large these errors in data recording actually were. As the authors had wide experience of industrial production problems we were aware of and thus prepared to tackle (a) the need for negotiations with shop-floor workers, and (b) the need for data collection as events actually happen, i.e. monitoring in real time.

9.8 Data Collection Systems in Use Prior to "Real-Time" Monitoring Exercises

9.8.1 Original Data Collection System for Company A

The data collection system consisted of a specially written software package produced by a local consultant to a specification written by the managing director. As far as AMT is concerned, it consisted of routines that could be used for:

1. Process planning
2. Job cycle time estimation
3. Job card production
4. Scheduling
5. Individual personnel performance reports
6. Accountancy information
7. Sales order processing
8. Purchasing

This very large database required operators to clock on and off each job card when the job was started and finished. Then each week the supervisor examined the pile of completed job cards and decided on the appropriateness of the hours booked. This was a subjective decision based on his knowledge of what actually happened during the week in terms of various delays, tools shortages, program faults etc. The main reason for this close manual examination was to check that the correct identification code (out of a total of 17) had been used to pinpoint problems met during manufacture.

The company clearly did not consider it feasible to trust the operators to indicate the correct code. This manual check resulted in some changes to the allocation of hours for jobs, based upon the performance of shop-floor personnel. These weekly checks took a considerable amount of the supervisor's time. It was considered that any further extension of the scheme would increase this activity by a large factor. In other words, manual verification of codes by the supervisor was a bottleneck activity whose accuracy was yet to be determined.

The corrected job card information was fed back into the database and individual operator reports were produced for analysis by management as shown in Table 9.5. In our audits completed job cards covering a period of 2 months were analysed by the authors, who cross-checked on such factors as the appropriate use of delay codes, the type and number of supervisor corrections, the performance achievement relative to set time, the extent of information available for making adjustments, etc.

Such an audit typically raises more questions than are answered. Every week the job cards showed some inaccuracies. Times were added in ballpoint writing rather than by the use of official printed clock times. Also, a significant proportion of "no-target-time" jobs were released to all operators. However, the most surprising fact was that although 17 codes (Table 9.4) existed for identifying the source of production delays, only 3 were actually used during this period.

The company database required information to be available from the job cards in order to analyse performance in both financial and operational terms. The authors considered this database to be unreliable, to say the least. At this stage it thus became obvious that considerable effort would need to be put into activity sampling in Company A in order to assess the actual performance of the AMT.

9.8.2 Original Data Collection System for Company B

The main difficulties of using top-down methodology in Company B were due to the multiplicity of software systems used, which were controlled by three different packages that did not "talk" to each other. Furthermore, there was a large demand for the product range manufactured by the AMT cell. This resulted in subcontracting outside the company of up to 50% of the demand, with the AMT cell manufacturing the other half. Rationalization of job schedules then followed. As a consequence, large quantities of two or three popular designs were then ordered against appropriate stock numbers. These stock items would later be delivered to particular customers, who normally order only in very low numbers – typically two or three, up to a maximum of 25, compared against the total production output of 500 per week.

Some of the batch sizes of popular products ordered were in the thousands, but to accommodate variations in customer demands and to meet delivery schedules, split batches were the inevitable consequence. Hence chaotic job booking resulted. This led to questionable output bonuses being paid as stock order numbers remained "open" for weeks. In turn, this amplified the problems of scrap, rework and overbooking, causing further distortion of the database. When this information was also disseminated through the

Table 9.5. Example of operator performance report

Weekly Work Sheet *Date: 1511*
Clock no. 525 *Name* *Shift M*

W-Grp M-C	Work code	P-No.	Item ref	Opn no.	Qty bkd	Est-(Sms)		Ex	S-hrs Prod	Elapsed times (hours)		
						Set	Each			Msd	Un-msd	Lost
505	0	254S	1	50	1.6	0	240.0	0	6.4	6.5		
505	0	384T	1	40	36.0	0	5.0	0	3.0	3.4		
505	0	254S	1	50	0.6	0	240.0	0	2.4	2.6		
505	0	254S	1	50	1.1	0	240.0	0	4.4	4.6		
505	0	384T	1	40	90.0	0	5.0	0	7.5	7.5		
505	0	254S	1	50	1.8	0	240.0	0	7.2	7.5		
505	0	254S	1	50	1.3	0	240.0	0	5.2	5.0		
505	6											1.0
505	6											4.5
505	6											0.3

Std hours	Msd hours	Unmsd hours	Lost hours	Ind. hours	Train hours	Clock hours	O/all eff
36.10	37.18	0.00	5.86	0.00	0.00	43.04	83.88
				Total batch qty = 132.4		opp. eff. = 97.10	

three separate software systems as already highlighted, all the classical ingredients for "loss of control" were present.

We noted a further complication regarding material supply which also encouraged large-quantity ordering. The material specification was so unique that it had to be produced for just this one customer. Economic purchase quantities often resulted in many tonnes being bought, even though the monthly usage rate was comparatively low. However, as a consequence, if jobs were apparently wanted then there would always be a ready supply of raw material to fuel the overproduction/overbooking phenomenon.

Some middle managers in Company B claimed to know what was really being produced and where it was located. Our investigations merely established that the requirements for the assembly department were generally fully met, and hence the customers were satisfied. The job booking and database were just a figment of what was really happening. For example, the costing figures often purported to show that it was cheaper to have parts made outside the company than manufactured in-house. Yet these subcontracting competitors did not have such advanced equipment.

The top-down approach to performance monitoring was limited to the identification of these problems. This resulted in management either losing confidence in the AMT installation or being unable to justify any further investment. Again, the need for bottom-up analysis to show what was really happening was apparent. With hindsight, it is now obvious why the negotiations for permission for the authors to monitor the performance of equipment was carried out by such strange means and why the compromise eventually achieved prevented management access to our results. The whole culture of Company B was one of mistrust, vested interest and information manipulation to suit the needs of the particular games player.

9.8.3 Original Data Collection System for Company C

This particular company is part of an international group. Provided they deliver the forecast profits and show regular performance improvement, the group gives autonomous management to the individual companies. The management at Company C has decided that so-called modern methods such as "just-in-time" and the OPT philosophy should be used as part of their improvement campaign. Hence they have definite strategies worked out for stock control, work-in-progress, batch sizes and customer service. The company already had some success in reducing their lead times via the policy of reducing batch sizes, making less for stock, and trying to monitor material movement via work-in-progress. However, the established shop-floor methods of route cards and job cards are still used as the information base for the company to input data into their MRP software. To increase production throughput they have tried the OPT philosophy of identifying bottlenecks and then attempting to exercise shop-floor control through them. However, this has proved to be a frustrating exercise because it appeared from their database that the bottlenecks were wandering month by month. This phenomenon could be considered to be the ultimate goal for balanced capacity. At the same time, it did not reflect the throughput requirements that good capacity balance was supposed to achieve. The only reasonable explanation which offered itself to the authors was the existence of database errors. Again, a top-down analysis established the existence of a credibility gap and this needed to be checked by viewing it from the "other side" of the process, i.e. using bottom-up analysis.

Before the bottom-up performance monitoring system was put into effect, we attempted the customary analysis of job card information. The result was most disappointing, since the job cards were almost unintelligible! It was as if random numbers had been added to the times and it took many questions by the authors to make any sense of individual cards. For example, night shift operators did not book any work at all! The day shift personnel completed the cards depending upon the number of extra jobs which were completed by the morning in question. When they did the booking, and how thoroughly it was done, was hard to determine. However, because the management of Company C knew that their new performance improvement strategies could not work unless their database and feedback of information were reasonably correct, they were happy to be involved in our detailed investigation into the effects of recent changes to shop-floor operations.

A problem inherent in this type of equipment monitoring is that it can appear that "Machine utilization is everything." This is the opposite of the OPT philosophy of only seeking to improve the performance of bottleneck operations. It is our experience that the reasons given for non-use of an expensive production unit always reveal to the enquirer much information about the organization and attitudes of people trying to achieve customer satisfaction!

9.9 Results of Real-Time Data Collection and Analysis

This section deals with the results as we have observed them in each company, and how they compare with expected performance data.

9.9.1 Company A – Results from Historical Records

Here we started with the first important set of data collected by the company over a period of a year and relating to operator performance on their CNC and conventional machines.

Figure 9.2 is a histogram showing the distribution of operator performance for both CNC and conventional machine operation. Classical studies would lead us to expect a normal distribution in each case. However, as one set of machines was operated by a consistent and predictable (but expensive) controller and the other set by a family of different people with different levels of skill, it might be argued that widely varying results might also be expected. The target times used to establish the performance criteria were set mainly by the estimation package and apply to all the machines. From Fig. 9.2 it is clear that the distributions are similar and no bias is evident in favour of the expensive controller machines. This feature applies to both the mean and the spread of performance, which establish the bounds for "good" and "bad" weeks. One conclusion that can be drawn is that if AMT is supposed to be more under management control (i.e. reduced spread) then these results do not support that view. In fact they tend to show the opposite.

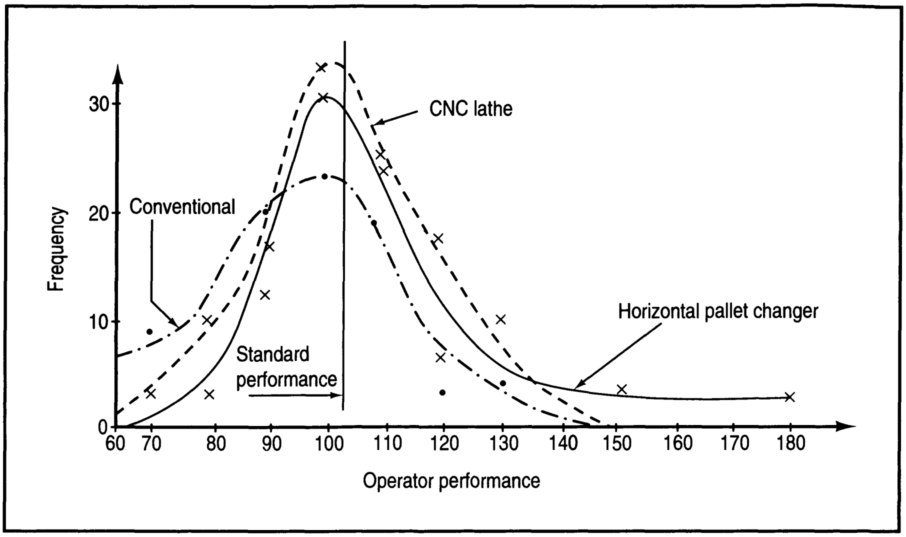


Fig. 9.2. Comparison of operator performances using conventional, CNC and pallet-changing machines.

9.9.2 Observed Results from the Two Machines at Company A

Our results show poor machine utilization brought about by a combination of operational factors and operator techniques. Table 9.6 gives the percentage time the cycle light was recorded "on" for a representative few weeks early on in the learning phase for installation (which commenced operating in week 19). Weeks 37 to 38 characterized a period of frequent breakdowns resulting in reduced working on the pallet-changing machine. The results show that operationally, CNC was only in charge of machining for between 26 and 48% of available time.

Also shown in Table 9.6 are the company performance figures relating to operator achievement for the various shifts for reference purposes. To give some idea of the cycle times involved, typical floor-to-floor times (in minutes) are also quoted. These poor performance indicators caused the

Table 9.6. Comparison of light-on cycle monitoring vs. official labour company performance

Week no.	Total hours	Light on utilization	Company 1st shift	Performance 2nd shift	3rd shift	Floor-to-Floor time (min)
31	124	47%	76%	78%	—	220
32	120	46%	98%	102%	—	40
33	111	45%	76%	84%	—	17 and 45
34	88	26%*	90%	115%	—	600 and 45
35	115	45%	70%	83%	84%	45 and 8
36	118	44%	101%	114%	110%	70 and 30
37	52	48%*	89%	80%	87%	50 and 15
38	59	29%	135%	—	—	120

* Lost time due to breakdowns.

authors to analyse the distribution of machine control activity, which clearly varied with circumstances. It was important that answers were found to such fundamental questions as: “For how long does the machine controller take over and how frequently?”, “What is the incidence of delays?” and “How long do these delays last?”

In pursuit of further insight on these questions, a typical printout is given in Table 9.7 of cycle times, ranges and frequencies for both up and down times in minutes. If a day’s results did not add up to 1440 minutes this gave a measure of the errors in the system. These were rarely over 2% and did not materially affect our conclusions.

The results are summarized for a 3-week sample in Fig. 9.3. Frequency analysis of this data confirmed what had been observed to happen in practice during our regular shop-floor visits, namely that constant interruption to the control cycle was carried out by the operators involved. Literally hundreds of times a week the “cycle on” button was pressed after an adjustment or check was made; then the machine would work for a matter of only one or two minutes before another interruption occurred. Breaks were often of short duration but always totalled enough to bring the controller utilization below 50% of the time available.

When this information is compared with the operator performance data in Table 9.6 it is apparent that no real AMT operation existed in Company A.

Here we mean that the AMT machine was being used as a conventional machine and the operator’s training was inappropriate to handle the new technology properly. Only occasionally was it demonstrated that the new equipment was used in a manner consistent with the original aims of the

Table 9.7. Company A – Analysis of up- and downtimes
Distribution of cycle time and downtime

Cycle times		
Total cycle time $[T\leq 1]$	= 81.38	No. of cycles = 171
Total cycle time $[1<T\leq 3]$	= 111.5	No. of cycles = 57
Total cycle time $[3<T\leq 6]$	= 31.05	No. of cycles = 7
Total cycle time $[6<T\leq 12]$	= 30.65	No. of cycles = 4
Total cycle time $[12<T\leq 24]$	= 0	No. of cycles = 0
Total cycle time $[24<T\leq 48]$	= 0	No. of cycles = 0
Total cycle time $[T> 48]$	= 0	No. of cycles = 0
Downtimes		
Total down time $[T< 1]$	= 38.73	No. of delays = 75
Total down time $[1<T\leq 3]$	= 64.13	No. of delays = 35
Total down time $[3<T\leq 6]$	= 80.52	No. of delays = 19
Total down time $[6<T\leq 12]$	= 140.45	No. of delays = 16
Total down time $[12<T\leq 24]$	= 90.10	No. of delays = 5
Total down time $[[24<T\leq 48]$	= 147.92	No. of delays = 5
Total down time $[T> 48]$	= 596.83	No. of delays = 3
Total cycle time for the day	= 254.58	
Total downtime for the day	= 1158.67	
% utilization	= 18.014 03	

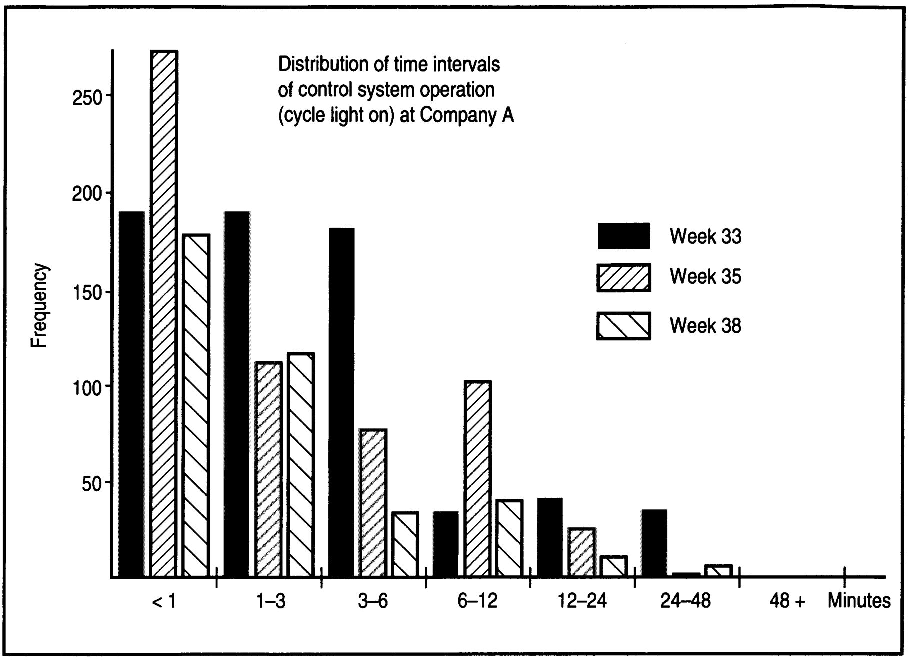


Fig. 9.3. 3-week sample of cycle "light on" time distributions.

AMT vendor. Thus the "time on" statistics demonstrate a paradox: "Who is the controller, man or machine?" Unless the CNC computer is switched on to drive the machine, the answer is the man!

Further sensors wired up to the second of the two pallets showed it was used only occasionally and then for particular jobs. Normally the one pallet was left in position under the main spindle and each successive job was loaded and unloaded while the machine waited for the cycle button to be pressed.

In theory, once set up the pallet change should run for several hours without interruption with the "cycle light on". Several successful installations we observed achieved 3 hours of continuous running as a matter of course. All deviations from this ideal are the proper concern of operational management.

9.9.3 Observed Results from Company B

Historically this was the first company in which we were able to undertake detailed monitoring. We were involved with a cell comprising a number of standard conventional machines, drill, mill etc., and a vertical machining centre. The conventional machines prepared or finished the components produced in large batches on the AMT equipment. One operator has control of the cell and two shifts (day and night) were worked. Utilization of the CNC machine, the bottleneck process of the cell, was poor and the reasons for this, when investigated, revealed a range of problems which included:

1. Machine interference
2. Operator absence
3. Tooling management shortfalls
4. Equipment reliability, particularly the swarf conveyor
5. Operational differences between shifts
6. Influences of an "incentive" scheme
7. Unscheduled changes resulting in extra setting allowances
8. Batch sizes ordered
9. Billet preparation

Examples of poor operating practice were detected via variations in times between the machine stopping and starting. These times represent unload and load elements, which should have been consistent (i.e. balanced) because the main objective of operational planning was to keep the machine busy. Sometimes the machine override controls were used to reduce cycle times in order to produce an extra component prior to a social break. The tendency to work at increased pace in order to take longer rests has always been a characteristic of operator-controlled manufacture, particularly for night shifts. Table 9.8 quotes typical utilization data for "cycle light on", "load/unload" and "idle time", which demonstrate the potential improvement possible if the operational management function was better organized and planned.

The results and shortfalls in planning thus shown up were considered acceptable by the management in the light of prevailing conditions on the shop-floor. No immediate changes in working practices were therefore contemplated. However, a large amount of production was subcontracted and a genuine management commitment existed to establish a switch to in-house manufacture providing this would effect reasonable savings. Because a duplication of what had been tried in the past was not favoured, a new approach was now called for.

Using the information obtained made it reasonably straightforward to re-engineer a specification for a different machining centre. This would have a better operationally organized operator controlling it so as to effect large savings mainly from higher utilizations and more regular activity. The second-generation AMT machine chosen was to be a two-pallet-loading, horizontal machine compared with the manually loaded vertical predecessor. The new swarf removal system was better designed and, with a better tool

Table 9.8. Company B – Example of time taken by load/unload operations
Summary Results for disc no. 01 Day = Tue

Total number of CNC OPS = 18
Total number of load OPS = 19
Total operating time = 5.66 h
CNC machining time = 4.18 h 73%
Loading machining time = 0.55 h 9%
Total lost time = 0.91 h 16%
Loading time as % of machining time = 13%

control system to be used, any *utilization figure higher than 70%* was predicted to give less than 3 years' payback of the investment. As with the first system installed, two shifts would be used.

Finally, the best long-term benefit of all was that the company now realized the value of constant performance monitoring and wanted to record everything from the very beginning of operations. The results for the first few weeks are shown in Fig. 9.1. The learning period in which changes in the working pattern were made is clearly indicated.

Early on, overmanning was deliberately used to familiarize workers with the system. There would then be enough operators available to take over when absenteeism would otherwise affect production. Normal tea breaks and lunch hours were taken, but these eventually have become unmanned work periods now that the reliability and quality of production is established. Labour efficiencies relative to machine-on time after week 38 quickly approached and exceeded 100%. These improvements were achieved by correct use of the pallet loading facility giving extra hours of production every working day. Time saved came from the machine running during tea breaks, lunch hours and the time between the two shifts, making a grand total of between 5 and 6 hours' extra unmanned output, depending upon the cycle times of the components being produced.

Not surprisingly, with the new AMT system being more reliable, closely monitored, and exhibiting new working methods, system utilizations of over 85% were obtained and many hundreds of pounds were saved each week compared with the original subcontract production.

The company are naturally very pleased with these results and plan further investments along the same lines. Most of our recommendations resulting from the initial investigation have been carried out on the new system with varying amounts of commitment but some still await a fair trial. Utilization and throughput are the main company requirements in the production of a high value-added component.

In conclusion, it is reasonable to state that if the same insight, commitment and awareness had gone into the first Company B installation it would have been a better producer of economic parts. However, once a pattern of work has become firmly established it was extremely difficult to change especially where pay and working conditions are not competitive enough to produce commitment from the workforce.

Note: During the period of investigation on the first system one of the two operators left to do a similar job elsewhere for extra pay of over £80 per week! No skilled replacement was immediately available internally, so production was lost for a few weeks until a training programme was completed.

9.9.4 Observed Results from Company C

This was the last of the three systems that were monitored by the authors via computerized data collection. From this study the main categories of lost time were:

1. Setting allowance/time taken
2. Tool adjustments/design problems

3. Operator differences
4. Size of batches
5. Non-use of pallet facility
6. Unidentified idle periods

The main results are shown in Fig. 9.4 and Fig. 9.5 for both day and night shifts over a period of a month. These were typical of results obtained during many months of monitoring. They clearly show the differences between operators. For example, the night shift operator used the control system but the day shift operator was very "quality conscious". He would not let the machine run without regular checking to certify that production was to specification. The fact that he rarely found trouble did not stop him looking for it. This action was justified when he did occasionally find a problem.

Setting time activity at around 20% was similar for both shifts, but the idle time difference is significant. Some idea of what occurred during this time was obtained from observation and questioning operators to identify every reason for such "idleness". Personal contact revealed that the main causes of this source of lost time were:

1. Realignment of boring bars
2. Setting of cutting tools
3. Loading and unloading of components with machine idle instead of concurrent use of the pallet facility

The activities recorded by the keypad were:

Key 0 Normal operation
Key 1 Setting
Key 2 Breakdown of equipment
Key 3 Swarf removal
Key 4 Rectification work
Key 5 CNC program proveout
Key 6 Shift completed
Key 7 Tooling problems

Two of these keys, 0 and 1, could of course be checked against the monitoring from the control panel which was continuing to function. This formed a double check on accuracy.

The results obtained from this analysis were found to be variable. Excuses given by the operators centred around forgetting to press the right key or thinking the delay would be too short to make the operation of the key worthwhile. When it became obvious that the delay would be a long one it was sometimes considered too late to press the right button! Sometimes the system worked well, but overall the pattern was not reliable enough to give definitive results during the first 3 months of operation. Table 9.9 shows the layout of the results of the keypad and it will be noticed that the actual results are given above the results from the keypad. Note that the machine was operational for 85 715 seconds, but according to the keypad was working for 92 707 seconds, a discrepancy of 5736 seconds or a relative

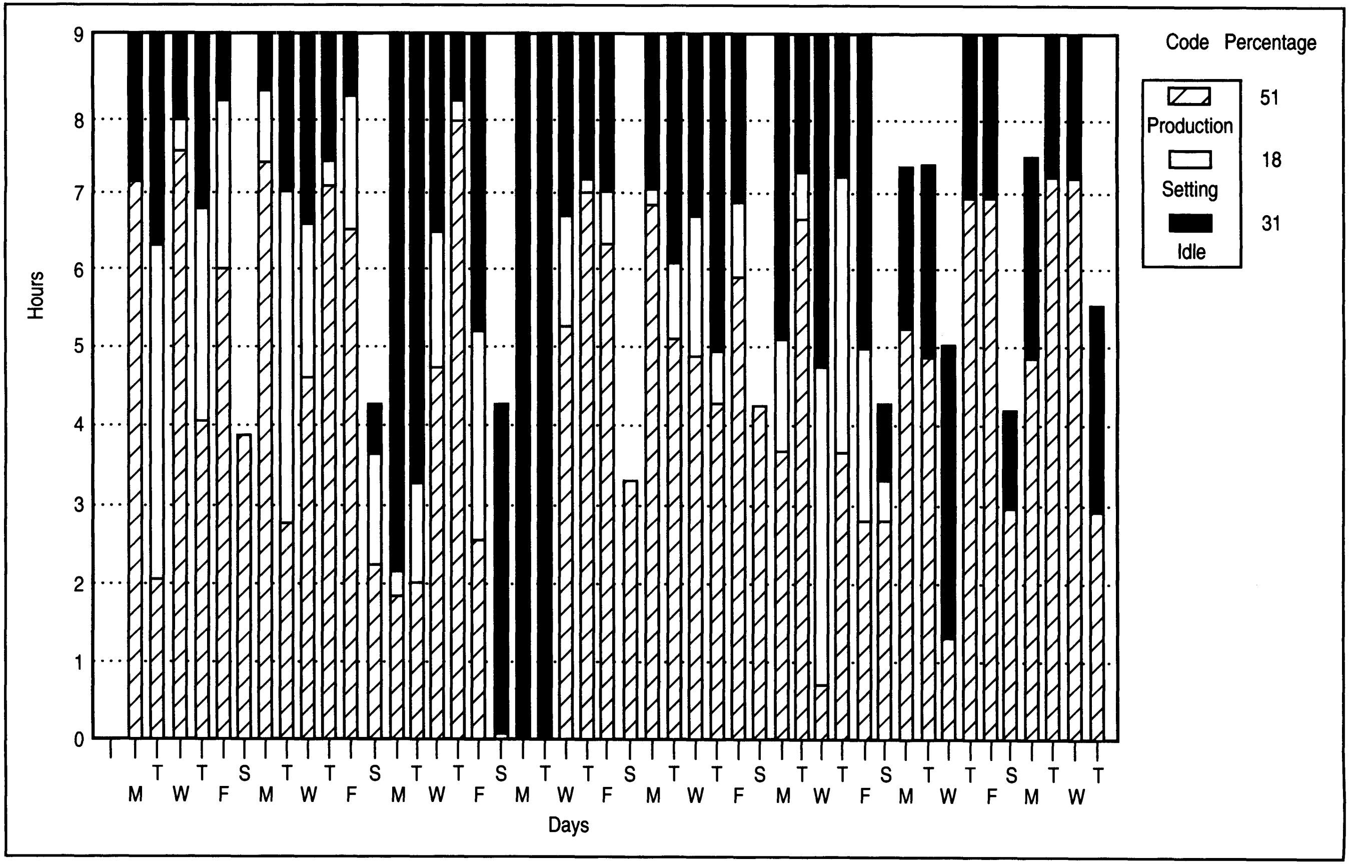


Fig. 9.4. Day shift analysis: total utilization.

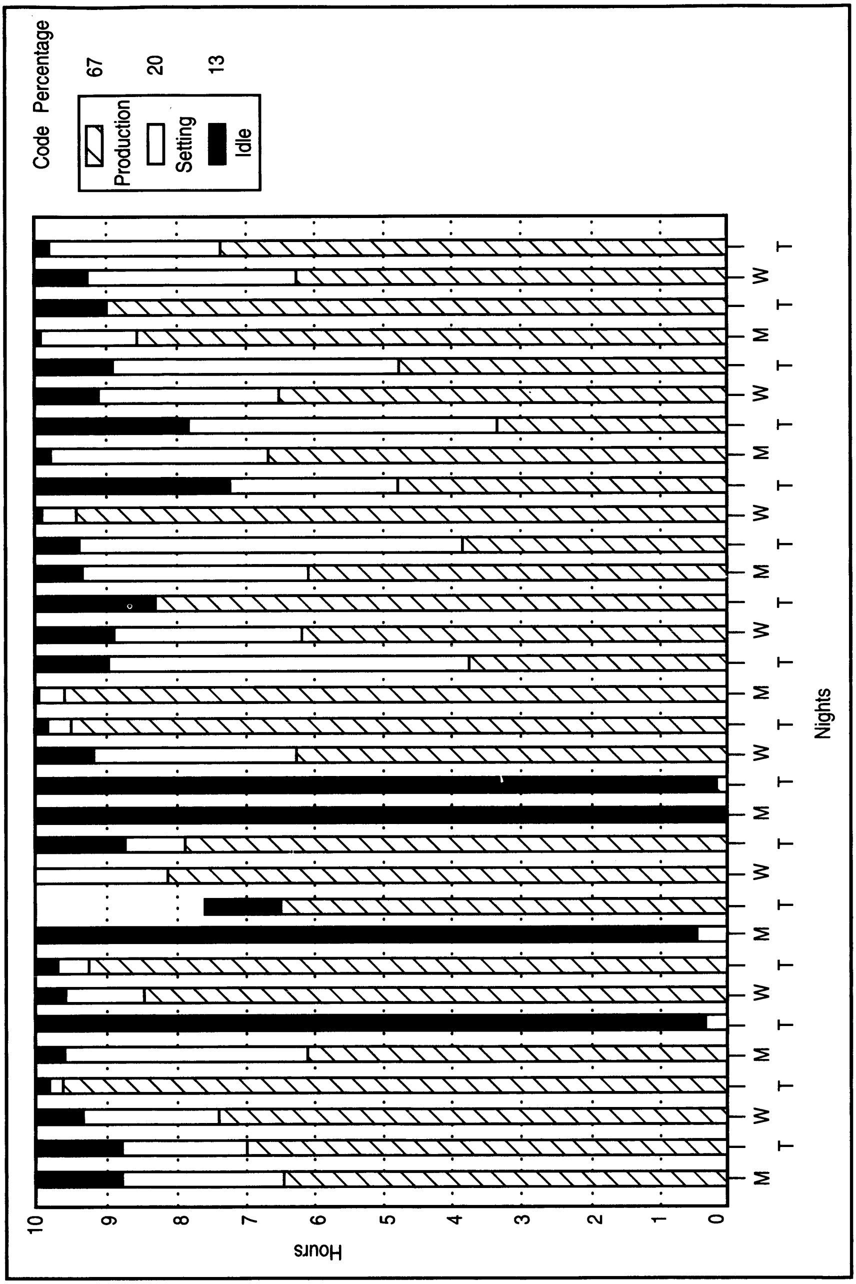


Fig. 9.5. Night shift analysis: total utilization.

Table 9.9. Incorrect keypad recording

```
Analysis of time period 21:00:00–07:00:00 from 03–13–1989 to 03–17–1989.
Length of time period scanned: 3 d 10 h 0 min 0 s (295200 s) – 3113 Events logged
Time accounted for 144000 s
Running: 85715 s  Setting: 19304 s  Idle: 38981 s

Total time cycle ON:        86971 s (60% of total time)
Total time cycle OFF:       57029 s (39% of total time)
--------------------------------------------------------------------------
Key 0:   92707 s  Normal OK       64%     ::::::::::::::::::::::::::::::::
Key 1:   16372 s  Setting         11%     :::::
Key 2:   34921 s  Breakdown       24%     ::::::::::::
Key 3:       0 s  Swarf/oil        0%
Key 4:       0 s  Rectification    0%
Key 5:       0 s  NC program       0%
Key 6:       0 s  Shift over       0%
Key 7:       0 s  Tooling          0%

                                          ..........................
                                                Percentage of time ——>

CYCLE ON    – keypad runtime:     5736 s (Keypad runtime = 72 707 s)
CYCLE OFF   – keypad downtime:    (Keypad downtime = 51 293 s)
--------------------------------------------------------------------------
```

error of 7% compared with less than 0.2% for Table 9.3, a more typical result. Also, the setting activity was measured as 19304 seconds according to our definition, but the keypad shows that the operator recorded that setting as occupying 16372 seconds, an error of 15%. For reasons mentioned previously, this operator chose not to use the delay keys regularly on this machine and so it was difficult to analyse productivity losses fully.

Hence basic operational control decisions needed full clarification before these tests became meaningful. Thus we had a real chicken-or-egg situation, highlighting the conditions of communication at shop-floor level.

The regular change of state from system control to operator control and back was of prime concern. To justify complexity an expensive control system should be operational for regular long periods. Table 9.10 gives typical results of the frequency of time intervals recorded before a change was made. Rarely does the control take over for longer than an hour, and the most frequent time periods are for a few seconds (1–20) or for about a 5-minute period (300 s). This was on long machining cycle times for large food mixer casings. The components were in small batches to keep the expense of work-in-progress down.

The "off" pattern is similar to the pattern for "on", leading us to the conclusion that 50% utilization in a random, short-cycle, scattered pattern is the normal performance. It is the conscious and continual abandoning of this operational style that is the key to future success by the company.

9.10 Summary of Results

It is clear that "normal" operation of AMT installations is flawed by old habits or lack of attention to new methods of operation. The operators are filling the void left by management by using their own past experiences.

Table 9.10. Company C – time intervals between events

Time breakdown of period:
03–13–1989 21:00:00 to 03–14–1989 07:00:00
Length of time period scanned: 0 d 10 h 0 min 0 s [36 000s] – 3113 events logged

Range(s)	Events	Seconds	Av. time	Longest	Shortest
Ontime					
1. 1–20 s	29	330	11	19	1
2. 21–120 s	14	922	65	107	27
3. 121–300 s	2	475	237	256	219
4. 301–720 s	29	18564	640	675	348
5. 721–3600 s	2	2245	1122	1289	856
6. 3601–7200 s	0	0	0	0	0
7. 7201–10800 s	0	0	0	0	0
Totals:	76	22536	296		
Offtime					
1. 1–20 s	27	255	9	20	1
2. 21–120 s	14	880	62	99	32
3. 121–300 s	26	4 710	181	284	141
4. 301–720 s	9	4 248	472	675	302
5. 721–3 600 s	3	3 371	1 123	1 518	752
6. 361–7 200 s	0	0	0	0	0
7. 7 201–10 800 s	0	0	0	0	0
Totals:	76	13 464	170		

Only when management takes the lead and monitors operations to show interest and commitment, and then makes changes to ensure targets are achieved, will performances improve to economic levels that can justify the capital expenditure of the AMT.

The culture of the management–worker interface needs to change, but a major stumbling block is the paradox that exists: is the aim of management to eliminate waste or to identify it? The authors were confronted on occasions by strict management policy of "no delays tolerated", which immediately inhibits the reporting of delays which still exist. In contrast, our policy was to identify all delays no matter how short, so that corrective action could be organized to eliminate the cause of the problems or at least reduce them. However, this conflicting paradox in ideology is not unresolvable, as the study of Company B demonstrates. The solution lies in demonstrating to everyone involved the benefit of measuring true performance.

By its very nature, machining centre operator training at vendor companies always leaves the detail of operational control required by a particular company to be organized by the AMT customer. The manufacturing system must therefore be established by the company employing operators and operational conditions that deliver the goods on time to the company's customers with both quality and price standards met.

9.11 Management Attitude to the Results Obtained

As already explained, Company B did take account of our findings and achieved an excellent result when investing further in AMT. However, the other two companies showed disappointing attitudes to our reports.

Company A considered the information reinforced its good results when really it did not. When persuaded to find out more facts on performance it failed to do so because of succumbing to shop floor-pressures, which were against doing anything at all. Company A were glad when we removed our equipment and left. Management did not want delays to exist; they gave instructions to this end, so supervisors ensured they were never booked even when they occurred in profusion. They wanted their own system that showed no delays in preference to the availability of a reliable performance monitoring scheme that highlighted the problem but was not permitted to take the next logical step to itemize it into constituent parts.

Company C would like to change the conditions but are faced with a problem of operators' attitudes and a pay scheme that makes replacement difficult. They take on only untrained people and develop them using vendors' programmes etc. to produce effective operators. This has had mixed success. It is a gamble to use untried, non-engineering personnel. They decided to direct all their managerial efforts to effecting cashflow, stock reduction and work-in-progress improvements. The utilization of key machines was ignored, with the overall result that there was indeed some initial saving on stocks and work-in-progress. However, 6 months later bottlenecks in the machine shop were holding back any further improvement.

When will companies learn to save money by understanding the need to relate material flow to operational control of AMT? It should only be a matter of time to achieve this goal if the correct operational plans are drawn up in the first place.

The pitfalls encountered when implementing these shop-floor data collection (SFDC) systems may be translated into operational planning traps in a manner similar to that listed as corporate planning traps in Chapter 1. Some of the pitfalls we have found are listed in Table 9.11 on p.174. It is important, however, to mention that all three companies have made improvements to their systems as a result of these investigations, even if some of our reports sound primitive.

In our opinion the effort involved in implementing on-line monitoring systems to investigate the startup and steady-state performance of expensive AMT is always justified. To some readers the situations described in this chapter may appear to be unreal, but many users will recognize the truth and identify with the problems we have described. We have manifestly found considerable variation in AMT performance but unfortunately have yet to find a trouble-free installation.

Table 9.11. Pitfalls in operational planning during AMT startup

1. *Failure to properly translate corporate objectives into effective operational decisions* by ensuring AMT capability matches market requirements.
2. *Failure of the planning function to identify and evaluate existing bad operating practices.* Instead, it is too often limited to technological planning, and does not evaluate the impact of these practices on the productivity gains expected following installation of AMT.
3. *Compounding of 2 by failure to recognize the effects on production caused by rigid, incomplete, technological planning.*
4. *Failure to provide an adequate range of tooling support necessary to cope with variable order quantities.* This is due to not undertaking the proper cost–benefit tradeoff analysis.
5. *Failure to obtain the necessary involvement in the planning process of supervisory management and operatives as the first step of establishing the "ownership" of the AMT,* particularly overlooking gains in downtime and quality performance possible by early discussions with shop-floor personnel.
6. *Failure to include supervisory and maintenance personnel in a comprehensive AMT training programme* which covers both operational and maintenance aspects.
7. *Failure to establish computerized and manual communication links* between existing and new systems to permit reliable data exchange.
8. *Failure to set up a regular cause-and-effect reporting system* which encourages corrective action to be taken at shop-floor level without resorting to the apportionment of blame.
9. *Failure to fully analyse effects of AMT on downstream and upstream activities.*
10. *Failure to analyse sources of productivity losses.* The degree of criticality relating these losses to corporate objectives should be assessed by the frequency and magnitude of delays and consequential interruptions in material flow and ultimately customer satisfaction.

10 Organizational Problems in the Introduction of AMT into the Large Firm

E. Schott and M.M. Naim

10.1 Introduction

The following study provides a detailed description of the non-technical, organizational factors affecting a £3.2m AMT project. The host organization is defined primarily in terms of its structure and culture before and after the AMT project. Prevalent attitudes among those in a position to influence AMT implementation and its operation are also revealed in transcribed excerpts of tape-recorded interviews.

10.2 The Methodology

In order to identify relevant organizational factors affecting the AMT implementation process representatives of all groups involved in the AMT project were interviewed on site and were asked (a) to identify what they considered to be significant events and milestones in the process and (b) to identify the promoters or prime movers of change and the motive (personal or corporate) for change. Participants were also asked to assess the impact of what Dr J. Parnaby of Lucas Industries calls "significant emotional events" (SEEs) and to indicate their impact by assigning each event a value on a simple plus or minus scale of 1 to 3.

Individual responses to these questions provided an indication of the company's culture, i.e. the norms operating in the company, communicated formally through briefings, annual reports and press reports and informally in the company's operating practices as reflected in individual and communal practice and individual and communal experience communicated by action, by convention and by "word of mouth".

Specific practices, anecdotal evidence and observations volunteered in tape-recorded interviews illustrate prevailing attitudes and motives operating in this specific company prior to the introduction of a £3.2m flexible manufacturing system (FMS) and identified the champions, influences and prime-movers of events and provided motives. The subjective rating of the importance of significant events by everyone concerned with the FMS/AMT project also helped to identify problem areas in the project and post-implementation phase and a consensus of opinion on the successes and failures of the FMS/AMT project.

A systems approach [1] to the case study sets this particular FMS/AMT project in the wider context, as shown in Fig. 10.1.

A top-down approach was adopted in order to identify the major business issues affecting the decision to invest in AMT, the financial implications of the proposed investment and the strategic importance of the project. A bottom-up approach was then adopted to obtain the views of the operators and managers of the new technology on the shop-floor. Middle management,

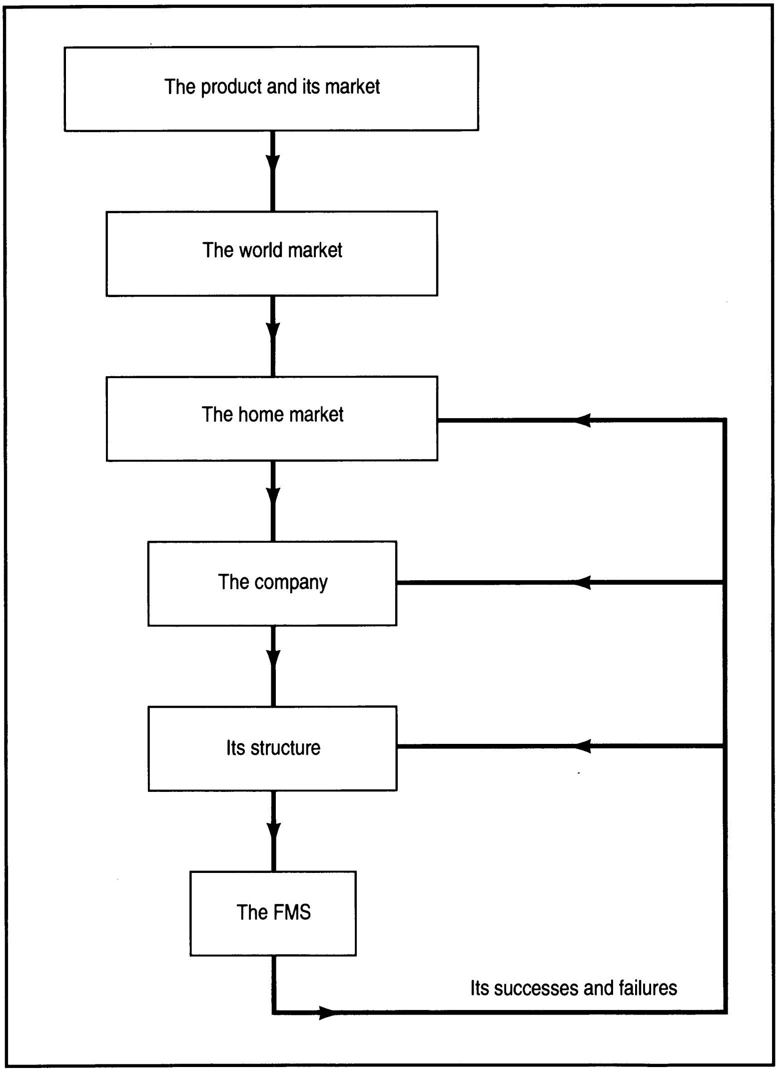


Fig. 10.1. Hierarchy of systems associated with the wider system of which an individual plant forms part.

the union and the vendors helped to provide a balanced view of the AMT process and a "systems perspective".

At every level in the host company participants in the AMT project were asked the how, when and why of the non-technical aspects of the project. With the agreement of the participants, tape-recorded interviews based on a list of open-ended questions were carried out. The agenda was handed to the participant, who proceeded to answer the questions in the order and the manner that was most comfortable. There was no hidden agenda and the questions were sufficiently open-ended to ensure that information on a specific topic was prompted but that significant events were determined by the interviewee, not the interviewer. It was found that such open-ended questions allowed a variety of interpretations and a degree of spontaneity, while supplementary explanations and/or questions needed to be asked only for clarification.

The following questions illustrate how one open-ended question provides information on several related aspects of organizational change:

"*Describe the changes in 'who does what' as a result of the introduction of the FMS.*"

The answers to this question helped to provide a description of:

1. Changes in work practices, duties and responsibilities as a result of the introduction of the FMS/AMT
2. Associated changes in the structure of the organization, increases and/or decreases in the span of control of those operating and managing the FMS and associated changes in the reporting structure of the organization
3. The control system operating in the organization, i.e. the degree of centralization and/or decentralization pre- and post- FMS
4. The manufacturing philosophy of the company pre- and post-AMT

"*Who will do what in the future?*"
Individuals' answers to the question not only helped indicate the host company's plans for the future but also indicate whether the company chooses to disseminate this information.

"*Who did what and why?*"
Answers to this question provided the SEEs, the milestones and the movers. Participants described what they perceived to be significant events in the implementation of AMT in the host company. If an explanation of the term "event" was requested by participants it was interpreted as "what happened next". This approach encouraged participants to relate events sequentially, providing the timing and the sequence of events.

"*Who did what and why*?" also identified "the prime-movers", "the interested parties" and "the influencers" of events and accredited and speculative motives, which in turn indicated the *modus operandi* or the culture of the company, some of the prevailing norms and conventions operating in the company and the attributes and attitudes of the prime movers or influencers in the company.

The impact of events
Participants in the AMT implementation process were asked to indicate the

impact of related events, using a subjective rating on a simple plus or minus 1 to 3 scale. As participants were representatives of a number of all groups involved in the AMT project, from board level to shop-floor, and from inside and outside the company, the impact of events affecting the project was gauged. The focus of the questions previously asked was non-technical, therefore the major factors that emerged were designated organizational. Organizational factors were therefore identified by those questions directly affected by the implementation process and their effect or contribution to the implementation process was then assessed.

Those interviewed were:

Representatives of the four teams operating the FMS
A shift manager from each team
A setter inspector from each team
A loader from each team
One of two AMT dedicated maintenance technicians
The shop-floor union convenor
The American vendors and their British distributors
The quality assurance manager in the host company
The AMT manager in the host company
The manager of the machine shop housing the AMT
The executive director of production

The following are examples of agenda targeted to elicit the type of information outlined in points above, together with expected returns.

1. *Agenda given to the executive director of production and the AMT manager at the host company*
   (a) The market position of the company when the AMT project was proposed. (This is to ascertain the company's market position, its major competitors, its strategic objectives and an indication of the company's manufacturing philosophy, placing the AMT in the wider context.)
   (b) The strategic objectives of this particular AMT project. (This is to provide further indications of the company culture, its manufacturing philosophy and the identification of prime movers.)
   (c) The structure of the organization before the AMT project. (The structure of the company reflects a combination of the culture and structure of the company and the interests of influencers in positions of authority.)
   (d) The AMT project – prime-movers, subsequent events, milestones and dates. (Who did what, when and why?)
   (e) The impact of events. (This is a subjective assessment.)
   (f) The successes and failures of the project.

2. *Agenda for AMT managers and operators*
   (a) Job title versus duties pre- and post-AMT. (Who does what versus who did what and who is likely to do what in future.)

(b) First knowledge of recruitment for the AMT project. (Who did what and why?)
(c) Rationale of recruitment process. (This indicates the company's and the individual's reason for volunteering.) (Who did what and why?)
(d) Milestones in the recruitment process (i.e. champions, influencers, prime-movers, vested interests *and* events). (Who did what, why and when?)
(e) The impact of significant events. (This means identifying significant events and placing a positive or negative value on them on a 1 to 3 scale.)
(f) Desired refinements/improvements in the AMT system and AMT operation. (What should be done, by whom and why.)

The results of these interviews, supported by literature provided by the host company and the vendors of the AMT (including the progress reports of the AMT project managers), provide a detailed case study of the non-technical factors/organizational factors affecting AMT implementation and its steady-state operation.

10.3 The Case Study

The Company History

The company was founded in the 1930s. Its founder and owner was the major employer in the county in which the company is sited and has employed generations of local men and women. Under his influence the culture of the company was both entrepreneurial and mechanistic. The founder was paternalistic in his attitude toward his employees, the organization was monolithic in that it was a "tall" organization [2] characterized by many layers of hierarchy and narrow spans of control, and the work force and production system were functionally specialized; each area of production was under the control of a manager responsible for the efficient manufacturing, quality control, supplies, etc., employees were closely supervised by managers and supervisors and the work force had highly specified duties which reflected their precise function in the production process.

The company was successful and continued to expand throughout the 1940s, '50s, '60s and '70s and diversified its interests. As a result, the subject company became a wholly owned subsidiary of a group bearing the founder's name.

However, throughout this period the founder's influence continued, ensuring that the organizational structure of the subject company remained intact, and essentially centrally controlled, with power emanating from himself in the centre, until his death in 1976.

10.4 The Competitive 1980s

The following "significant emotional events" [3] or SEEs affecting the company in the early 1980s were identified by staff at various levels in the host company during tape-recorded interviews:

Company-wide reorganization to become more competitive
Worldwide competition
Increased customer awareness
Reduced investment in capital equipment

In 1979 the company was split into five divisions representing the company's five separate product ranges as shown in Fig. 10.2. Each division had its own board of directors reporting to the group's board of directors at head office.

Because the host company supplies capital equipment for the mining industry, it was adversely affected by the demise of the industry following a worldwide economic recession in the early 1980s and the use of alternative fuels (namely oil, natural gas and nuclear fuels) following the Miners' Strike of 1984.

The company has worldwide interests; the world market contracted and became more competitive. Long-term customers, aware of the increasing competition, demanded more from their suppliers, namely shorter lead times, more customization and more design changes later, i.e. nearer to the point of production, and longer warranties with more clauses for allowing for rework at no additional cost. The nature of the work also changed, as more customers wanted refurbishment of existing equipment because they could not afford to replace the expensive items of capital equipment manufactured by the subject company.

10.5 The Response to Market Forces

The following events were identified as SEEs, affecting the introduction of the new FMS/AMT facility by personnel in the host company. The company launched a number of local and group-directed initiatives to retain their market share in the 1980s.

1. At a local level the subject company tried in 1981 to establish quality circles or work-improvement groups, where shop-floor staff were encouraged to meet regularly to suggest improvements to the production system. The venture failed to improve the contribution of the work force and/or raise quality consciousness, because the work force saw this venture as a means by which the company "got something for nothing".
2. In 1983 each of the five divisions of the group, including the subject company, became five separate cost centres or strategic business centres (SBCs).

   A strategic business centre is defined by Glueck and Jauch [4] as "an operating division of a firm which serves a distinct product or market segment or a well-defined set of customers or geographical area . . . given the authority to make its own strategic decisions within corporate guidelines provided they meet corporate objectives".

   As an SBC the subject company was allocated funding according to need. The profits from all five divisions were pooled and expenditure on capital equipment had to be justified and agreed by the board at head office.

3. At the local level the subject company was reorganized along product lines to be more customer-orientated, i.e. instead of producing a quantity of parts, later assembled for an unidentified customer, orders were identified as a finished product for completion and delivery by a certain date for a known and valued customer (see Fig. 10.3).

   However, despite a declared intention of reorganization of the production process along finished-product lines, a hybrid, part-functional, part-product structure emerged as a result (in the participants' opinion) of a lack of commitment on the part of senior managers and reluctance on the part of certain managers to lose functions previously under their control. (*Note*: A product unit such as the valve group in the subject company should in theory [2] have been self-contained, i.e. the product manager should have had direct control of support services necessary for the production of a particular product range, his own research, finance sales, planning and scheduling staff and so on. In this case, the valve group (which was the section of the shop-floor which would house the new FMS/AMT facility in 1984–6) had its own purchasing and planning services with the rest of the site.)

4. A group-directed quality assurance initiative was launched in the early 1980s and Part 1 of the prestigious BS 5750 was awarded to the company as a British Coal supplier.

   In 1980 the Quality Control Department employed 274 people and in 1988 the renamed Quality Assurance Department consisted of 64 people.

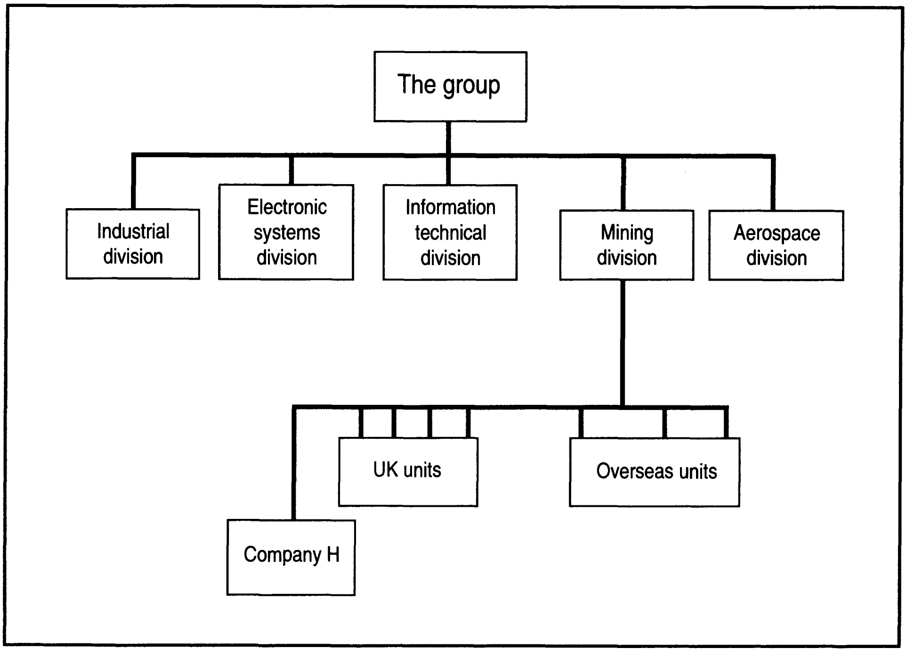


Fig. 10.2. A corporate overview of Company H.

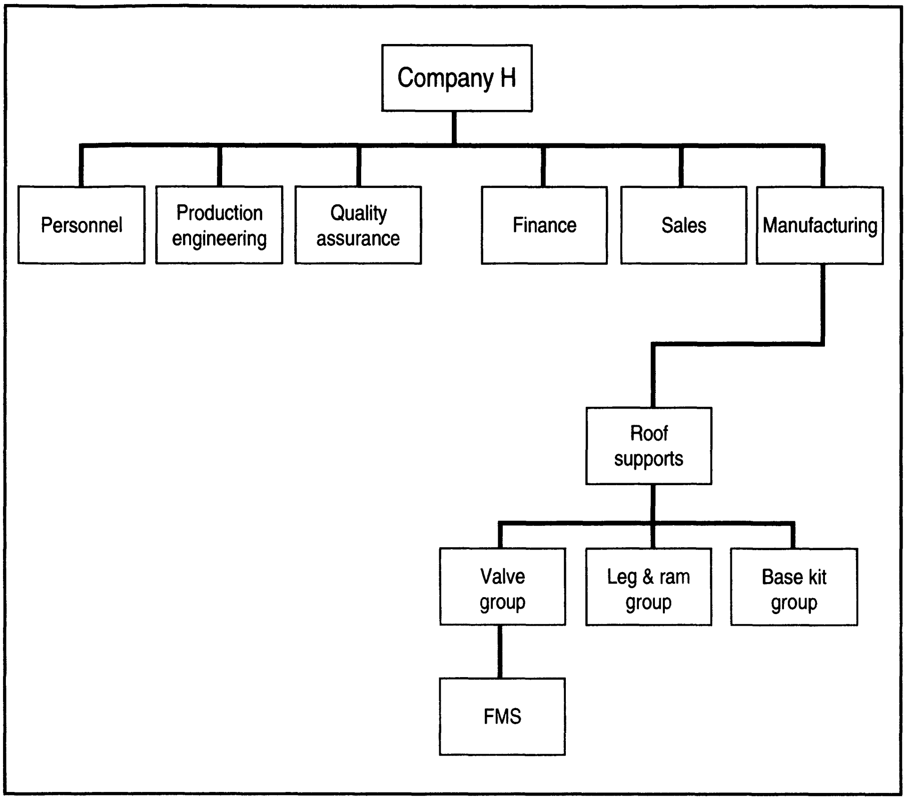


Fig. 10.3. Organizational structure of Company H.

A customer–supplier relationship now exists between departments throughout the company (according to the quality assurance manager), as a result of a drive to improve the quality of products produced by the company and a "right first time approach" to production which helps production managers keep to production schedules and which in turn improves the company's delivery date performance.

A further top-down company-wide quality initiative was launched in November 1988 which involved all the directors in the company attending a three-day course on quality assurance objectives. In 1988 the quality assurance manager anticipated that as a result of collective responsibility for quality replacing the "policing" of the quality assurance department his department would be reduced to approximately 20 staff and there would be no management team and no supervisors responsible solely for quality, but so far these changes have not yet been implemented.

5. *Sales initiatives*: in the mid-1980s the company launched a new product, a compact valve and jet flush filter, and the sales force managed to sell the company's existing products in new markets. Hydraulic kits for local fabrication were sold in Eastern Europe and to owners of private opencast mines.

6. The application of new technology, i.e. the introduction of AMT, in the form of a "full-blown" FMS, is an adjunct to all of the above initiatives (although the FMS was not the company's only experience of new technology) because it assisted the implementation of all the above initiatives and is the focus of the case study.

10.6 The Organizational Effects of Introducing New Technology

In 1982 the company placed an order for a "full-blown" £3.2m FMS, one of only 52 FMSs planned or operational in 1987 [5].

AMT in the form of an FMS replaced 36 existing "conventional" machine tools (some CNC machines and some NC machines) [6], allowed the company to manufacture its new products more easily and improved sales because the company could now offer a more reliable product and service as a result of the improved quality of parts, the increased speed of production and the scheduling and manufacturing flexibility of the FMS.

The improvements in manufacturing ability as a result of introducing the FMS in the subject company are well documented [7, 8]; this case study concerns the organizational effects of introducing AMT and describes the accompanying physical, structural and cultural changes in the host company.

The FMS project was and is seen as a catalyst of change within the company and the most significant of the various initiatives launched by the company to increase competitiveness in the 1980s. The AMT project involved a larger budget than any of the other initiatives quoted; it is also a showpiece for the company and heralded a significant change of direction for the company as an AMT user and an opportunity to change the culture of the workshop. The FMS was promoted as a major means of gaining competitive advantage and it was also the means of introducing flexible work practices.

The "business reason" given to the board and to the work force for the introduction of AMT were that present facilities caused:

Large batch sizes

Low utilization rates

High labour costs

Long lead times

High work-in-progress levels

An imbalance between the machine shop (large batch production) and the assembly shop (small batches)

The introduction of flexible work practices is partly a reflection of the company and the industry's history, and partly a reflection of its culture and a combination of economic and market conditions.

The company was organized on traditional functional lines until the 1980s. Operating practices involved close supervision and strongly defined functions. Job descriptions and duties were synonymous and demarcation protected functional specialism until the early 1980s, when the company was affected by the worldwide economic recession and the market began to decline. The work force was 2000-strong in 1982, but a series of redundancies reduced the number of employees before, during and after the AMT project to 870.

The union representing the majority of the shop-floor staff lost credibility during the early 1980s, at a national level because it was affected by the Conservative government's anti-union legislation and the collapse of the national Miners' Strike in 1984, and at the local level by its inability to prevent or reduce the number of redundancies between 1982 and 1984. The demise of the coal industry and the union and the resulting contracting of the market threatened the existence of the company and made it possible for the company to introduce radical cultural and organizational changes, the most radical of which was a "no-demarcation" rule which was introduced as a condition of employment for those who wished to work on the new FMS/AMT facility.

10.7 The Process of Organizational Change

A board-level decision was taken to place the FMS on the shop-floor alongside existing NC and CNC machines, rather than use a greenfield site. The FMS or AMT was meant to illustrate a new way of doing things, a new direction and an investment in the future of the company.

The FMS was justified to the group's board by traditional direct and indirect benefits and by "less tangible" [9] benefits such as being able to:

Promote the company's image and increase sales

React to frequent part and production programme changes (increasing customer satisfaction and sales)

Improve the accuracy of the existing MIS

Introduce a multi-skilled, multi-disciplinary workforce

The order for the FMS was placed with the vendors in January 1984, the machines were delivered late in the same year, and the implementation process, which consisted of installing and debugging the system, writing part programs and bringing the system into production took 15 months, from January 1985 to March 1986.

In the spring of 1984 the existing, "more traditional" machinery was moved to clear a site for the new FMS section. Contractors laid underground wires for the two automated guided vehicles (AGVs) which would serve the FMS and resurfaced the floor in the new section. An elevated FMS manager's office and clean room housing the computer controlling the FMS were erected and the machine shop in which the FMS was sited was repainted.

With regard to staffing, the FMS was to be manned by 4 teams consisting of an FMS shift manager, 2 setter/inspectors and a loader and 2 FMS-dedicated maintenance engineers. Of the FMS managers 3 were young graduates and the fourth a "time-served" shop-floor supervisor. All 4 were originally project managers and were involved in setting up the system. The remainder of the teams were recruited directly from the shop-floor.

10.8 Structural Changes

In structural terms the organization of the shop-floor housing the FMS was physically cleared, cleaned and altered. An FMS section on the shop-floor was created and fenced off from the rest of the area. The section operates as a semi-autonomous production "cell" and runs 24 hours a day, 7 days a week, whereas the rest of the site works a 5-day week. Each FMS shift manager supervises and is entirely responsible for FMS production for the shift. The reporting structure, showing the lines of authority and the control of the section, is given in Fig. 10.4.

As a shift pattern (see Fig. 10.5), the FMS teams elected a three-shift rota (of days, evenings and nights) which involves "doubling back", i.e.

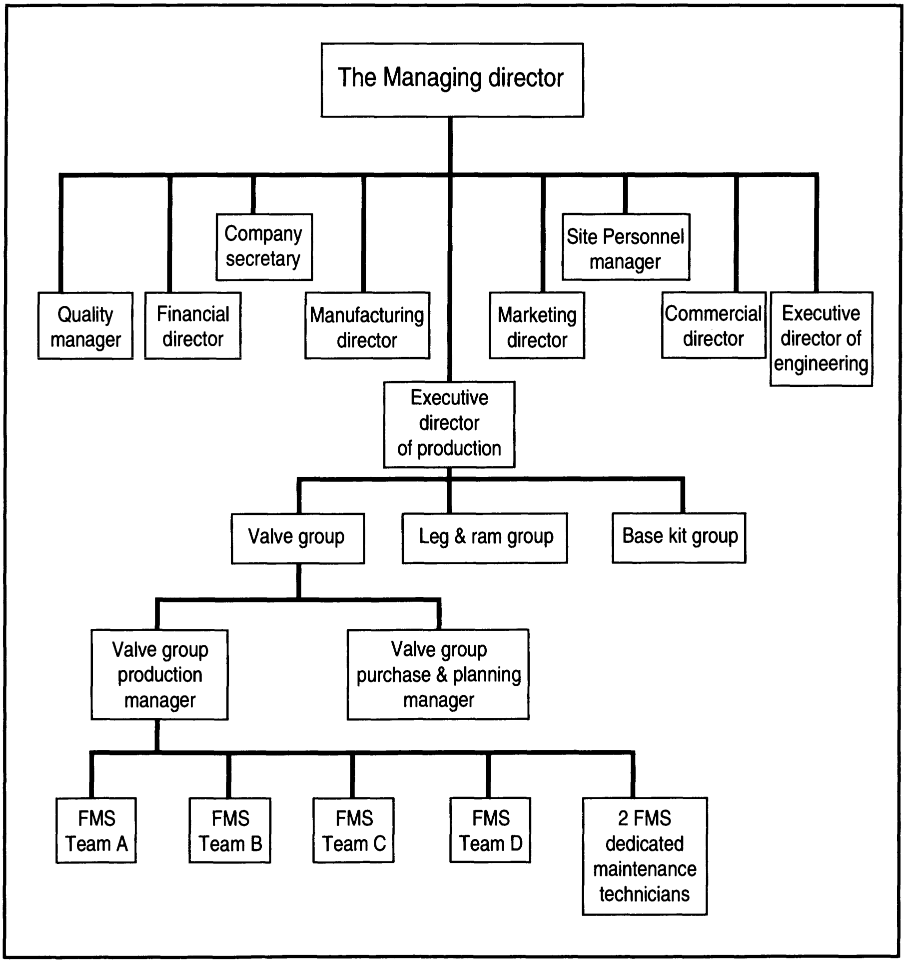


Fig. 10.4. Reporting structure at Company H.

coming off a night shift at 8.00 a.m. and coming back into work the same day, for the evening shift at 4.00 p.m., with one weekend in 8 free.

As a result of three shifts being worked, canteen facilities were not available for the FMS staff working the evening and night shifts and at weekends and the company provided a rest room with washroom facilities and a fully equipped kitchen.

10.9 Cultural Changes

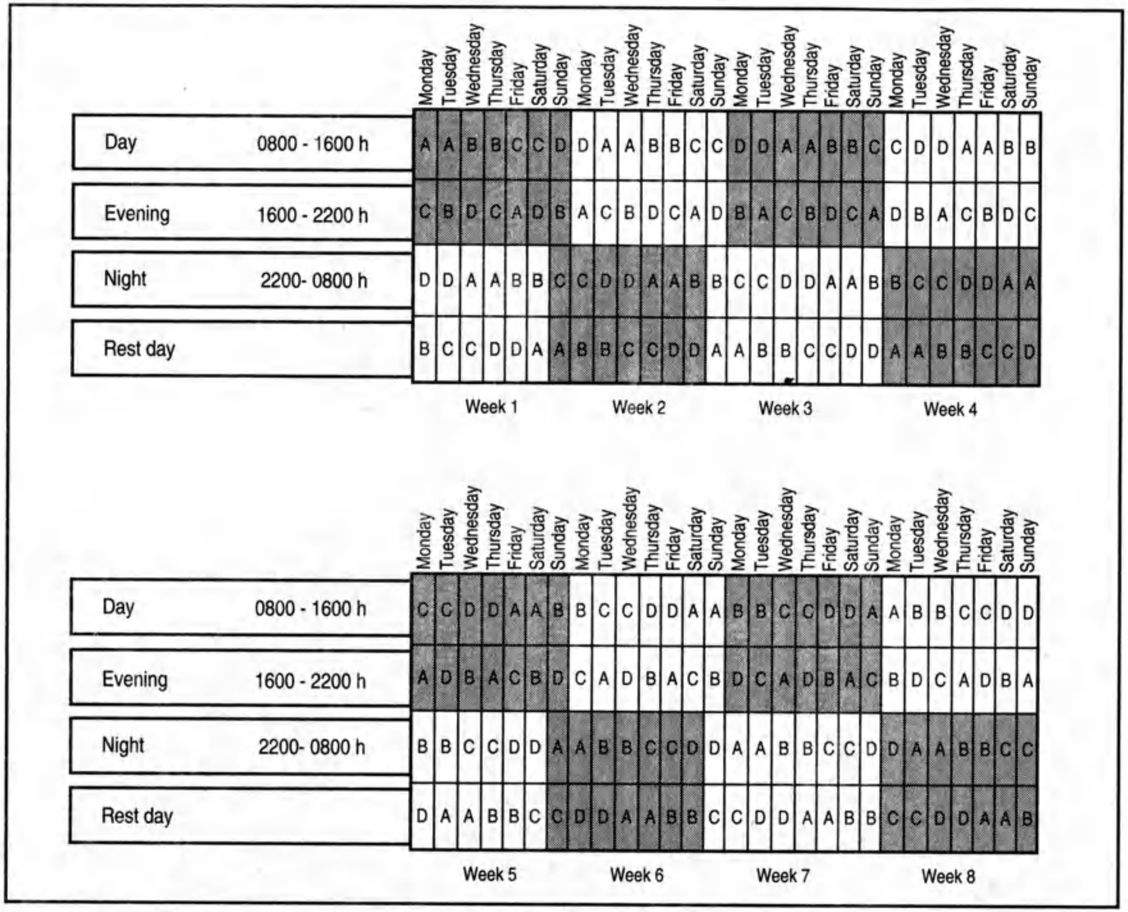
The FMS was heralded as an expression of the company's desire and determination to be more efficient, more flexible and more competitive. The introduction of the FMS therefore presented an opportunity to "change the way things were done" [9].

Aided by the economic position of the company in a shrinking, more competitive market, the company was able to insist on flexible work practices and a "no-demarcation" rule to ensure that the FMS ran continuously. New work practices were introduced whereby all members of the FMS teams performed a multi-role function (see Fig. 10.3). The company also introduced the concept of autonomy – each shift manager is entirely responsible for FMS production and the quality of goods produced by his team on his shift. The FMS teams are not free to act completely autonomously, however, because the quality of goods produced depends to a certain extent on the availability and the quality of the tools and recutting service available elsewhere on the shop-floor. The availability of suitable raw material also reduces the autonomy of the FMS section to operate as a wholly autonomous unit; however, it is semiautonomous, and shift managers are able to schedule and optimize FMS production within the section, for their particular shift. Also, owing to a lack of team spirit and a variance in the quality of goods produced by some of the teams, the practice of stamping the parts produced per shift to identify the team responsible for the quality thereof has been introduced by the management. A compensatory practice of uneven pressure on the stamp so that the team identity is not clearly imprinted has subsequently (and unofficially) been introduced by the less committed members of some teams [10].

10.10 Attitudinal Changes

To the rest of the work force in the machine shop housing the FMS, personnel employed thereon have achieved job security in that they have taken the opportunity to develop skills needed to operate a computer-controlled facility and advanced manufacturing technology; also, they are (a) less likely than the rest of the work force on more traditional machinery to be made redundant, and (b) highly skilled, multi-skilled men more likely to find higher paid, alternative employment elsewhere if they choose.

FMS personnel also receive more than a third more pay than other employees on the same grade because they are paid "shift premiums" for working unsocial hours. FMS personnel also have slightly better working



		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Day	0800 - 1600 h	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B
Evening	1600 - 2200 h	C	B	D	C	A	D	B	A	C	B	D	C	A	D	B	A	C	B	D	C	A	D	B	A	C	B	D	C
Night	2200- 0800 h	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A
Rest day		B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D
		Week 1							Week 2							Week 3							Week 4						

		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Day	0800 - 1600 h	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D
Evening	1600 - 2200 h	A	D	B	A	C	B	D	C	A	D	B	A	C	B	D	C	A	D	B	A	C	B	D	C	A	D	B	A
Night	2200- 0800 h	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C
Rest day		D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B	B	C	C	D	D	A	A	B
		Week 5							Week 6							Week 7							Week 8						

Fig. 10.5. Elected shift pattern.

conditions in that their section has a new floor (for the underground wiring for the AGVs) and a private rest room, and they can take their meal breaks when convenient rather than at a set time and are allowed to park on-site as they work unsocial hours.

Within the FMS section the main criterion is that the facility should operate continuously. The system is designed to run unmanned (in high-volume, low-variety production) and at times the operators are unoccupied. Provided the FMS constantly achieves the 80% machine utilization target set by the board, the production manager does not object to FMS personnel apparently "standing idle". Elsewhere on the shop-floor it is not acceptable for a man to stand idle beside a machine. The difference in attitudes and work practices is a result of the faith senior managers have in the data produced by the FMS. The system automatically records machine utilization and downtime, i.e. lost machining-time and its causes.

The FMS section is a clean area, fenced off from the rest of the machine shop; it is also a much-publicized, frequently visited showpiece. Visitors are required to wear protective eye glasses when entering the section and unmanned, automated guided vehicles (AGVs) moving between the machine tools in the section enhance the "high-tech" appearance and the difference between this section and the rest of the machine shop. In the opinion of those directly involved in the process of introducing the FMS, the equipment was the most significant factor in the company's fight to retain its market share to survive "the competitive eighties". The investment was perceived at the time as an investment in the future and was welcomed by the work force as such. An extension of the FMS section by the addition of a CNC Gildermeister lathe (under the control of the FMS shift managers) is considered a further demonstration that linked facilities and centrally controlled computer-controlled machines are the way forward for this company. However, to date the CNC lathe has not been linked or fully integrated with the FMS. The anticipated shift to a completely autonomous FMS work centre has not been achieved because production schedules are dictated by an MRP centrally controlled scheduling system, the raw material is supplied in bulk and final assembly orders are for small batches. In short, the company has not attempted a human-centred approach to CIM [11] "in which the technology is shaped around people" and links the existing organizational framework and technology.

The most significant organizational changes brought about was the creation of an FMS section and the new, flexible work practices needed to maintain continuous output and payback. Agreement to a "no-demarcation" rule for FMS employment was an initial condition of employment on the section and has set a precedent. It was only possible to obtain agreement to such a rule because of the prevailing economic conditions. Even so, the agreement and recruitment were delayed several months because of union opposition [12]. The union blacklisted the FMS and advised its members not to apply for employment thereon as they were not happy with staffing levels and the conditions of employment generally. However, recruitment proceeded when a union representative applied for the post of setter/inspector on the FMS section. The union still does not recognize [13] the FMS, which means that if union members who disregarded the union's advice have a complaint or a claim against the company for industrial injury, victimization, etc. they do not have union support, nor would the union represent such a member at an industrial tribunal, for example.

Staff recruited for employment on the FMS section believe they were appointed because they were willing to expand and increase their present duties and responsibilities and were flexible in their approach to work.

Conclusions

The company regard the installation of an FMS a success. The project was well managed, the system has achieved a steady 80% utilization rate in operation and the company has achieved payback within the period stipulated by the board. Despite increased competition the company has also managed to maintain its market share mainly by increasing the amount of refurbishment work undertaken and whereas the FMS originally had overcapacity and had to undertake "unsuitable" work to keep the utilization rate high, the company now subcontracts work out again because the FMS is under capacity. The company was recently subject to a management buyout, but there have been no major organizational changes since the buyout in mid-1990. The introduction of an FMS did not bring with it an accompanying change of culture because a traditional us-and-them culture prevailed. Senior managers believed a sea change in the company's culture could be accomplished by introducing mandatory changes in work practices. The changes in work practices as a result of installing the FMS were purely for the company's benefit, to protect its investment. In order to achieve a change in culture, firstly planned changes need to be widespread, not localized, secondly they must be top-down driven and implemented, not bottom-up, and thirdly a positive, long-term commitment to the proposed changes needs to be reinforced by feedback and a continual updating of goals.

In this case the original aim of autonomous, multi-skilled FMS teams manning the system 24 hours a day, 7 days a week was only partly attainable under the circumstances; the FMS section is not an autonomous unit, its supplies and the schedule of finished products supplied directly to the customer being dictated by factors outside its managers' control. The shift managers can control production only within the section and must maintain continuous production despite shortages at times of suitable raw material and tooling. The final-assembly section has priority and calls parts off the FMS in small batches to assemble the finished product, so that the section has to balance keeping a sufficient supply of raw material available to maintain continuous production against priority orders from the assembly section. The supply of goods and services to the FMS reflects the division and the lack of coherence in the organization. The flexibility of the facility, its managers and operators is therefore a critical factor in the company's ability to respond to customers' demands and remain competitive, despite this lack of coherence. Initially support for the FMS was strong, but since the target figure of an 80% utilization record was achieved and maintained, senior management's interest has waned and the responsibility for maintaining FMS production at the required level has been transferred to the shift managers and their teams. The shift system prevents the four shift managers from meeting as a group to discuss day-to-day problems and medium-to-long-term problems. This ongoing communication problem reflects a deeper organizational division. Throughout the organization top-down communication (i.e. of information the company wants distributed) is written, formal and relatively efficient; lateral communication between personnel of similar status is frequent, informal and verbal and friendly; whereas there is no formal mechanism for bottom-up communication other than official grievances. As a result of this case study it was suggested to the company that daily briefings should be held at each level of the company and that a conscious effort should be made to inform the work force of changes likely to affect the business as a whole. If the company wish to effect a cultural change then a thoroughgoing top-down change in attitude is required, and a philosophy of shared interest, shared responsibility and mutual accountability for the company's present and future position must be adopted.

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11 AMT Vendor Experience

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11.1 Introduction

In examining the conception, design, planning, implementation and steady-state operation of the flexible manufacturing system (FMS) as a production facility (as described in Chapter 7), it is necessary to ensure that "fact" is filtered from "fiction". This is not to say that facts are intentionally withheld, or that rather colourful claims are deliberately made. However, if an FMS is treated in isolation without obtaining a relative perspective of its capabilities and performance then it is very easy to make false judgements.

Figure 11.1 shows the context into which an FMS should be placed. If it is seen solely as a self-contained system then a "black box" analysis of its

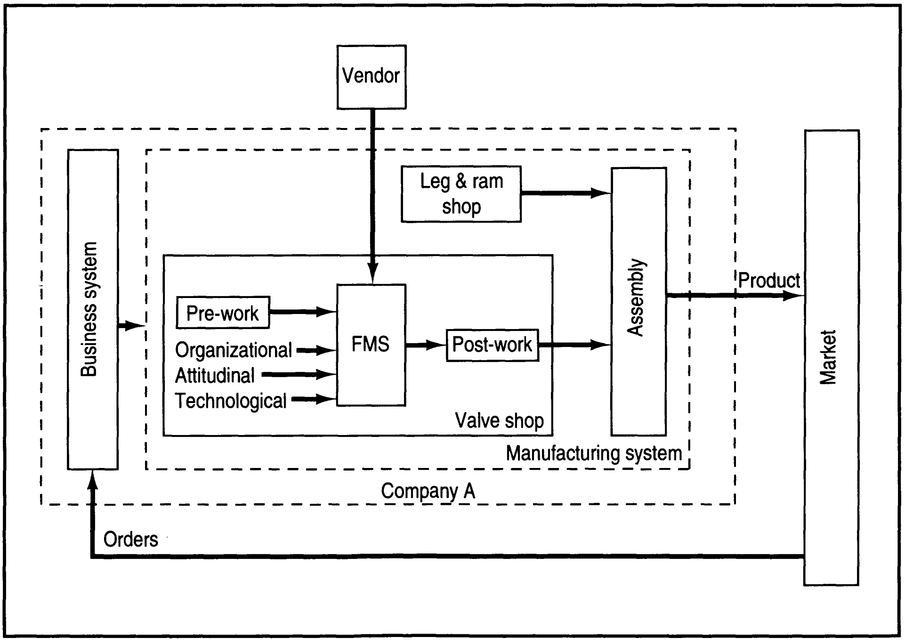

Fig. 11.1. External influences on Company A's FMS.

performance would be merely to examine the immediate outputs of that system and to relate them to its inputs. However, the inputs and outputs of the FMS are related directly to other surrounding manufacturing systems which may be seen as subsystems of the total manufacturing process. The FMS is then a subsystem (with inputs that may be categorized broadly into technological, organizational and attitudinal factors [1], whose main output is a final product) of the overall total company business system. The business system in turn reacts (or in some cases proacts) to a market demand, supplying customers with specific products in order to make money that is reinvested, after some filtering, into the company. Apart from the marketing source, which affects it only indirectly, the main external influence on the FMS is the vendor of that system. The FMS vendor too will have its own organizational, attitudinal and technological factors and a business policy that will greatly influence its output product [2–5].

The information obtained from the investigations of Chapters 7 and 8 has been almost totally from the user's point of view, in the context of the company as a business, with some examination of the customer/market perspective and initial soundings from the supplier's sales/distribution agent in the UK. So, in order to ascertain a "truer" picture of the FMS, it was considered important to ascertain the vendor's viewpoint. It is the results of a visit by the authors to a major vendor, plus contacts made with other leading machine tool manufacturers, that are presented in this chapter.

11.2 The FMS Vendor

The company was founded at the end of the last century. Initially it was situated in a building with 1200 square feet of floor space, and manufactured milling machines. The company soon achieved both national and international recognition for its milling equipment, winning international honours and obtaining orders in England, Australia and France before 1920.

The Second World War saw a rapid expansion of the vendor's plant to 500 000 square feet; the firm now employed 5000 people and produced 800 milling machines per month. At this time the company became the first to employ assembly line techniques in the manufacture of machine tools, and this method was retained for peacetime purposes. In 1957 their first numerically controlled skin mills and profilers were installed, followed a year later by a numerically controlled (NC) machining centre.

The early 1970s saw the development of their first computer-controlled machines. Their direct numerical control (DNC) system was introduced in 1970, while 1972 saw production of the first computer numerically controlled (CNC) machining centre. The flexible manufacturing system (FMS) concept was also introduced during this time and their first FMS was installed at a local plant by 1974. That year a diagnostic communication system (DCS) was made available. This allows remote location (customer plant site) diagnostic maintenance of CNC machining centres.

Since the war the vendor has introduced a wide variety of products: machining centres, controllers, manufacturing systems/cells and diagnostic systems. Their most recent innovations have been the laserhead, a bar code reader for tool identification, and ADEC (automatic dynamic error compensation), a heuristic machine control system that ensures process predictability.

By 1988 the vendor had approximately 1200 employees in a 500 000 square feet production facility at its headquarters. As shown in Fig. 11.2, the company is made up of four divisions:

Modular machine (MMD)
Factory automated system (FASD)
Synetics
Manufacturing

The final organizational structure shown in Fig. 11.2 resulted from recent attempts to reorganize the company to best meet customer requirements in quality of design, manufacture, delivery, implementation and support. The present structure operates both vertically and horizontally. Each division is independent of the other. Synetics is responsible for control systems that are subsequently incorporated into stand-alone machining centres developed by MMD, which in turn may be used by FASD for their manufacturing system. Synetics also supply FMS host controllers. Each division has its own mechanical, electrical and hydraulic engineering departments. Thus a customer–vendor relationship exists between these divisions.

A common horizontal division is that of manufacturing. In fact, manufacturing division are engaged only in the assembly of supplier parts to produce their final products. There has recently been a redesign of the shop-floor, based on group technology techniques with the view of achieving just-in-time (JIT). A fifth horizontal service division also exists. Its responsibilities are in the after-sales support given to customers.

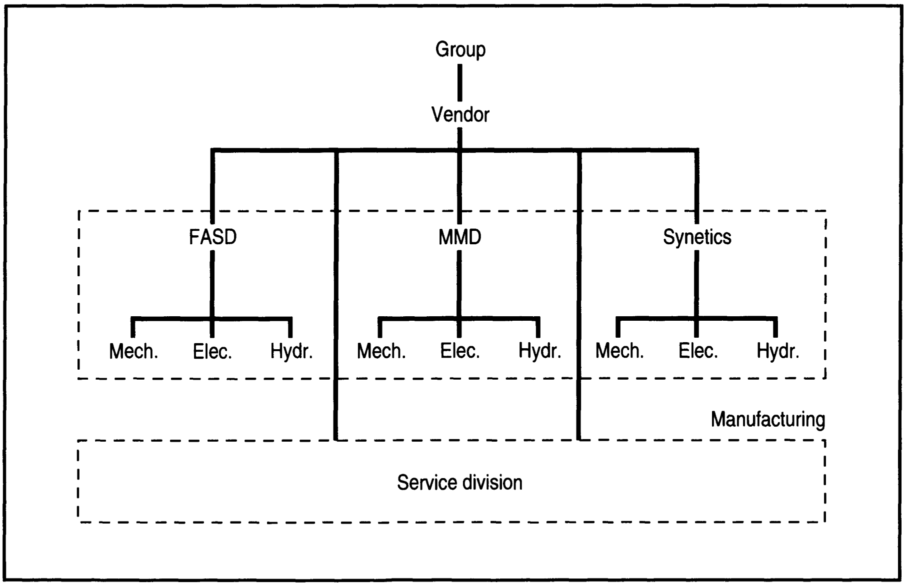

Fig. 11.2. Vendor's company structure.

11.3 Company A's FMS

A refined version of Company A's original requirements produced the schematic shown in Fig. 7.1. To recap, the system was designed to ultimately consist of nine CNC machines serviced by automatically guided vehicles (AGVs), with eight load–unload stations and managed by a DEC 11/44 computer. The first phase, which is the system currently operating at Company A, comprises four CNC machines, two AGVs and four load–unload stations.

The problem defined, or as understood by the vendor, was to produce economically a set of parts, comprising 27 basic families, on a to-order basis for service and for new applications. The manufacture of high-quality products, and meeting due date targets, were Company A's primary considerations. The vendor felt such requirements could be met via the installation of a manufacturing system that could produce parts with a varying product mix, changing product volumes, continually new product variations and changing schedules. This adequately describes the manufacturing situation at Company A.

The second phase of the installation has not materialized as yet, and is in some doubt. Approaches were made by Company A to determine the possibility of obtaining an additional two machines, but plans were frozen when it became apparent that the cost of the two would be excessive compared with the cost of the four original machines. It seems that the vendor offered the first four machines at a discount because they were eager to have a showcase in Europe. Their previous UK installation, at Company B, was a very secret operation. It was soon dismantled when Company B realized they did not have the product order volume to justify maintaining their system.

Company A's FMS was one of the last "classic" systems implemented by the vendor. Although it is like the present FMSs in that it is comprised of proven machine tools, system configuration, modular software and computer hardware, the system is based on the traditional demarcation between the shop-floor and the computer control room in an observation tower. This type of system also emphasizes the demarcation between operatives and management. Recent technological innovations (in the development of the Microvax) have allowed operators on the shop-floor to become system controllers [6]. This aspect of FMS implementation is discussed in more detail in Chapter 10.

11.4 FMS Implementation

Following discussions and consultations concerning customer requirements, the vendors prefer the user to direct the implementation procedure for the duration of a project. Following a preliminary assessment (in which costs are discussed and the financial justification for the purchase may be made), the customer gives the go-ahead for a detailed design to begin. Although the customer may not be involved in the details of the design, the buyer is encouraged to participate in the overall objectives so as to encourage awareness of the system process by assessing the extent to which the proposed design will meet with product requirements and the original design objectives.

The vendor then insists that the user becomes directly involved in the subsequent preparations for implementation and in the introduction of the system. The vendor recommends that a project management team is set up, as shown in Fig. 11.3, with the user project manager usually being the "product champion". The product managers then become the direct link between vendor and buyer and ensure that a master schedule is adhered to and project specifications are maintained. Any problems or conflicts are resolved by them or communicated to higher management.

Various other tasks and lines of communication are shown in Fig. 11.3. In addition to, and as part of, this management structure Company A created a project core team comprising four project engineers who subsequently became the systems managers. The systems managers visited the vendor in the USA for classroom lectures on the system software and, more importantly, visited vendor sites to learn from user experiences. The bulk of their training was "hands-on" back in the UK during the implementation stage, part proving and preparing for full production.

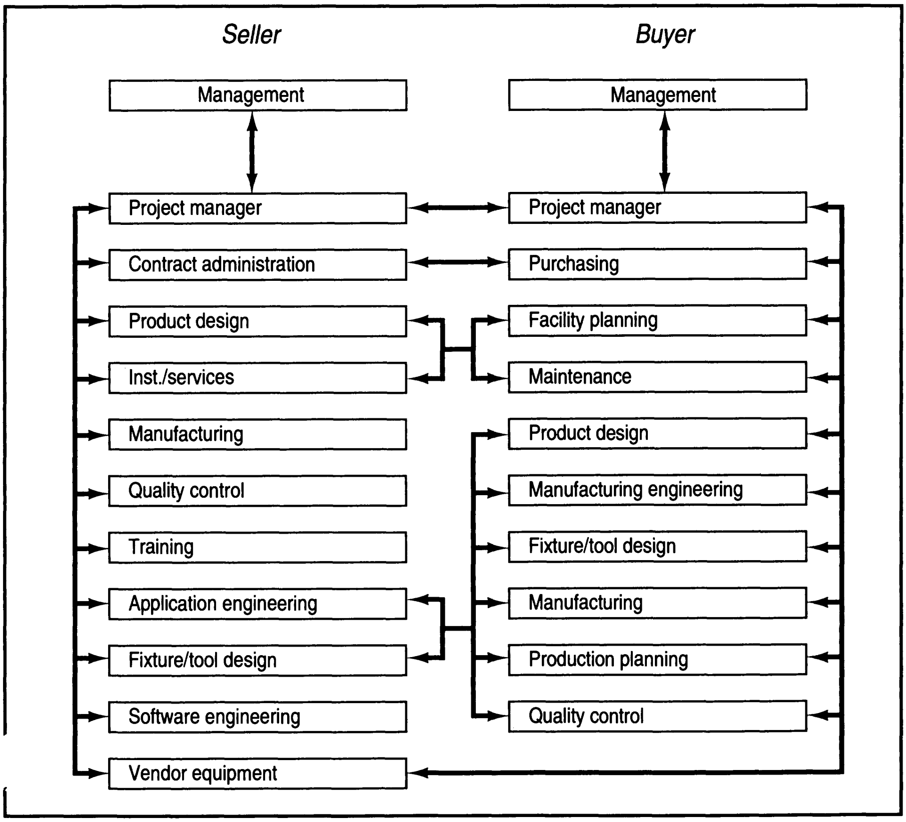

Fig. 11.3. FMS implementation project management.

The implementation of Company A's FMS saw few setbacks. Initially there were problems with the coolant enclosure and swarf containment. The coolant could have caused major problems if it had been allowed to fall onto the floor. The positioning of the AGVs is based on the distance covered by their wheels. Hence any skidding that occurs will "disorientate" the system. Problems had also resulted owing to excessive swarf contamination, causing jammed shuttle tables and damaged spindle probes. New enclosures were designed by Company A, manufactured and placed on the machines. This was rapidly carried out by a local firm, and led to a two-week delay in schedule.

Other problems included system software crashes (where the tool database "went down" and took a week to redefine) and interface incompatibility between the machine tools and tool changers. The latter actually occurred during steady-state operation and was basically due to a poor interface design. The machine centres are usually manufactured with a 68-tool toolholder, but owing to the degree of customization of Company A's products the capacity of the toolholder was increased to 110 tools, although the vendor did recommend at the consultation stage the use of more generic tools.

Overall, the vendor was highly impressed by Company A's project management team, the smoothness of the operation and the efficient way the enclosure problem was handled. As a postscript to this particular section it is worth noting the lack of feedback to the other vendor divisions from services following the successful implementation of a system. A recurring problem with Company A's machining centres is that the *z*-axis motors fail on a regular basis and are replaced by the vendor's service engineers. Those involved in the installation of the FMS were unaware of such a fault and cited the fact that the machines used were not originally intended for 24-hour working as a possible source for the problem. They claimed that the faults could be easily rectified by using an alternative larger motor.

11.5 The Vendor's User Philosophy

As mentioned above, the vendor insists that, as far as possible, the intended user of a system is closely involved with the whole project of purchasing, development and implementation of the proposed system. This is much preferred to (the more expensive) turnkey systems, although they can be supplied if the customer insists. Close user participation during implementation aids familiarization with the day-to-day running of the system and allows experience to be gained in solving common errors, which in turn ensures rapid recovery when faults do occur during production. Extensive system management training is given to those selected for the job. System managers pass on their knowledge to other members in the FMS team on an informal basis. Training includes management of the system, tooling and fixtures and actions needed to be taken in case of certain foreseeable faults, such as shuttle jams or tool breakages.

The vendors also prefer one person, a "product champion", to be responsible for the FMS from the initial approach made to the vendor, through implementation and to the subsequent steady-state running of the system. The vendor feels it is imperative that such a person is available. A person dedicated to the concept is more likely to ensure survival! A "product champion" ensures commitment and continuity to project objectives. A criticism that the vendor does have about Company A is the fact that their "product champion" orphaned their FMS soon after startup.

Management commitment is also a vitally important issue. Senior management must be involved not only in implementation but also in the decision to buy. The following case cited by the vendor illustrates the point. An FMC was installed at Company C in Wausau, Wisconsin. This plant, via its product champion, investigated the possibilities and ultimately justified the purchase of an FMC as part of the rationalization of the whole factory. The company headquarters in Racine, Wisconsin, agreed with the purchase and, without consultation, insisted that a sister plant in Brazil, also undergoing a period of change, should purchase exactly the same system. Both plants are identical; but although the FMS in Wausau was up and running in a short period of time with few problems, the identical system in Brazil was still not in production after almost a year, because of management resentment and grievances about the lack of consultation.

11.6 Technological Enhancements

During the installation of an FMS a primary consideration is the establishment of a suite of telecommunication points. This allows modem connections to be established with the vendor's headquarters so that the DCS may be made available to the customer. The DCS is used mainly for the diagnosis of any teething problems that may occur with the system itself or a component of that system. The customer can use the DCS directly or can call in a vendor's service engineer who uses the DCS to establish the type of fault and correct it.

Company A had a comprehensive telecommunication network available prior to installation, allowing the DCS to be used for problem-solving right from day one of implementation. Telecommunication points are well placed within the FMS adjacent to machines, loading areas and the host computer. Other companies have been less well prepared, one to the point of farce. That particular company had only pay-phones available in the vicinity of their FMS! Even a minor problem became a major headache because accessibility was so poor.

The vendor has been working with the Digital Equipment Company (DEC) since the late 1970s, as DEC hardware is considered the most appropriate for FMS use. Company A was one of the last companies to use the 11 Series control computers in their FMS. Due to the control system's size and sensitivity a large clean room is necessary to house the computer. Hence the evolution of the control tower and its social implications. Around 1986 the development of the Microvax computer system (which proved to be far smaller than the 11 Series, more robust, cheaper, and with sufficient processing power required for system management) allowed the host computer to be placed directly on the shop-floor in a simple, specially designed dust- and dirtproof cabinet. Although the original benefits associated with the Microvax were based mainly on cost reduction, the introduction of operator-controlled systems led to a rethinking of the manning of the systems and a change in hierarchical management control.

Company A's FMS was not only a classical design; it is manned traditionally. A systems manager is responsible for the overall management of the system and a number of technical staff (operators, inspectors, setters, and maintenance) ensure the efficient running of the system. The employment of a specialist team, combined with the special circumstances under which the FMS was operated (control tower, 24 hours a day, 7 days a week working, plus a barrier surrounding the system) leads to its isolation, with poor integration within the company organization and the total manufacturing process. The introduction of the Microvax has led to the demise of the control tower, and the emphasis has been placed on ensuring that the "mystique" that surrounds such systems is eliminated so that they no longer remain isolated islands of automation. System managers are no longer necessary and teams consist merely of trained operatives in the factory. While the customer is made aware of the specialization of a system, the system itself is treated like any other piece of equipment that has to be integrated to ensure global success.

The trend towards this type of system is shown by the vendor's sales figures. 1985–6 saw no systems incorporating the Microvax, while in 1986–7 4 out of 8 such systems were sold and in 1987–8 8 out of 9 installations were Microvaxes. The solitary system of the 9 that was not a Microvax controller was installed at customer insistence as the result of a US Army contract. The regimental aspects of the control tower were a stipulated requirement.

Not all supposedly technical innovations have been successful. As part of Company A's contract a software planner was included. This was basically a long-term scheduler for attempting to predict such aspects as market demands and the number of part families available to the system. Unfortunately, the planner is based on steady, predictable markets that no longer exist in an increasingly competitive environment. The development of the software cost the vendor $500 000 and a single package was sold to Company A for $50 000. Only two other planners were ever sold and the vendors have obviously now shelved the concept.

Utilization of individual machines within Company A's FMS is based on the measure of actual cycle times and therefore determines whether a centre is machining or not. Recent advances by the vendor now allow for an additional comparison between actual and nominal cycle times. Although this may be useful for assessing efficiency levels, it seems of doubtful value for measuring utilization.

The system installed at Company A is also (theoretically) capable of running unmanned. An identical system was installed at Company D in Columbus, Ohio, at the same time as the FMS in Company A. Company D's FMS consists of six machining centres and it has the same manning structures and runs unmanned during the night shift. This necessitates a conscientious effort prior to the night shift on the part of the shift manager. He has to ensure that the system is set up to run without stopping or breakdowns throughout the night, which entails setting system priorities and scheduling AGV routes before the shift commences. Although the product mix at Company A is that much greater than Company D (100 parts compared with 2), the vendor feels that, via simulation studies, the system could be set up for unmanned working.

The vendor feels that tool migration is an important aspect that needs to be tackled for the future success of FMS. Rather than having ever-larger toolholders for their machining centres equipped with dedicated tools, the move will be towards automatic JIT transport of a few generic tools to where they are required.

11.7 Company C's FMC – a Comparative Study

Company C's business is the manufacture of agriculture power equipment for farms, and earthmoving equipment for the construction industry. Its main domestic competitors are from the USA and Japan, and Company C has recently bought out a local competitor. The specializations of the different companies vary. One USA competitor is involved solely in agricultural equipment, while the other deals only with construction equipment. The Japanese make heavy- and light-duty excavators for both markets, as does Company C but in the mid-range of equipment.

After recently buying out a local firm, Company C decided to rationalize their plants to prevent duplication and thereby reduce costs. It should be realized that all the above companies have, like Company A, until very recently been working within declining markets. Three sites were closed and the site at Wausau was reorganized and reopened. The Wausau site was chosen because:

1. The machinery at the other two sites was older.
2. Wausau was not unionized (although its workers are now becoming organized under the United Automated Workers Union (UAWU)).
3. The then managing director at Wausau organized and involved the local community in the fight to keep "their plant" open.

The corporation was so impressed with the lobbying led by the MD at Wausau and the local community campaigning to keep its major local employer, that it chose Wausau as the site to be retained.

The FMC at Wausau, as the FMC in Brazil, consists of two CNC vertical millers, served by a linear transporter controlled by a Microvax II computer. The Microvax allows real-time supervisory control of pallet movements, material, fixtures, tool data, production schedules, process routing and station operations. It also allows management interface for semiautomatic system commands and data handling of NC programs, schedules, routes and tool management. A schematic of the system is shown in Fig. 11.4.

In Wausau, the project manager responsible for the FMC (the "product champion") describes himself as a "hands-on" engineer, who believes in eliminating the "them-and-us" attitude that is commonly found in industry and is responsible for separatism and lack of unity. The project manager has personally been responsible for training the system operators and is determined to eliminate the mystique surrounding computer-operated machinery. In Company C the FMC is treated as just another machine tool.

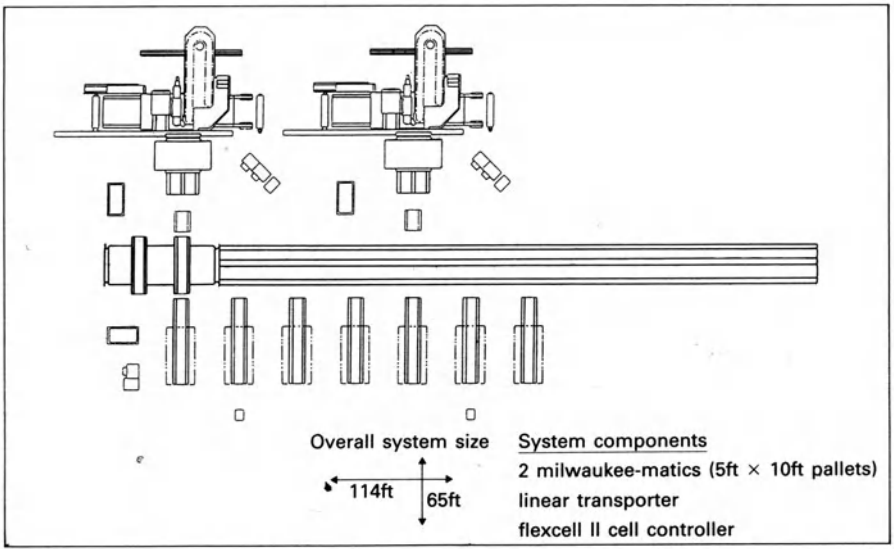

Fig. 11.4. Company C's FMC.

The FMC operators are skilled (time-served) journeymen who operate the system via a Microvax control system situated adjacent to the machine tools, with only part-time assistance from the project manager. There is a small office on the shop-floor but it is not a clean room. It is used to house tool spares and the machine tool control terminals. The system operates on two 12-hour shifts while the rest of the plant presently works single 9-hour shifts plus overtime. It is envisaged that the whole plant will soon be working 24 hours. Each team presently consists of one operator and two loaders, although this will change to two operators and one loader when more operatives are "trained up" by the project manager. All training is, and has been, "hands-on" and on site.

As has been mentioned, the FMC is not considered as a major advance in machine tooling or treated as such. The FMC has been installed as part of corporate strategy to consolidate a multi-plant organization and is therefore seen only as a contributing factor, i.e. a fraction of the overall redevelopment of the company. The new plant layout has involved the use of group technology techniques to orientate the manufacturing process to just-in-time (JIT), as the vendor itself has been doing. Parts are manufactured JIT for assembly and scheduling is MRP or customer-due-date driven. In fact, scheduling is said to be "taken care of by the process", that is, the production process ensures that machined parts arrive JIT for assembly and delivery. The system also includes DNC and Ethernet integration capabilities, although as yet there is no host computer.

The FMC is also perceived as being product-orientated, that is, a product designer was involved in the design of the FMC and all future products designed for manufacture, i.e. they will be designed with the process and production capabilities of the FMC in mind. It machines three basic products, the front, rear and lift arms of excavators intended for both construction and agricultural use. These designs are updated annually and it is estimated that about thirty variants will ultimately be accommodated.

The system is said to produce zero defects, although this is due more to the nature of product specifications than to the capabilities of the FMC. Tolerances are very low and thus little machining precision is required. Should a product be bored oversize then the fabrications are rewelded and remachined. A more realistic 10% rework figure is quoted by the vendor. A 90–95% utilization is also claimed, although when the plant was visited no operations were being carried out. This was apparently due to shortage of supplies from sister companies in Spain (due to a strike) and Brazil (which was 9 months behind schedule).

Overall the FMC at Wausau is considered a resounding success by both Company C and the vendor. The only word of warning came from the vendor. Although the "demysticism" and integration that has been developed has ensured that the system has not remained an island of automation and its startup a success, long-term fortunes are not guaranteed. Company C have failed to realize the specialization of the system. By the very fact that it is treated as just another machine tool it has been left open to mistreatment. Company C have contracted out the maintenance to the vendor and have no one available in-house. Maintenance is not scheduled but is only carried out when a problem or breakdown occurs and the company relies entirely on the vendor's DCS. Cleanliness is minimal and swarf contamination excessive. Since the machine tools are new these drawbacks will not result in any deterioration of the system for some time to come, but in the vendor's opinion Company C are likely to experience significant problems in the future.

11.8 International Machine Tool Show (IMTS-88), Chicago

The visit to the USA by the present authors also incorporated a tour of the IMTS-88 exhibition held at McCormick Place, Chicago. The IMTS brought together machine tool manufacturers from all over the world, notably the USA, West Germany and Japan, with other main contributors being Switzerland and Sweden. The show offered an excellent opportunity for manufacturers to display their wares, and it is calculated that IMTS-88 produced orders in the value of $750m. In all, over 1000 exhibitors were present.

The vendor of the systems described in this chapter did not attend, as they feel that the show does little to promote their products, and neither did other major US companies, such as Ingersoll Milling. Another major FMS manufacturer, Cincinnati Milacron, did attend, but merely showed stand-alone machining centres.

FMS/Cs on show included LeBlond Makinos Module MMC and Werner und Kolbs FMS 630-2. The MMC showed Makinos modular approach to expanding machining centres into flexible manufacturing cells. The cell included two MC86 horizontal machining centres, each with its own GE Fanuc Series 15 controller, combined with two pallet stockers. The 630-2 showed the capabilities of the Werner TC 630 machining centre with a robot carrier for tool exchange and a pallet transport vehicle for materials handling. Some discussions were also held with Mandelli Industriale SpA, who were exhibiting their software packages for system monitoring and control, which basically featured simulation models and statistical process control techniques.

Overall, it seemed evident that FMS on its own is no longer a marketable proposition. Vendors are now turning their attention towards the integration of the islands of automation that have sprung up within customer plants. The vendors appear to have moved from the automation to the automation–integration business. Is it just a matter of time before, as businesses, they compete directly with management consultants and become involved in simplification–automation–integration? Or is that concept to be left to consultants or customers? From our consultations with the vendor at least it seems that they at least are well aware of *all* the preliminaries required to be carried out prior to the installation of advanced manufacturing machine tools.

11.9 Conclusions

Company A's FMS installation performed as well as could have been expected. Company A were totally professional in their attitudes and laid the necessary ground work for smooth implementation. Their project engineers were very eager and quick to learn. Technical problems that did occur were soon solved. The installation of the FMS, based on a project network analysis, fell behind by a couple of weeks due to software problems. The main delay in system startup was due to disagreements between management and the workers' union at Company A.

Although Company A's preparation ensured smooth installation the company failed to appreciate the range of organizational and attitudinal changes that would have to take place for a totally successful startup. Integration of the FMS has been poor, there is poor communication between departments and this has led to an imbalance in material flow on the shop-floor. Technologically, apart from the recurring axis-motor failures and problems still prevalent with swarf containment, the system seems very sound. Company A's wish to be actively involved with the implementation ensured that problem solving is quick and efficient. Tooling has been a major problem, but this has been due to lack of support from production engineering and stores.

The answer to successful introduction of an FMS/C is: "simplify – automate – integrate". "Simplify" means that prior to the purchase of AMT you need to understand your present business and manufacturing process in order to determine the likely effect of introducing AMT. If necessary the manufacturing system may have to be redesigned and restructured to ensure successful integration. The move to AMT should not be seen as a major change in manufacturing, but just as another, more efficient tool to solve the problems at hand. Nevertheless, the specialization of such a tool should not be underestimated. In the vendor's opinion the most important factor is that the necessary framework must be prepared to ensure that organizational or attitudinal barriers are not preserved or built into the system.

System implementation must not be left to the "experts". Customer participation allows the user to understand the workings of the system, which leads to a smooth and rapid startup and the elimination of the early, or infancy, stage of the learning curve [7].

If the simplification and automation stages are closely adhered to, then integration will follow.

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12 General Methodology for Smoothing the Introduction of AMT

J.E. Cherrington and D.G. Coward

12.1 Introduction

Most of the organizations investigated in this study had some experience of computerized equipment and were interested in acquiring more. Some of these organizations were recognized as brand leaders, with excellent reputations in applying high technology. Even so, only a few companies were obtaining the full benefits of AMT as measured by such parameters as programmed unmanned running. The reasons for this were many, but more often than not amounted to organizational faults. With hindsight, these were inexplicable, because it is likely that all these organizations would recognize the stages outlined in Fig. 12.1 as those comprising a general methodology for smoothing the successful introduction of AMT. However, no organization would necessarily accept the reasons why it had failed to adopt the methodology completely.

As shown by the flow chart in Fig. 12.1, the general methodology identifies nine sequential stages, but the figure does not illustrate the continuous and iterative decision processes contained within and between stages. To achieve organizational and operational control constant reference must be made throughout these nine stages to the business and manufacturing objectives planned for AMT.

The methodology summarized in the flow chart incorporates long-established methodologies. It assumes that a draft proposal for AMT has been formulated and passed to higher-level management for evaluation. A summary of all the essential steps is given in Appendix 1.

12.2 Stages in the Methodology

12.2.1 Definition of Corporate Strategy

This stage involves the formulation of a business plan which identifies the contributions that the proposed development will make in terms of overall company performance. Definition of the benefits of AMT must include any

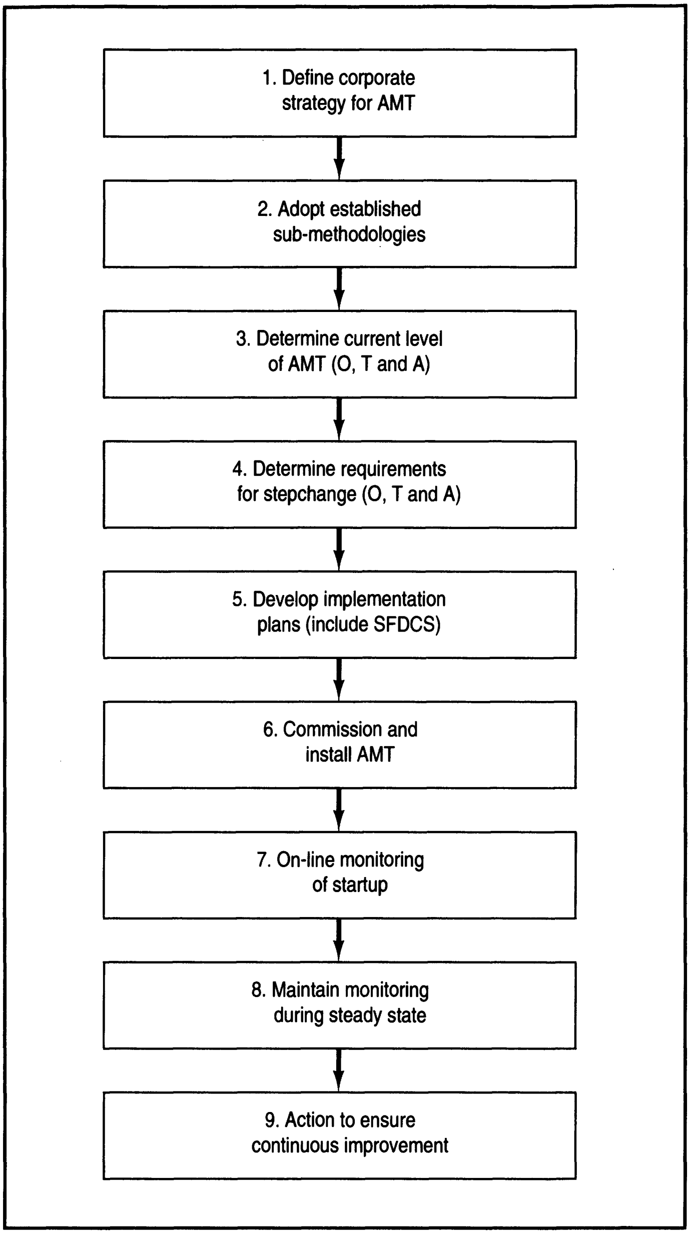

Fig. 12.1. Sequential stages in the general methodology for the successful implementation of AMT.

competitive advantage. As earlier emphasized by Hill (see Chapter 3, reference [8], it is essential that the manufacturing strategy be integrated with the other business strategies. This aspect is often overlooked if the proposal for AMT is generated by the manufacturing sector as part of a "technology-driven" strategy. Other pitfalls of this approach must be recognized and evaluated at this stage.

A major requirement is for all functional managers, that is design, quality, marketing, manufacturing and financial, to understand the implications of introducing AMT and to evaluate the effects that it will have on their duties. Of even greater importance is the involvement of higher-level management at each methodological stage.

Time must be found for considering more than one capital investment at a time. On average, about 10–15% of the existing output should always be under review at any time so that its effectiveness in terms of investment can be ascertained. The periodicity of review should be in line with that of technological change. A rigorous continuous-review procedure should be adopted instead of the all-too-prevalent, inconsistent short-term attitude to plant replacement and upgrading. The less frequently investment appraisal is made then the greater the eventual demand will be on the company's knowledge and financial bases. In these situations, full turnkey purchase of AMT should be considered, coupled with an intensive training programme.

Two kinds of strategy apply, one for new products that are considerably different from "normal" products and one for "normal" products that are increasing in sales demand and need cost reduction exercises. Both requirements were found in our studies; their solutions require different approaches to the introduction of AMT.

12.2.2 Adoption of Established Sub-Methodologies

This general methodology relies on principles developed from long established sub-methodologies. For example, the arguments for the stages involved in a human-centred approach to the introduction of new technology have been defined by Lupton [1] and are compatible with the proposed generalist method. Again, the management implications when introducing AMT have been described by Tranfield and Smith [2] and appropriate recommendations made for a "step-by-step" philosophy. Corrective action taken at each step ensures that not only are mistakes remedied more easily at each step, but that the overall system response is much quicker in the long term.

Even more relevant to our general methodology are the long-established techniques of project management and method study. Many of the problems encountered during the implementation of AMT are caused by not following the basic rules of project management and method study, such as the allocation of responsibilities for planned activities and the detailed questioning required for knowledge acquisition. The wider implications of the introduction of AMT into organizations does mean that both these techniques must be adapted to avoid the danger of suboptimization caused by the "logic of efficiency" syndrome sometimes associated with these techniques.

In conclusion, then, this stage formulates the way in which the introduction of AMT is to be organized. A multi-disciplinary project team will be required to evaluate the organizational, technological and attitudinal (O, T & A) feasibility of the proposal. The team must be led by a product champion or a project manager who has the necessary authority to control the project from this stage through to the end.

12.2.3 Determining the Current Level of AMT

Basically, this stage answers the questions regarding the level in the progression towards computerized integrated manufacture that the company has reached and how efficiently it is currently operating at this level. The answers are found by exhaustive analyses of the organizational and technological capacities and of the attitudes of both management and workers. The rewards for additional implementation effort at this stage are exceedingly high. One of the misconceptions often quoted is that technological advantages of AMT are easily defined and available. Our experience is that while this hypothesis may apply to certain machining parameters such as physical size and rate of metal removal, other factors such as accuracy and repeatability of the existing equipment are less precisely defined. Hence, before embarking on an extension of their technological capabilities firms are advised to perform standard process capability tests. The same reasoning should be equally applied to their management capabilities and in particular the computer literacy of supervisory and middle management.

The effectiveness of the existing working methods in the areas selected for AMT enhancement must be evaluated. Without knowing how good or bad present methods are, it is difficult to make realistic decisions or to be certain which bottlenecks to prioritize. Consequently, all known information about these areas must be recorded and analysed and report-back procedures established.

It should be possible to arrange for simple local studies to check productivity losses such as how jobs pass through the section concerned so that all delays, scrap, absenteeism, breakdowns and other problems are known. These studies should give information concerning actual achievements in floor-to-floor times and machine utilizations. Results are then available to be compared with those to be achieved by the new process. The new "challenger" process under consideration itself needs testing with suitable work to establish floor-to-floor times, either by computer simulation or by direct observational studies at the vendor's works. The latter approach is particularly relevant if a change is contemplated which is outside the local experience. One example of this is in the introduction of pallet-changing machines as discussed in Chapter 9.

Detailed costs need to be considered in order to justify large capital investments. Ideas on fixed-cost distribution frequently distort the decision making process. Emphasis should instead be placed on shop-floor variable or marginal costs when considering the contribution made by competing AMT equipment.

Our studies reveal instances where shop-floor operators are highly computer literate, even in some cases to the extent of possessing personal computers. The main barrier to the introduction of computers on the shop-floor is the distrust that the operators have for the way in which management intend to use the data collected on the computers. Therefore, much effort should be expended at this stage to determine the state of industrial relations and the attitudes of management and operators to changes in their working practices. Any potential "road blocks" to change must be identified and removed by this route. Such "road blocks" will include artificially low "targets" set by operators as a result of poorly designed incentive schemes and the lack of communication links both between work centres and supervision and between operators using the same equipment on different shifts.

12.2.4 Determining the Requirements for Step Change

A step change in AMT operations can be achieved only if a genuine desire to plan and organize the manufacturing area exists, starting with middle management's own responsibilities and activities. In particular, operations management needs to offload some of the day-to-day routine decisions to others so that time is found for both internal and external appraisal and analysis. The results of constant "fire-fighting" were all too readily apparent in our studies. Only by making time available for management thinking can the previously mentioned capability studies and planning for continuous improvement exercises be carried out.

Once the capability studies have been completed it is necessary to define the organizational, technological and attitudinal requirements necessary to facilitate the introduction of the proposed AMT. The process involves detailed feasibility studies covering education, training, motivation, product definition, demand patterns, working methods, productivity and quality improvements. Higher-level management must be concerned directly with the decisions made here because the step change will automatically affect the financial, quality, design, marketing and manufacturing functions. Every opportunity should be taken to obtain information regarding the way other organizations have successfully negotiated this step change.

It is necessary to be able to estimate the projected AMT workload, whether for one, two or three shifts, while at the same time allowing for shorter cycle times on AMT equipment. Failure to identify sufficient workload creates a utilization problem that cannot be financially justified. The whole reinvestment philosophy needs examining in the area of reduced cost of operations, with increased throughput of saleable work without increases in stock and work-in-progress. The step change in one part of a production facility has interactive effects on the rest of the production function. These effects must be understood, evaluated and allowed for. In essence, the successful introduction of AMT requires a high standard of industrial engineering expertise, whether this is provided by the user, by management consultants or by vendors.

The main problem here is the failure to ensure that the specification for the AMT matches expected variations in individual product requirements and demand patterns. It is a regular feature of AMT installations for them to be accused of inflexibility in the face of such variability. The effects of this weakness may be often offset by formulating decision support procedures which encourage flexibility. An example is the design of versatile tooling, which can enhance significantly the range of AMT capability.

Another step forward is to plan to have ancilliary (but important) machining operations conducted off the AMT installation so as to assist throughput. An example of this is the establishment of datum faces on irregular components using conventional equipment, thereby leading to improving setting times and metal removal rates on the more expensive AMT installation. It is not unknown for setting time to exceed machining time when this kind of product analysis is not carried out, which represents a terrible waste of AMT resources.

12.2.5 Development of Implementation Plans

As the project moves sequentially through the various stages the amount of detail increases proportionally. Consequently the main problem involved in developing these plans is the discipline required to revise and update the various activity time project milestones and target dates. Neglect of even simple activities can be disastrous.

One of the main failures observed between the vendors and customers of AMT equipment is inadequate communications. Difficulties arise where the vendor has not fully appreciated the demand to be placed on his equipment and/or the user has not planned how to maintain it effectively. Clearly the major causes of these situations are the incomplete studies undertaken at the previous stage. The amount of time lost due to machine breakdowns in the startup stages of these installations bears testimony to the lack of attention to detail. It is not sufficient to rely on warranty claims to mitigate the effects of productivity losses incurred.

It may be necessary to analyse a full year's workload to obtain a realistic machine specification. Any excess hours above a full load can be used as a flexible decision tool in selecting specific equipment such as control systems, tool equipment changers, horizontal or vertical machines and swarf disposal systems. The objective is to provide a range of capacities to meet variable demand patterns.

As mentioned earlier, the basic questions faced by companies concern the degree of their involvement during the implementation phase. At one end of the spectrum are bespoke systems which are purchased from a vendor and commissioned inside the customer's plant by the vendor and handed over only when the specification is achieved. An installation used by one company in our study was thus very successfully initiated by a West German vendor.

The other end of the installation spectrum is to purchase an "off-the-shelf" standard machine with a minimum-only training package and thus leave the design of working methods to the purchasing company. This strategy allows more freedom in equipment selection but relies on efficient planning and operational control by the company. As we have already made clear, our experience suggests that this is an area where there is regrettably little evidence of management involvement.

Both these AMT acquisition *modi operandi* extremes require the consideration of price, delivery, contract details, space and training. In this respect, the more competition there is for the contract the better. Again, if similar installations can be viewed by the customer and typical work pieces produced by the selected vendor then the confidence in the selection decision increases. Unfortunately, this very important activity requires time and effort on the part of management, who cannot perform unless fire-fighting is eliminated.

The final decision will be based upon many factors, and, it is to be hoped, not on cost alone. It will depend on whether there is one outstanding candidate or a variety of shortlisted vendors observed to possess individual advantages. It is essential that a number of managers endorse the eventual recommendation to the board of directors and that they have a clear vision of the advantages to be gained and how to ensure they are achieved in practice.

We also strongly advise that a company-wide knowledge bank be created on the diagnosis, prevention and servicing of equipment faults. The classification of such faults into those suitable for being serviced by the operator, the "in-house" maintenance technician and the external service engineer, respectively, should be made a priority.

12.2.6 Commissioning and Installation of AMT

When the AMT order is eventually placed and a delivery date agreed then a paper plan should be made to smooth the introduction of the technology, principally by letting all concerned know full details of the scheduled startup. Figure 12.2 gives in Gantt chart form a typical planning period which can be modified to suit particular circumstances. The main points to observe are the preparation of programmes and the a priori experience gained in the machine manufacturer's works.

Planning activities should include obtaining qualification test samples from the vendor, the offsite training of the customer's personnel and the study by the vendor of the customer's existing work practices. All of these contribute to effective AMT commissioning. As much offsite training should be done as possible before the machine is installed. These training activities should overlap.

Further in-house training is necessary to enable the operational planning

Activity	
Feasibilty study	xxxxxx
Make decisions	x
Decide specification	x
Place order	x
Programmer training	xx
Select 6 months load	xxx
Determine tooling	xxx
Acquire tooling	xx
Prepare and prove programmes	xxxxxxx
Operations training (vendor)	x
Operator training (company)	xx
Production at vendors	xxx
Publish operational strategy	x
Inform and consult workforce	xx
Confirm site	x
Check out services	x
Prepare and lay foundation	x
Maintenance training	xxxxx
Installation	xxx
Commission by vendor	x
Monitor performance	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Fig. 12.2. Typical planning activities showing relative lead times for installing AMT.

to be achieved. This involves installing production methods and report-back/action procedures to ensure that feedback of information is accurate and reliable. The programmer should be aware of the tooling, operation and maintenance requirements of the AMT, and the maintenance technicians and operators should also be aware of each others' duties and of the programming aspects.

The operational running of work through this expensive AMT installation should not be left to the operator. Procedures need to be designed and decision criteria established to ensure the target is achieved on a day-to-day basis. This involves specifying setting methods, tooling used, job cycle activities, inspection methods, etc. If for any reason the operator cannot comply with the established method then a reporting system monitored by management should be used so that problems can be quickly rectified. Only then can the on-line monitoring data be interpreted in a meaningful way.

If these activities have been performed successfully then the commissioning and installation of AMT should not present too many difficulties, provided of course that the basic preparation activities for locating the equipment and connecting the supplies have been completed satisfactorily.

12.2.7 On-Line Monitoring and Control of Startup

In order to profit in the future from the knowledge and experience gained when overcoming the difficulties encountered during the startup phase it is necessary to record the features of these difficulties in sufficient detail. This recording activity is a prerequisite for the acquiring of knowledge mentioned previously. Some progressive companies keep comprehensive logs of the commissioning and startup phases (which is our firm recommendation). Most others do not, and are extremely reluctant to indulge in any kind of post-mortem activity. We think this is very wasteful of resources and hinders the learning process.

Monitoring can be accomplished at the individual machine/work station level, at the cell level or at a departmental level where the monitoring merely records improvements in overall output and quality levels. It is preferable to record as close to the workface as possible, but this may lead to industrial unrest. The design of the shop-floor data collection system (SFDCS) must be agreed between management and workers at the earliest possible stage.

There will be significant losses in output before the AMT reaches its planned steady-state operation if effective planning is not used; an example is shown in Fig. 4.10. During the planning stage estimates are required not only of this target productivity level, but of the time taken to reach it and of the rate of change in output during this time.

In addition estimates should be made of the productivity losses caused by "unavoidable breakdowns". Without this information it is impossible to prepare accurate contingency plans to ensure continuity of production and to attempt to justify the financial investment of AMT.

With knowledge gained from previous similar installations, each startup phase can be controlled successfully by setting dynamic targets and by signalling out-of-control situations so that appropriate corrective action can be taken quickly.

12.2.8 Maintaining Monitoring and Control During Steady State

The time taken to reach steady-state operation depends on the complexity of the AMT, the amount of preplanning and the available physical resources. Examples of such response times range from days to years. In some situations the steady state lasts for a shorter time than the startup period because new developments are introduced. Again, much of the attention given to a new piece of equipment is often prematurely stopped. This applies to management thinking as much as to the actions of consultants. Although productivity losses usually decrease with time, efforts to reduce them during the steady-state phase are often worthwhile. For these reasons, and particularly to avoid expending too much effort to determine the characteristics of new AMT when considering further developments, it is recommended that monitoring and control procedures are not removed once the startup phase is completed. They should be used for operational feedback on a continuous basis.

12.2.9 Continuous Improvement Action

Establishing management commitment and credibility to ensure that the AMT meets the required performance levels, particularly quality, involves the holding of regular review meetings where the different non-conformance reports are analysed and appropriate corrective action taken.

The recording of these meetings is essential to ensure that knowledge acquired on one AMT installation is transferred to another and maximum cross-fertilization achieved.

It is our contention, as described in Chapter 1, that most of the delays in implementing AMT would be avoided if a firm recalled its previous experience systematically.

12.2.10 Investment Appraisal of AMT

Much research effort has been expended on investment strategies for the implementation of AMT. We refer in the next three sections to the way in which investment influences our general methodology and not to specific appraisal techniques.

Investment appraisal is often thought of as "spending to save", and cash inputs versus cash returns have dominated this area. This is more akin to replacement theory and as such plays little part in AMT investment. The latter investment, because it is for advanced technology, is bound to involve a stepchange in resources and opportunities and so it cannot be judged on replacement alone. Hence it cannot be assessed just by cashflow in and out. The business reasons that have created the demand for AMT need to be realized and written down because they form part of the company strategy in this area. In other words, what is the investment for? Is it to gain competitive advantage, improve quality or service, cut lead times, obtain better schedule adherence, improve management control, or achieve flexible manufacture, or what?

The investment is in a complex piece of technology, expensive and potentially highly productive. Hence it is particularly sensitive to how it is organized and used. The potential profits are more than equalled by the size of the potential losses if planning and operational skills do not work effectively.

12.2.11 Investment Parameters

The cost of the equipment and total installation expenses should be accurate to within plus or minus 5%, as should the projected outputs whether in standard hours or pieces of production. A proper plan for capacity based upon 1, 2 or 3 shifts, with or without maintenance, absenteeism, unscheduled breakdowns, setting or adjustments, will enable the expected available hours to be stated to within plus or minus 5%. Here scientific appraisal finishes and the art of costing begins.

Decisions have to be made concerning how long before the company wants capital overheads to be returned, i.e. 2, 3, 4, 5 years or longer? How large is the number of indirect workers in the company and how many of them will be supported by the AMT output? These and other factors increase the overhead rate on the system and can make it appear unprofitable or not as profitable as it could be. All this seems a distraction and unfair burden when inter-business competitiveness is at stake. The attempts to produce a machine-hour rate in which some of the costs are notional further affects management thinking.

A simpler, better way is to consider trading profit or contribution from a productive AMT already installed with the company and let this cash generation pay for whatever system the company has. As an example of this it is not unknown for companies who would state they never use leasing, because it is too expensive, nevertheless to have a set of calculations tucked away that show their machine-hour rate for ownership of the installation to be in excess of the cost of leasing for 5 years! Because they do not bother to compare the estimates they do not know that leasing would be beneficial.

12.2.12 AMT Investment Ideas Using Net Cashflow

Taking the initial capital investment, adding interest payments and opportunity costs and then dividing by 5 yields the yearly capital cost. Most plants should run for more than 5 years, so any extra that is generated after this time can be used to pay for a more expensive replacement. By dividing this yearly figure by the useful output hours available the cost of owning per hour is established. To this figure has to be added the hourly cost of power and services and the hourly maintenance cost of both inplant and external service agreements. Manpower per hour also needs adding, and here savings can be made by effective operational design, so that either machines are shared or unmanned running is catered for. Both are strong features of a planned, disciplined, organized activity. Extra cost will be incurred by the monitoring system set up to evaluate performance against the set standard for output cycle times, quality and utilization. The losses in this area are considerable, so this expense can repay good dividends.

Any other costs identified that are particular to the installation and not the company can be added in a similar way.

All these costs will be offset by the production of parts that can be related directly to selling price in the case of subcontract items. However, parts for further work require a different assessment. If a component has only one or two of its operations done by AMT and the rest are by conventional processes then the alternative for comparison is the cost of outside purchase. A few subcontractor quotes for the operation will give the clear alternative cost that is available should the production orders be placed outside.

It is necessary for companies to do this because if they cannot economically produce parts then it is better to get them made outside the company. A clear distinction can then be made between the technologies which the company can use to make money and those that are not viable commercially. The firm must have a strategy that leads it towards the area of its own expertise and not get sidetracked into running alternative systems that they are not equipped to run because of volume, range, attitude, culture, forward load or whatever. Essentially the difference between monthly cash cost and monthly cash revenue can be compared. This cash generation is the AMT contribution; it is sensitive to change and the appraisal of whether the investment is worthwhile or not depends upon the expected performance being maintained as judged by the feedback monitoring system productivity. The above philosophy can of course be expressed as a simple formula, but the reasons behind it need articulating. These are given in Table 12.1.

These ideas switch the company attitudes in investment appraisal to the important areas of operational efficiency, operational utilization and operational performance. The money emanating from each area is rapidly

Table 12.1. Net cashflow cost contribution formulae

C = capital cost plus installation cost plus services
N = number of years plant in operation
I = interest/opportunity cost
A = actual hours of operation
H = hours available per year for operation
P = cost of power and services
M = maintenance cost and service agreements
L = labour cost per year [full, part or unmanned]
F = cost of feedback from manufacturing system
O = other costs identified with particular AMT
E = expected output (= parts per month × selling price)
R = actual output (= parts per month × subcontract)

$$\text{marginal cost per hour} = \frac{C + I + P + M + L + F + O}{H}$$

$$\text{utilization} = \frac{A}{H}$$

$$\text{contribution} = \text{revenue} - \text{cost per month}$$
$$= \frac{R - C + I + P + M + L + F + O}{12}$$

contribution variance = actual revenue − potential revenue identified, and its non-appearance quickly detected when there is a delay of any kind. This enables monetary targets to be set, while delays expressed in pounds clarify the position. The use of standard hours or items of output miss the vital ingredient of capital. This information is too often found high up in the management hierarchy. It needs to be the responsibility of the product champion and/or someone else with direct responsibility.

12.3 Conclusion

AMT investment appraisal starts as a paper planning exercise, with its practicality cross-checked by vendors evaluating typical jobs to establish realistic cycle times. When the decision to proceed is eventually made, appraisal should be updated throughout training, preparation and service phases. When the equipment arrives and is installed management should continue finding out reasons for delays and correcting them. Early production runs are then monitored for productivity improvements, breakdowns and learning difficulties. Appraisal continues by trying to make certain the original paper exercise planned is bearing the fruits of cashflow so essential to the company's well-being. At no stage should the complications of distributing overheads to a particular cost centre inhibit the clear view of keeping the AMT installation producing to specification. All changes made to improve performance can then be judged against the basic criterion of contribution to cashflow.

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Appendix 1. A Methodology for Smoothing AMT Introduction

Features

1. Adopt well-established sub-methodologies by:
   (a) Ensuring accurate capability definition of existing AMT
   (b) Religiously following project planning and control guidelines
   (c) Designing operational methods that support AMT
2. Formalize data collection and analysis procedures for:
   (a) Reliability assessment of equipment
   (b) Analysis of work patterns and hence removal of bad habits
   (c) Formal design of decision support systems

   (d) Shop-floor communications requirements

3. Set up on-line productivity monitoring and control systems for the following phases:
   (a) Commissioning and installation
   (b) Startup
   (c) Steady-state operation
4. Encourage computer literacy on shop-floor by:
   (a) Providing free access computing facilities in cell
   (b) Setting aside daily period for compilation of report diaries

Part A: Guidelines for Successful AMT Introduction

The following four global prerequisites are obtained from combining the well-defined top–down business strategy approach with the alternative bottom-up technology-driven strategy of AMT implementation.

1. A definable corporate strategy capable of demonstrating clearly the contribution that the proposed development will make in terms of overall company performance.
2. An effective vertical and horizontal business organizational structure showing unhindered decision-making and sound management of motivation to succeed.
3. A good operational environment where organization and technology interface.
4. The adoption of a policy for the identification and elimination of waste, with appropriate performance measures.

Other research emphasizes the importance of integrating these strategies successfully and this is the objective of the proposed guidelines:

1. Technological feasibility to evaluate product requirements relative to process capability and floor-to-floor times.
2. Organizational feasibility will evaluate alternative working methods to handle variation in product mix, changes in capacity and feedback monitoring.
3. Attitudinal feasibility will evaluate industrial relations, motivation of staff and workers, and training requirements for AMT.
   (a) The main initiation of the above should be by and through a dedicated product champion or project manager, who is essential to ensure the successful implementation of bespoke or even turnkey systems.
   (b) This champion has to have the necessary authority to set up a project team to evaluate the attitudinal, organizational and technological feasibility of the proposal.
   (c) Regular meetings of the project team are required to translate

results of feasibility studies into potential improvements in quality, material flow and adherence to schedule.

(d) Comprehensive appraisals of all potential savings are needed to determine economic feasibility and potential constraints to the success of AMT.

(e) Ensure that commitment to the project is obtained from all levels within the organization (board, departments, operators), thereby realizing its wider acceptance and integration within the company.

(f) Ensure that the project team retains control throughout the preplanning, commissioning, installation, startup and steady-state stages. Turnkey system users should be aware of the dangers of "black box" mentality.

Part B: Specific Guidelines for Product Champions and Consultants

1. Change managers must recognize that there is a planning and control gap where their traditional top-down approach ends, i.e. just above the shop-floor.
2. Their handover of responsibility for the AMT installation to the company is often premature and must extend into the steady-state operational stage. Guideline (f) in Part A supports this continuity for management responsibility.
3. Change managers must ensure that detailed plans are produced for site preparation, commissioning, startup work schedule and steady-state working or operational control.
4. Manufacturing audits should be formally prepared to ensure that the details involved in (c) do not slip from their planned completion dates.
5. The audits should constitute part of a comprehensive data collection and reporting system.
6. Change initiators should prepare target availability curves with suitable "out-of-control" boundaries. (On-line monitoring does not necessarily imply computerized monitoring, although our projects have generated suitable monitoring and analysis software.)
7. Nominated responsible managers should investigate working practices to determine the existing degree of operational control and attitudes.

   We do not think it is necessary for consultants to perform extensive on-line studies, because selected observation of, for example, changeovers between shifts and products will usually reveal quickly any evidence of poor scheduling and communication. Estimation of the time taken to produce good-quality components can also be illuminating.
8. Consultants should investigate the flexibility of process planning procedures by examining process times and estimating the ratio of AMT time to total process time. Alternative scheduling policies should be available based on batch-flow and man–machine principles, use of ancillary labour and versatile tooling. Removal of work from AMT to

cheaper technology should be advised where possible. "Non-disturbance" attitudes to AMT work should be analysed.

9. Detailed on-going machine capability studies are necessary to ensure that the product specifications are met. Related information concerning the frequency and type of machine breakdowns should be collected.
10. Investigators should insist that only operators willing to work to more exacting AMT standards are selected.
11. Operator training should ensure adherence to company working methods as well as covering supplier-based AMT training.
12. All supervision levels require additional training in cell/AMT management principles.

Subject Index

Achievement of objectives 153–4
Acquisition process 126
Advanced manufacturing technology (AMT). *See* AMT
Agglomeration schedule 51
AGVs 110, 112, 188
AMT
  background research 5–7
  benefits 27
    analysis 10
    intangible 7
  definition 7
  design evaluation 13
  determining current level of 208
  effective use of 33
  failures vs. successes 13
  financial justification of 37
  implementation. *See* Implementation
  introduction 3, 7, 205–19
  reasons for failure 10
  service profile 127
AMT champion. *See* Product champion
Attitudinal factors 97
  interactions during planning and implementation 15
  management 25, 91
  shop-floor personnel 91, 186–9
  supplier 15
Auditing requirements 13
Audits of data collection systems 157–8
Automatically guided vehicles (AGVs). *See* AGVs
Availability 92

Best previous peak (BPP) approach 101–3
Black box 66, 112, 191
Bootstrapping 83
Bottlenecks 32, 136
Bottom-up approach 37, 144, 148, 154
Breakdown statistics 128
Bright's index 36

Capacity loss during startup 73
Capacity planning, dynamics of 91–108
Capital investment 26, 27
Case studies
  companies involved 149–53
  Company A 149–50, 153, 155–6, 158, 162–5, 194, 196, 198–9
  Company B 151–4, 156–7, 159–61, 165–7
  Company C 152–4, 157, 161–2, 167–71, 197, 199–201
  Company D 198–9
  Company H 181, 185
  monitoring exercise 154–71
  organizational problems 179
  overview 147–9
  strategic decision-making 153–4
Cashflow 26, 27, 214–15
  and startup performance 12
Cause-and-effect analysis in FMS performance 120
Cause-and-effect diagram of lost utilization 94
Centroid values 103
Classification index 38, 45
Cluster analysis 40, 44, 49–52
Combined company profiles 35–55
  creation of 38–41
  future developments 53–4
Commissioning 211–12
Company profiles 20
  see also Combined company profiles
Company response profile 22
Company stage states 41
Competitive advantage 10, 35
Complementary cultures 31–3
Compressibility mode 65
Computer-aided design (CAD) 125
Computer-aided manufacture (CAM) 125
Computer-aided production management (CAPM) 37, 125, 149
Computer-aided simulation part proving (CASPP) 120
Computer numerical control (CNC) programming 125
Consultants, guidelines 218–19
Continuous improvement action 213
Control process, steady-state operation 213
Corporate planning, major traps in 8–9
Corporate strategy
  definition of 205–7
  formulation of 10
Corrective action 207
Costs and costing 208
  effect of discontinuities in operating conditions 97
  investment ideas 214–15
  learning 93–5
  lost productivity 93–5
Crossman theory 68–9
Cultural issues 20–33, 186
  management–worker 172

Cultures
  complementary 31–3
  operational 30
Cumulative percentage utilization 132
Curve-fitting procedures 80
Customer requirements 31
Customer satisfaction 31
CUSUM analysis 119

Daily variability 72
Damping 83
Data collection and analysis systems 26, 41–2, 122, 150, 197
Data collection systems
  audits of 157–8
  in use prior to real-time monitoring exercises 158–62
  real-time 162–71
  shop-floor 144–7, 212
Decision classification 141
Decision-making 26
  algorithms 112
  in implementing AMT 6
Delayed time-constant model 65, 69, 70
Dendrogram 40, 45
Design and development (D & D) 109
  discrete event simulation (DES) 121–2
  results 117–18
  simulation model 111
Deterministic errors 62
Differential equations, solution of 62
Discounted cash flow (DCF) 137
Discrete event simulation (DES) 109–23
  case study 111–18
  design 111–16
  design and development (D & D) 121–2
Dynamic discrete event simulation (DDES) 122
Dynamics of capacity planning 91–108

Energy loss 72
Equipment design 127
Equipment faults 211
Equipment supplier 126–8
Expansionist situations 97
Experience curves 2, 14, 93
External influences 191

Financial effects of poor equipment design 127
Flexible manufacturing cells 13
Flexible manufacturing systems (FMS). *See* FMS
FMS
  case study 110
  causal information 120
  poor performance 10
  use of discrete event simulation 109–23
FMS A 98–99, 130
FMS B 93, 132
Forecasting via learning curves 77–90

Group stage states/profiles 41

Human factors 19
Hydraulic jack servomechanism 64–5

Implementation
  decision-making in 6
  development of plans 210–11
  general methodology for smoothing 205–19
  methodology 10, 13
  programmes 19
  project management 195
  step-by-step approach 13
  strategy 7
  sub-methodology 11
  successful 35
  vendor experience 194–6
Improvement curves 58
Industrial relations 208
  see also Trades union
Industry learning 61
Information system 73, 154
  software 150
Information technology 125
Initial productivity 91
Installation 211–12
International Machine Tool Show (IMTS-88), Chicago 201–2
Interviews 27, 148, 178
Investment appraisal 213
Investment culture 21–7
Investment parameters 214

Jewellery industry 35, 43, 45–9
Job security 16
Just-in-time (JIT) 10, 199, 200

Knowledge acquisition 207
Knowledge bank 211

Laplace operator 63
Laplace transform 62, 64, 79
Las Vegas modelling 103–5, 130
  alternative approach 105
Learning costs 93–5
Learning curves 9, 93
  adequacy of models 66
  estimating lost capacity from 73
  forecasting via 77–90
  industrial dynamics family models 66–8
  modelling errors 61–2
  models 2, 7, 57–75
  parameters 12
  practical use of 58
  prediction problems 66–7
  selection of models 68–70
    for hardware systems 62–5
  sequential models 70–2
  transfer-function-based 68, 79, 94
Learning data, collection and evaluation of 9

Least-squares error (LSE) 77–8, 130
  learning curve algorithm 80–2, 85
    development of 87–90
    results obtained from 82–3
  modelling 86–7
  time constant model 103
Log-transform technique 77
Long-term decisions 32
Long-term strategic advantage 26
Loss in production. *See* Production losses
Lost utilization. *See* Production losses

Machine "off the shelf" 210
Machine utilization 126
Maintenance 72, 92
Management, attitude problems 91
Management attitude, to informing operatives, monitoring 154–7
Management attitude to results obtained, monitoring 173
Management attitudes
  problems of 91
  to AMT investment 25
Management ownership of AMT project 30
Management style and structure 30
Management–worker interface culture 172
Manufacturing methods 48
Manufacturing strategy 13
  definition of 10
  development of 8–11
  linking implementation of new technologies with 43–9
Market forces 180–3
Materials requirements planning (MRP) 37
Materials requirements schedules 136
Mathematical models 110
Maximum productivity 72
Mean repair time (MRT) 128
Method study 207
Modelling
  errors 62, 64
  startup 1–2, 93, 118–19
  techniques 91, 109–10
  see also under specific applications and techniques
Modem connections 197
Monitoring process 145–7
  audits of data collection systems 157–8
  bottom-up 148
  data collection systems in use prior to real-time monitoring 158–62
  equipment 155–7
  management attitude to informing operatives 154–7
  management attitude to results obtained 173
  on-line 212
  results of real-time collection and analysis 162–71
  steady-state operation 213
Multiple learning curve 99–101
Multiple startups 97, 130

National Economic Development Office (NEDO) 7
New technology 47
  as strategic asset 20
  assimilation of 19–20
  benefits of 20
  human-centred approach to 207
  linking implementation with manufacturing strategy 43–9
  organizational factors 183–4
Non-financial criteria 27
Non-value-added activities 13

Objectives, achievement of 153–4
On-line monitoring system 86–7
Operating conditions, changes in 97
Operational control 5, 142
Operational culture 30
Operational learning 2
Operational management 32
Operational planning decisions 142
OPT (optimum production technology) 154, 161, 162
Organizational change 32, 177, 188
  process of 184
  structural 185–6
Organizational control 5
Organizational factors 19–34, 97
  new technology 183–4
Organizational learning 2
Organizational problems 175–90
Organizational profile 36–7
Organizational structures 26
Overall utilization 92

Pallet-changing machines 147–8
Payback targets 29
Peak performance 101–3
Peak values 142
Performance
  assessment 13, 27
  evaluation 109–23
  monitoring 137
  unsatisfactory 11, 13
Planned maintenance 72
Planning 47
  activities 211
  prior to equipment installation 3
Plateaux phenomena 93
Previous peak performance (PPP) values 101
Principal component analysis (PCA) 21
Product (AMT) champion 27–30, 196–7, 207
  guidelines 218–19
Production losses 32, 72–3, 91–3, 95
Production performance 126
Production targets 29, 103
Productive capacity 91

Productivity 35
  increased 72, 91
  losses 12, 58, 98–103, 141–4, 208
Profit margins 31
Progress curves 11
Progress functions 58
Project culture 27–30
Project management 11, 19, 29, 195, 207
Project manager 29
Project review team 128
Project team 29, 207

Questionnaires 41, 45, 48, 49, 148

Random errors 62
Regression analysis 130
Reliability 126–7
  problems 10
Repair time 92, 128
Ripple model 65, 68

S-curve 66, 69, 70
  algorithm 85
  model 84
  versus time constant model 84–6
SERC 35
Shop-floor data collection systems 144–7, 212
Shop-floor experience 125–39
Shop-floor personnel attitude factors 91, 186–9
Short-term decisions 32
Short-term gains 26
Signal-to-noise ratio (SNR) 95
Significant emotional events (SEEs) 175, 179–80
Simulation modelling 109–10
Skills
  development 126–7
  requirements 16
Small firms 19–34
S-model 79
Standard cost of learning (SCL) 95–7
Startup 128–32
  control of 212
  FMC 84–6
  FMS 118–20
  forecasting 118–19
  lost capacity during 73
  modelling 1–2, 93, 118–19
  multiple 97, 130
  performance 3
    and cashflow 12
  protracted 91
Startup curves 3, 4, 58, 93, 98
Startup profile 130, 132
Steady-state operation
  control process 213
  monitoring process 213
Step-by-step philosophy 207
Step change requirements 209–10

Strategic decision-making 153–4
Strategic planning 32, 35, 49
Suboptimization 32
Supplier attitudes 15
Support organization problems 91
Supporting techniques 11–16
System failure 92
System bespoke 210
System utilization 92–3, 132–7
Systems perspective 177

Target values 74
Taylor series expansion 80
Taylor series LSE estimator 80
Technological enhancements, vendor experience 197–9
Technological factors 19, 97
Technological index 36
Technological problems 91
  see also New technology
Technological profile 36–7
Telecommunication points 197
Time centre values 103
Time constant learning curve model 63, 74
Time constant model 60–1, 69, 93, 94
  versus S-curve 84–6
Time domain equation 63
Tooling problems 137
Top-down approach 37, 148, 154, 176
Top-down–bottom-up approach 20
Trades union
  attitudes 15
  issues 137
  priorities 16
  see also Industrial relations
Training 16, 211
Transfer function 62–5
  models 58, 70
Transfer-function-based learning curves 68, 79, 94
Trend line 93, 95
Turnkey approach 12, 128

Unmanned operation 3, 29, 92, 125, 143, 188
Utilization 92, 132–7
Utilization curve 3

Vendor experience 191–203
  and user philosophy 196–7
  company profile 192–3
  implementation 194–6
  product champion 196–7
  technological enhancements 197–9

Ward's method 39, 45, 51
Warranty claims 142
Witness package 111

Zero–one modelling 83–4
Zero–one modifications 97