Automation in the Food Industry

C.A. Moore

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Automation in the Food Industry

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Preface

This book is designed to be everything its title suggests—a practical guide to automation within the food industry. It is the first book to offer practical advice on what can be a most bewildering subject in an industry where the use of effective automation is of paramount importance. There are many books dealing with the theory and practice of control systems in both the food and other industries. However, these tend to offer too much detail in both areas to be classed as overviews, or cover too much of the more obvious detail and gloss over, or avoid, the elements where the decisions are hard—even though these are the areas which are fundamental to successful and expansive projects.

This book identifies those elements of any automation scheme which have to be considered first, and that form the foundations for any successful project. The editorial introduction outlines the content of the book and is a useful starting point. Examples are used, wherever possible, to show what can be done, how it can be achieved, and what to avoid. A glossary of definitions is included at the end of the book. All the chapters have been written by engineers, with many years' experience in this field, who have been able to express their views freely. The result is a book which covers the key areas of the subject, using a minimum of the technical jargon with which this subject abounds, in a readable, practical manner.

This book is intended for process engineers, electrical engineers and food technologists working in the food industry. It will also serve as an essential source of reference for production managers considering the purchase of new equipment.

Acknowledgements

I would like to pass my sincere thanks to all the contributors who have put in many hours of hard work to make this book not only possible but also useful. It is their breadth of knowledge and real engineering experience which makes their chapters valuable and enables this book to meet the objectives established right at the start.

I must also express my gratitude to AMEC Design and Construction Ltd. who have tolerated the inevitable disturbances that editing this book has created, and I thank them for their support during this venture.

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Tony Dodd read Mathematics and Philosophy at Oxford and then spent the years 1973 to 1978 doing research into set theory, gaining an M.Sc. in 1974 and a D.Phil. in 1978. From 1978 to 1983 he was a research fellow first of New College and then of Merton College in Oxford. He published a monograph on constructible sets in 1982. He first became interested in computing while doing research in logic and developed an interest in the theory of formal languages and compilation. He joined Expert Systems Ltd. (as it then was) in 1983 to work on Prolog-1. In 1984 he designed and led the implementation of Prolog-2, and in 1985 became Technical Director of the company. He led the design team that produced the Prometheus expert system shell, is an active member of the BSI Prolog standardisation committee and secretary of the UK Association for Logic Programming. His book 'Prolog: a logical approach' is due to be published by OUP in 1990. In 1989 Tony joined Chemical Design Ltd. as Expert System Product Manager, and early in 1990, together with three other employees, set up Expert Systems Ltd., of which he is Chairman and Managing Director.

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introduction of new plant and processes, running the facility for the development of new processes for existing and new products, having responsibility for in-house engineering research and development, and setting up and running a corporate systems engineering department with a special remit for packaging systems. In 1987 Tom and a senior colleague completed a buy out which gave Cambridge Consultants majority ownership of the Systems Engineering unit and has enabled the team of mechanical, electrical and software engineers to gain experience of solving production problems in a variety of industries, especially in consumer orientated industries such as food, confectionery, pharmaceutical and health care. Tom is able to draw on some 35 years' industrial experience.

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Colin A. Moore graduated in Control Engineering and spent a number of years with the British Steel Corporation engaged on all aspects of the design and construction of multi-discipline projects throughout the Steelworks Division. During this time he expanded his understanding of business operations by gaining a diploma in Accounting and Finance. In 1981 he joined IDC Limited where he became involved with the design and construction of electrical and control systems for major projects. He was directly responsible for the successful completion of these, a large number of which were within the food industry. He was appointed Divisional Director–Engineering in 1985, and in this role has assisted the company to strengthen its standing in the food industry in particular, and in other industries in general. In 1990 he became responsible for all Process, Control and Systems Engineering aspects within IDC Limited (now AMEC Design and Construction Ltd.)

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application of d.c. based control systems for electric vehicles. Upon completing four years with that company, he joined Thames Board Mills Ltd. and commenced his career in project engineering. At Thames Board Mills he was involved with the application of d.c. drives, a.c. motor control equipment and general electrical distribution schemes. During this time he was part of a large project team involved with the design and installation of a new card-board machine. He joined IDC Ltd. (now AMEC Design and Construction Ltd.) in 1984 as a Senior Engineer, working on control systems for process applications. He is currently Technical Manager, responsible for all the Control and Systems Engineering operations. Roger Pilkington has had considerable experience on food industry projects involving complex control systems.

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Derek Spencer joined the English Electric Company as a technician apprentice in 1957, working in the Relay Development Laboratory on electronic distance protection. Later he joined Field Engineering to work on power-station commissioning and then computer-systems commissioning. Since 1968 he has been firmly committed to automation. He became Head of Engineering of the Automation Division at GEC Electrical Projects Ltd. in 1982 and Divisional Manager in 1984. In 1988 he transferred to GEC Industrial Controls Ltd., Kidsgrove as Manager of the newly formed Control and Process Systems Division.

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Editorial introduction

The food industry has been a major investor in control systems over recent years and predictably will continue to be so. This investment is driven to a great extent by the need to continually market new product lines, and also by the need to increase throughput and efficiency. In practice this means the industry wants to, or has to, apply sophisticated control techniques to provide repeatable and automatic controls which allow accurate records to be kept and fewer operators to be used to produce the same or an increased amount of product.

This book contains contributions from highly experienced engineers who have spent many years working within and for the food industry. Some have spent their working life with manufacturing companies, others have supported manufacturers for many years as suppliers of control systems. By combining their views on the various topics covered it has been possible to express a highly representative view of the industry in a way which no single author could hope to achieve. This book sets out to be not only factual and useful, but also:

- to be *real*, with the information put forward based on practical experience combined with practical examples;
- to be *readable*, with the minimum of jargon, theory and formulae so that those with a minimum of knowledge, or some understanding and those with a more general interest are able and will want to follow it;
- to improve *opportunity* for people in the industry, by indicating what can be achieved now, what is likely to be possible in the future, and how these goals can and should be achieved.

By meeting these objectives this book is appropriate for readers drawn from a number of different situations. This includes students studying the subject at college or university, who are rarely exposed to practical problems or real life knowledge: there are very few books available which offer a *real* view of controlling a process plant or how to apply the theory which has been learnt. Also there are many practising electrical engineers who know how to design elements of the control scheme but would benefit if they understood how the *total* system might be put together.

Within the project teams implementing these schemes are those who understand the process well enough to know how it works but do not know what computers are capable of, and those who understand computers but do

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not have the experience or knowledge required to use them to their full advantage. Furthermore, people such as the plant or production engineers may have a wealth of experience of how the process works or how the product is really made but may not understand how modern controls can help them (and maybe do not want to admit it?). Lastly (but not least) are those who are being asked to invest on average 30% of the total project cost in sophisticated control systems. It is easy to imagine that they might like to know what they will get for their money.

As stated above, the important principle maintained throughout this book is that it is practical and easy to follow. There are many books around which offer pages of formulae and complicated control engineering theory which are rarely used by most practising engineers, let alone those who operate on the fringes of the business, or who have yet to experience the vagaries of a food processing plant for the first time. Of course control theory is very important if you need to study the detailed operations of a process, but most food processes do not require this level of detail. What is required, and most fundamentally so, is a good, common sense, pragmatic view of what can and should be achieved. This book is aimed at developing this by indicating the key areas where attention must be directed if a successful project is to be the result.

It is inevitable within a book covering such a wide subject that not all aspects of automation can be covered. Equally, not all food industries can be represented by example. However, it is fair to say that automation systems are reasonably general in their suitability if the problem is defined correctly. It is this definition which is usually the major contribution to the application of advanced systems, not the systems themselves. Given a meaningful examination and understanding of the processes, and how they relate to the other process stages and the overall factory operation, a full automation strategy can be identified and implemented.

This book identifies those issues which make a fundamental contribution to the success or failure of a project. It is worth noting that few automation schemes 'fail' as such, but all too often they do not deliver the potential they are capable of.

Within this book, therefore, the scene is set in Chapter 1 by examining food processing as an industry, and the role of automation within this. This chapter indicates how, by looking at the stages of food preparation through to final product, this is not such a daunting task, as long as it is considered as several elements.

Whilst it is necessary to identify separate modules or stages within the process itself it is essential to maintain a total view of what is to be achieved. This suggests a 'total systems' approach, where not only the automation of the plant is considered but also the way the factory is run. This may not only require a review of what automation is appropriate, but also how production is scheduled, how management structure their operations and so on. The need for this approach is expanded in Chapter 2.

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The next two chapters look at how integrated factories can work, what is possible if this approach is adopted and how one can prepare specifications in such a way as to ensure that the final project achieves the ambitions set.

In order to ensure a good background of understanding, the various types of computers available are examined in Chapter 5, with an insight into what they can achieve and how. This is followed by reference to a most important part of any automation scheme: the interface with the people who will work the plant once built. Operator interfaces must be designed for operators and managers, and not just to satisfy the engineers who design them. This demands a good ergonomic approach and Chapter 6 highlights some of the main features to consider.

Having examined what is possible by adopting the right approach the book then looks at how these objectives can be achieved. Important factors which have to be considered are that the accuracy of the final system must be good enough, and that the components of it must be reliable. Unfortunately the automation industry abounds with loosely defined terminology and these two elements fall within this area. Chapter 7 looks at what these terms mean in practice, and how to assess what is required, and what is achievable. There is a need to include some formulae in this area, which tends to make this chapter appear somewhat mathematical, but as both of these subjects rely heavily on mathematics and statistics some presentation of this was unavoidable. However, to maintain some sanity the formulae presented have been kept brief, and examples have been used to illustrate the point. Furthermore, lengthy proofs of the final formulae have been excluded in the interest of keeping the book readable.

Chapter 8 reviews how food processes can be automated in practice with examples of how, or how not, to approach the problems encountered. It develops the themes established in the earlier chapters and illustrates the fact that automating a food factory need not be a daunting task.

It is essential within any project to keep a realistic view of what needs to be achieved, and this will normally mean using currently available technology—tried and tested—to satisfy this. However, if the plant is to be expandable in the future it is vital to maintain a longer term view, and an understanding of future developments must be retained whilst applying 'today's' technology. In this way updating with new techniques or equipment will be relatively easy. The final two chapters look at the direction in which the industry is moving, and Chapter 10 in particular identifies what could become an advanced technique in creating friendly, controllable process plants within the food industry.

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1 Introduction to food processing

TOM GREEVES

1.1 Introduction

The food industry employs a very wide range of processes in order to prepare and package food products for the consumer. These range from simple cleaning and sorting operations, to complex size reduction, mixing, heating, cooling and forming processes. The food industry has evolved along with the consumer market, each stimulating the development of the other, the requirement of the consumer market being for food products in convenient form, of uniform quality, and with sufficient shelf life. An important consequence of this development is that packaging in some form or other constitutes a key element in all food processing operations.

The food industry depends for its raw materials on the agricultural industry, both at home and abroad, and the purchasing of good quality produce, handling and storing it correctly, and managing the complex interaction of supply and demand is an essential part of successful operation. Both supply and demand are often strongly seasonal and not necessarily in synchronism and so the discipline of logistics must be applied to manage the supply chain. Uncontrollable variables such as the weather can affect the quantity, quality and price of the raw materials and the manufacturing system must continue to operate in spite of these difficulties.

The output from the manufacturing plant is likely to pass through one or other of the major outlets, who have increasing buying power and place further pressures on manufacturers to reduce costs. The low-cost producer has the advantage, but at the same time the consumer is demanding wider choice and so manufacturing systems must offer not only efficiency but also flexibility. In addition, the quality expectations of the consumer are placing a premium on tight control at all stages.

In order to meet the problems of erratic supply and demand it is necessary to carry stocks of raw materials and finished goods. The cost per unit of finished goods is considerably higher than that of the raw materials and packaging materials from which it is made up due to the addition of factory costs such as staffing, energy use, maintenance, depreciation and various services. It is therefore preferable, if technically feasible, to carry any sizeable stocks as raw materials.

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Nevertheless some stock of finished goods is inevitable in order to ensure continuity of supply and to respond to sudden demands. Going 'out of stock' may result in a loss of sale which cannot be recovered later and this will have an adverse effect on the year's profits.

Another reason for carrying stocks of finished goods is to enable manufacturing plant to run on a given product for a reasonable time before changing to another. Changing from one product to another loses production time and the machines nearly always take time to settle down again after a change. Frequent changeovers therefore lead to inefficiencies in production and there is a trade-off between the cost of carrying stocks and the cost of frequent changes. A flexible plant capable of rapid and efficient changeovers will enable lower stocks to be carried with consequent savings. Automated monitoring and sophisticated plant scheduling are often necessary to enable potential benefits to be realised.

The task of the project engineering team designing a new manufacturing system, or reviewing an existing one, is to find the best way of resolving the various demands which will be made on the system so as to give the optimum return on investment. To meet all the demands fully may cost too much, to go

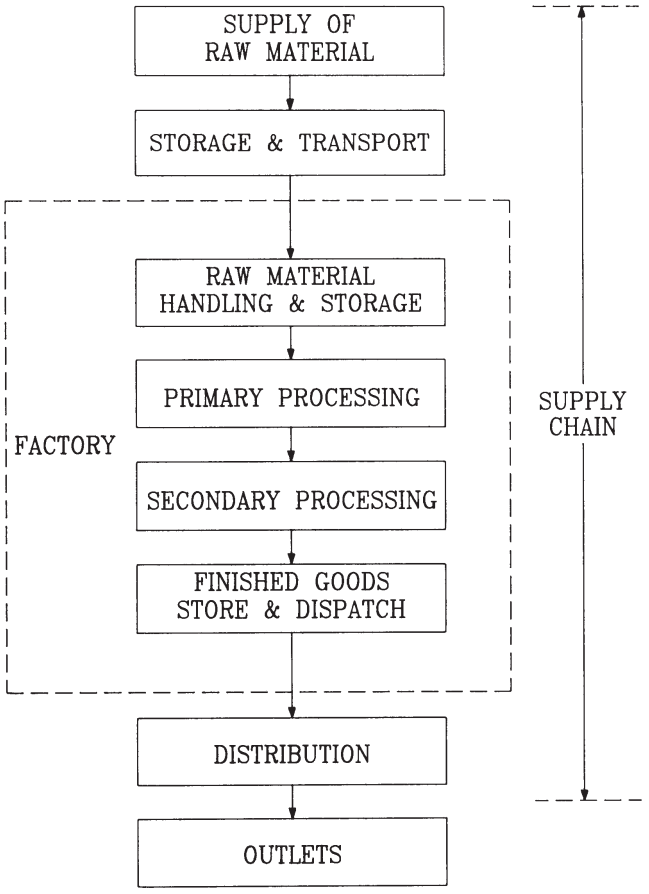


Figure 1.1 Stages of manufacturing system

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for the least cost option may not be acceptable in terms of technical or commercial risks, therefore it is often necessary to evaluate a range of options so that the best all-round solution can be selected and agreed by everyone concerned. The level of the control specification often lies at the centre of such debates and it is important for control engineers to be aware of the wider context within which their system should operate as well as the technical requirements of the processes which must be controlled.

In what follows we are primarily concerned with the technical requirements and in the next four sections the essential characteristics of food processes are discussed. Although food processes are very diverse in nature it is nevertheless possible to identify major process stages which occur in most cases. These are set out in Figure 1.1.

Within each of these stages it is possible to identify three types of systems requirement: the control of individual machines or process elements; the coordination of groups of machines and process elements to form an effective production line; and a range of communication tasks to enable the coordination and scheduling of the line by providing interfaces with machines, operators, maintainers and management.

In the following sections attention will be focused on the control of machines and processes. Later chapters will deal with the coordination and communication aspects.

1.2 Raw materials handling and storage

1.2.1 *Categories of materials*

A wide variety of produce and materials may need to be handled. Figure 1.2 indicates some of the general categories into which raw materials may be divided together with the most likely means for conveying and storing them.

Categories 1 and 2, i.e. liquids, powders and granular materials, lend themselves readily to bulk handling. These are likely to be received from a primary processing factory such as a sugar refinery whose output has been stored in tanks and/or silos so that transfer to a bulk road or rail tanker and subsequent transfer to receiving tanks or silos can be effected under automatic control.

Sugar, in liquid or granular form, glucose, various fats and oils, milk, salt and flour are typical examples in these two categories and the technology for handling and storage of these materials is well developed.

Category 3, i.e. processed beans or grains, requires a more individual approach. Some can be pneumatically conveyed in either dense phase or dispersed phase systems; in other cases mechanical systems such as a chain driving paddles through a tube, or a screw conveyor, are preferred; or in the case of fragile materials belt conveyors may be used which exist in a variety of ingenious forms to improve the containment of the materials. Examples in this

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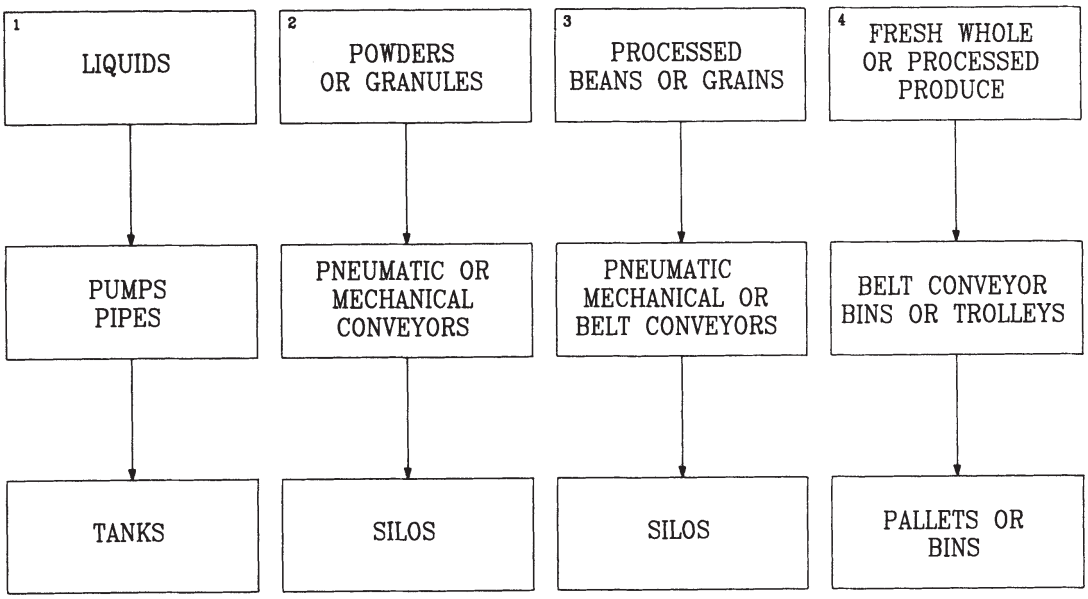


Figure 1.2 Raw materials handling and storage

category include cocoa or coffee beans, cereals, rice and nuts. The pre-processing may include fermentation and drying, shelling and dehusking, or merely separation from trash.

In the case of category 4 materials, i.e. fresh produce, either whole or pre-processed, the produce may arrive in bulk or in bags or sacks. Belt conveyors are likely to be used or the materials transferred in bins, trays or pallets and moved around by trolleys or overhead conveyors.

1.2.2 *Identifying incoming materials*

In all cases it is important—and with certain produce vital—that the incoming delivery is correctly identified, its quality verified, its quantity measured, and the delivery stored in such a way that its identity is preserved to the required degree. Fresh produce must be packed and dispatched, or put through a preservation process, within a closely controlled time span to avoid deterioration. With bulk materials such as sugar, it may only be necessary to record the quantity for cost control purposes and ensure rotation of stock.

An excellent way of keeping track of deliveries is the bar code system. A unique number is allocated to the unit of delivered materials which is coded as a series of variably spaced bars which can be read by an optical detector. The code relates to records stored in a computer and the system relies on the primary data being entered correctly, preferably at the point of despatch. Such a system readily lends itself to the capture of a wide range of relevant data about the delivery. In the absence of suitable equipment and personnel at the despatch point, the raw data must be entered when the delivery arrives at the factory. Data required might include: origin, date despatched, date received, quantity, quality index(es) and unit cost.

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1.2.3 *Control and information requirements*

The principal control requirement for the raw materials handling area is sequence and conditional logic to control the transfer of materials to and from their correct storage location. A wide range of programmable logic controllers (PLCs) is available which can fulfil this function. Computer-based systems are used for large installations. In order to keep track of the quantities delivered there is also a need for metering and weighing.

The data acquisition and management information systems are generally structured so as to be independent of the control system although information exchange between the two systems can be provided. Various attempts have been made over the years to facilitate such interchanges by standard communications protocols with, until very recently, limited success.

1.2.4 *Example of tank farm*

As an example of bulk handling, Figure 1.3 shows a tank farm for liquid fats. Depending on their setting temperature, the fats may have to be kept warm to ensure their liquid state; so the tanks will be double skinned to form a jacket with hot water circulated through it. All pipework is also likely to be jacketed at a controlled temperature. These fats might be required in a bakery for biscuits, pastries or cakes, or in an ice cream factory as the base material, or in a chocolate factory as the fat for chocolate or for various confectionery materials such as caramel or fudge. In addition to the tank farm a blending system is shown which constitutes the first process in the manufacturing system.

Whatever the end use of the fats, they must be identified precisely on arrival and routed to the appropriate storage tank. Once in store it may then be necessary to measure key properties of the fat and blend it with other deliveries in order to produce a result with the required properties. Fats of the same nominal type may vary in their precise properties, for example their setting temperature, due to the effects of soil and climate in different growing regions together with small genetic differences. Blending based on suitable measurements leads to consistent product quality, consistent performance of manufacturing plant and a minimum cost blend. A combination of these factors can result in substantial overall cost savings as well as protecting the quality of the end product in the market place.

Such a system requires three pipework systems, one delivering from the reception point to the individual tanks in the tank farm, another transferring from any of the tanks to a blender and a third pipework system from the blender to two or more blended fat storage tanks. The amount of blended fat storage is kept to a minimum to maintain maximum production flexibility as well as minimising the added cost to the inventory. The blender shown in Figure 1.3 consists of two simple jacketed stirred vessels, used alternately, which are similar to the storage tanks but smaller, with a second and still smaller tank mounted above them for minor additions.

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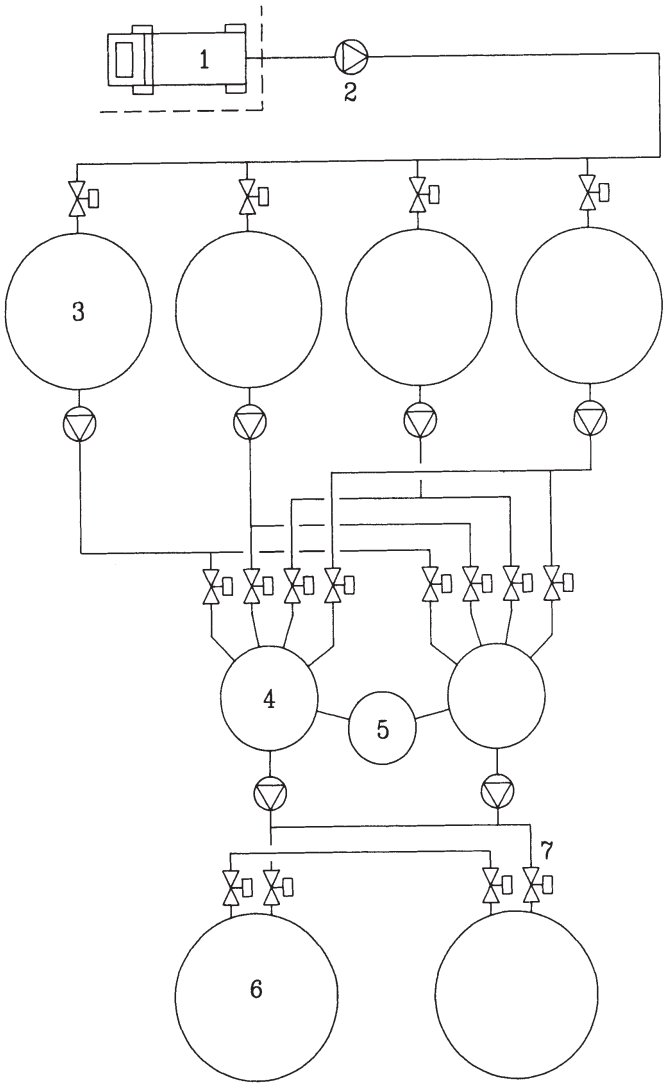


Figure 1.3 Tank farm for fats. Key: 1, Delivery tanker. 2, Reception transfer pump. 3, Typical storage tank. 4, Blenders. 5, Small additions vessel. 6, Storage tanks—blended. 7, Motorised valve.

The effective operation of such a system depends on getting the fats into the correct tanks without cross contamination, obtaining an accurate measure of the quantity in each tank and transferring the blend quantity to the blender with the required degree of precision.

Reliable transference without cross contamination is achieved by power-actuated valves used to set up the correct route from the reception point to the tank in question. In the example given the routing is very simple but it is essential that the position of every valve is confirmed by means of limit switches before the pump is started.

The pipe route selected may be of considerable length and thus contain a significant quantity of fat; it is therefore usual in some situations to use a 'pig' to sweep the pipe clean at the end of each delivery. The pig is a plug, often spherical, which is inserted behind the end of the batch and driven through by compressed air or by the next batch.

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Pigging systems require the pig to be returned and involve some degree of manual intervention and are therefore only used when less rigorous methods are not acceptable. It may, for instance, be acceptable to use the next batch to drive the end of the previous batch into its tank, switching the routing valves on a basis of time or pump revolutions to the new tank at the optimum moment. This will not give a perfect cut-off but may be good enough.

In other cases it may be considered that adding the contents of the pipe to the wrong tank is acceptable and can, for instance, be taken care of by measuring the relevant properties after the tank contents have been thoroughly mixed. Clearly, if the liquids were so different that they must never be mixed, then completely separate pipe systems would be used.

An important requirement is to measure the quantity of fats at all stages in the process, such as for stock control (in which case high accuracies are needed), or for the control of blending, where the accuracy does not need to be quite so high.

In view of these requirements it has become common practice to mount storage tanks on load cells. This provides a reliable and accurate measure of the total weight of the tank and if the weight of the tank when empty is subtracted then the weight of the contents is obtained. This is a relatively expensive solution which is justified in the case of expensive materials, or where high reliability is required, or where difficult materials are involved which are not amenable to cheaper measurement techniques such as level detection or the measurement of pressure at the bottom of the tank. The connection of pipes and pumps to tanks on load cell may create a problem and care is needed to ensure that the pipe stresses are not affecting the weight.

The two blending vessels are also likely to be on load cells since, although the quantity transferred from the storage tanks is obtainable from their loss in weight, they are likely to be up to ten times larger than the blending vessels, with a corresponding loss in accuracy. The same argument applies to the 'small additions' vessel which may be an order of magnitude smaller than the blending vessels.

The alternative is to use flowmeters to measure the quantity as it is transferred; for simple liquids such as fats this is perfectly feasible. But the problem of maintaining high accuracy in flowmeters and the difficulty of routine calibration makes the load cell alternative preferable in many cases. The question of metering and weighing is dealt with in more detail in a later section.

1.2.5 *Example of flour blending*

Figure 1.4 shows another example of bulk handling, this time for the various flours used for biscuit making. As with fats, the properties of flour vary considerably and it is necessary to bring together the right blend for each type of biscuit. The bins receive deliveries of flour in the same way as the tanks

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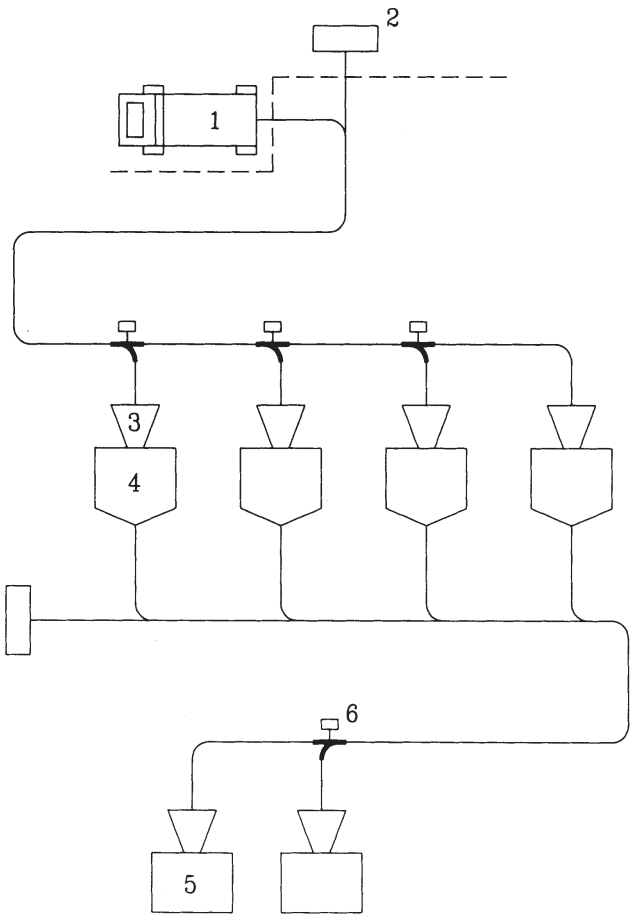


Figure 1.4 Silo system for flours. Key: 1, Delivery tanker. 2, Blower. 3, Cyclone/filter. 4, Typical silo. 5, Dough mixer. 6, Diverter valve.

receive deliveries of fats, and the relevant details of each delivery need to be entered into the control system, including laboratory test data, so that the appropriate blends can be determined. From the storage silos correct quantities of the various flours must be transferred to the dough mixer, which then mixes the flour with water, fat and other ingredients and kneads them into a dough for feeding to the biscuit-forming machine.

The silos and the dough mixer are likely to be on load cells, and as the dough mixer is small compared to the silos its gain in weight, as each successive flour is added, is used to control the amount of each type of flour. Since the pneumatic conveying air clears out the pipe after each batch the problem of dealing with the pipe contents is reversed; the question now is when to stop the silo feeding so that the quantity 'in-flight' makes up to the correct amount in the mixer.

To overcome the problem of flour 'in-flight' the silo discharge must be stopped before the weight in the dough mixer has reached the required value. This is known as 'in-flight compensation'. It is common practice for systems to incorporate self-tuning in-flight compensation. The control system is programmed with a value for the estimated weight of flour in-flight from each of

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the silos and when the weight in the dough mixer reaches the required value, less the in-flight weight, the silo discharge will stop. The resulting weight is then checked, and if it is a little too high or too low a corresponding correction is made to the in-flight weight to be used next time. In this way the system can settle to a high accuracy after two or three batches. The system will start up next time with the figure it ended up with on the previous occasion.

1.2.6 *Example of milk reception and storage with CIP system*

A final example of bulk handling is milk reception and storage. Whereas the fat storage tanks had to be heated to keep the fat liquid, for milk it is necessary to reduce temperature below 5 °C in order to prevent the growth of bacteria. In addition there is a need to clean and sterilise the milk processing plant at regular intervals to remove any solid materials that could provide sites for the build up of pathogenic organisms. In the past the whole system would be dismantled and the components manually cleaned in tanks of hot detergent and rinse water. Clean in place, or CIP, systems avoid this laborious process by pumping the fluids through the system.

In modern farms the milk is stored in chilled tanks rather than churns, with the farm having its own chiller unit. Periodically a tanker visits the farm and transfers the milk to the dairy for bottling or to processing factories producing various other products. A sample is taken at each farm to enable quality assessments to be made such as fat percentage, percentage total solids and microbiological counts. On arrival the milk is transferred to a storage tank and is released into the process if the quality is satisfactory. Payment is usually related to total solids.

A very simple reception system is illustrated in Figure 1.5. All pipes, tanks, valves and pumps will be in stainless steel to BS 316 or equivalent so as to withstand attack from the cleaning and sanitising chemicals.

The pipes, pump, tanks and heat exchanger used for milk must be periodically subjected to the CIP process. In its full form this has five stages: wash through with hot water; recirculate hot detergent; rinse with hot water to remove the detergent; rinse with a sanitising fluid; final rinse with hot water to remove all chemicals, followed possibly by a rinse with cold water to cool all the pipework and tanks.

The effectiveness of the process depends on the flowrate which must generate turbulence to remove 'soil', the concentration and temperature of the cleaning fluids and the time allowed for each stage in the process. All the parameters must be closely controlled and monitored, as is the operation of valves so that cleaning fluids cannot contaminate the milk. Special valves are used with double seats and limit switches to give a positive indication that the valve is fully open or fully closed. The concentration of detergent and sanitiser is monitored by conductivity meters.

In more complex systems it is common to divide the process into categories

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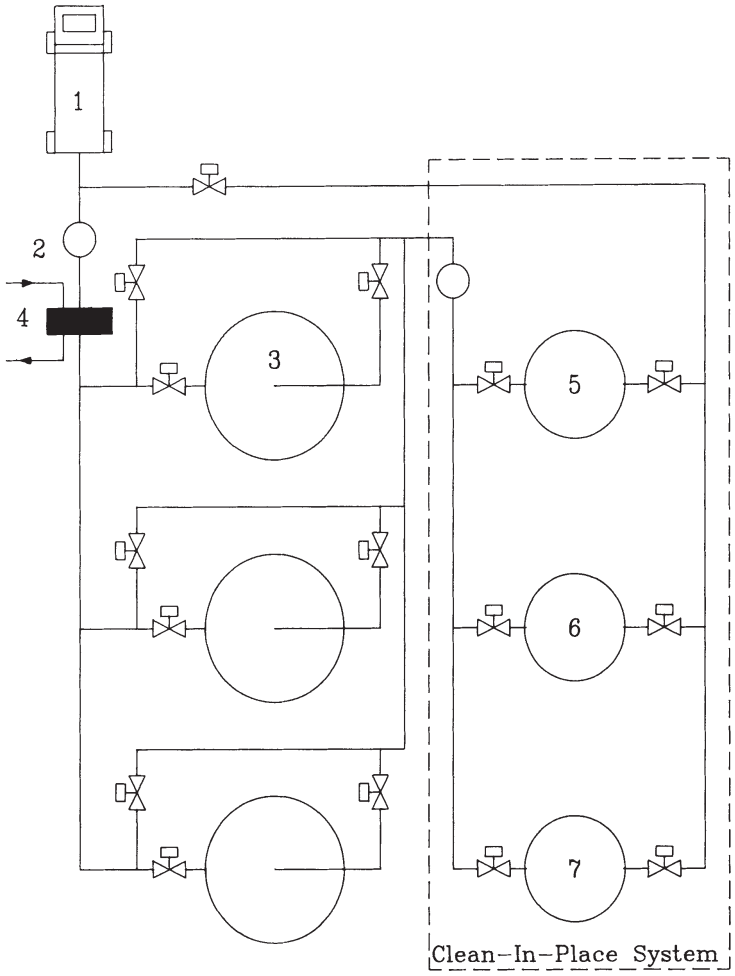


Figure 1.5 Milk reception with CIP system. Key: 1, Delivery tanker. 2, Reception transfer pump. 3, Chilled storage tanks. 4, In-line chiller. 5, Hot water wash tank. 6, Chemical cleaning fluid. 7, Hot water rinse tank.

of plant which may require different flowrates and/or cleaning fluids. Typically pipework would fall into one category, equipment such as heat exchangers into another and tanks into a third category. For tanks a spray ball is fitted in the top of the tank and the various clean and rinse fluids fed to it under pressure.

Some CIP systems operate on a once-through basis, others recirculate all the fluids to their respective tanks, whilst a third category is a combination of the first and second. Recirculation saves energy and chemicals but might compromise cleanliness, whereas the combined system incorporates the best features of the two extremes. CIP systems form an important adjunct to many primary processes. In those where heating takes place cleaning requirements are particularly onerous. Cleaning inevitably wastes some good product and there is therefore an incentive to switch to drain at the last possible moment during the time the milk is being flushed out of the system with hot water. Both turbidity and conductivity meters have been used to detect the boundary between milk and water.

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1.3 Primary processing

As stated in the introduction, there is a wide range of processes used in the food industry, some of which do not require a great deal in the way of control whilst others require feedback control for their effective operation right from the outset. For instance, pneumatic three-term controllers were used to control many thermal processes as much as forty years ago.

1.3.1 *Batch versus continuous processes*

Whilst batch methods are still preferred in some cases, the trend over the years has been towards continuous processes. The control requirements for these two categories are significantly different; continuous processes need constant conditions to be maintained whilst batches require the control of changing conditions. Sequence and conditional logic are at the heart of batch processes, but for continuous processes the main requirement is for two- or three-term controllers, sequence and conditional logic being confined to automatic start-up, routeing, shut down and emergency procedures. Continuous processes which are required to vary in output are usually viewed with some apprehension and this topic is taken up again later.

Some typical processes are listed in Table 1.1.

Table 1.1 Process operations, devices and process types

	Device type		Process type	
Process operation	Sensors	Actuators	Continuous	Batch
Sieving		M	1	3
Water washing/separation	f	M,V	1	—
Air separation	f	M	1	—
Grading		M	1	—
Comminuting (cutting up)	e	M	2	2
Grinding (size reduction) and sizing	e	M	1	—
Mixing to work the material	t	M	3	2
Mixing to combine materials	t,m,w	M	2	2
Blending powders	f	M,V	2	2
Blending liquids	t	M,V	2	2
Freezing	t	M,V	2	2
Drying	t,f,m	M,V	1	3
Heating to develop flavour	t,p,f	M,V	1	3
Moisture reduction/control by evaporation	t,p,f	M,V	1	3
Cooking to change key properties	t,p	M,V	2	2
Baking	t	M,V	1	—
Pasteurising	t,f	M,V	1	—
Sterilising	t	M,V	1	3

Sensors type: e, electric current; f, flow; m, moisture; p, pressure; t, temperature; w, weight.
Actuators: V, valve; M, motor.
Process type: 1, usually; 2, often; 3, sometimes.

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1.3.2 *Modularity*

In approaching the design of the system it is important to view the process as a whole and, where appropriate, to coordinate its operation with a supervisory control system. It is also important to identify the unit operations comprising the process and create each logical unit as a manageable module. The mechanical elements of the process, the electrical control gear and computer hardware, and the software should, as far as possible, conform to this modular structure and its existence should be reflected in the operator's interface—indeed one or more modules should ideally coincide with the responsibility of an operator. In this way the plant becomes easier to understand and training of operating and maintenance staff is facilitated.

1.3.3 *Mixing*

The description given of flour handling and blending in a dough mixer in the previous section is similar in principle to many batch mixing processes. With batch mixing the gain in weight of the mixer may be used to control the addition of the ingredients, which might include powders, granules, liquids and pastes. In the case of liquids there is the option of using flowmeters to measure the quantity added to the batch, and for thicker liquids and pastes the measurement would be of the number of revolutions of a positive displacement metering pump.

With materials which are unstable or in a dynamic state the mixing is best done as a continuous process so that the resulting mix reaches the next stage in the process in a uniform state. The nougatine centre of a confectionery bar line is a typical example: sugar syrup, fondant and egg whip must be blended with, say, nuts, raisins and crispies, and then spread to a uniform carpet for cooling, cutting and covering with chocolate. Batch processes lead to cyclic variation in key properties such as density and hardness whereas a continuous process gives a more uniform result.

For continuous mixing flowmeters or metering pumps are essential. In the case of pure liquids of low viscosity, such as are found in the soft drinks industry, reciprocating metering pumps of high accuracy are used to add colours and flavours to the basic sugar/glucose mix. The sugar concentration is continuously monitored and the ratio of sugar to water modulated to achieve a constant concentration. Measurement may be by density or optical refraction.

In other industries where high viscosity liquids or slurries containing solid materials must be handled, reciprocating metering pumps are unsuitable and therefore less precise rotary pumps must be used. It is desirable to include a flowmeter so that the speed of the pump can be modulated to produce the required flow more precisely.

Magnetic flowmeters provide a ready solution for water-based liquids and slurries but fat-based slurries have too high an electrical resistance and other

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physical properties must be used. Some of the many types of flowmeters are described in a later section. Where no suitable flowmeter is available it is necessary either to rely on the performance of a positive displacement pump or to employ the loss-in-weight principle. The latter has the great advantage of being based on integrated flow rather than instantaneous flowrate and this leads to much greater overall accuracies.

Powder or granular materials are generally fed by screw feeders or similar special purpose devices. They are either treated as positive displacement devices—which in reality they are not—or the speed is modulated on the basis of the loss-in-weight from the feed container. Caking up or bridging can be an intractable problem with powders especially when they are hygroscopic. Raisins and similar soft ingredients present particularly difficult feeding problems, and these products warrant special attention.

1.3.4 *Evaporators and heat exchangers*

A major requirement in food and confectionery processing is the reduction and control of moisture. Many confectionery processes begin with the need to dissolve sugar in water and maybe to add glucose, milk or emulsified fats. The resulting mix must then have much of the water removed again in order to create the conditions for sugar crystallisation, as in fondants and cremes, or to produce sugar glass as in boiled sugar sweets, or to produce chewy materials such as caramels, toffee or nougat.

Special purpose heat exchangers have been developed for each of these requirements, and in all cases very precise temperature control is required. Plate, concentric or spiral tube and scraped surface heat exchangers are all used in this industry. The latter is inevitably the more complex and expensive but is often essential in dealing with difficult materials. Steam is virtually always used as the heating medium as it is readily generated and distributed around the factory, is controllable and is non toxic and hygienic. Passout steam from 'combined heat and power' systems provides a cost effective solution.

Having defined the moisture content by boiling to a predetermined temperature the material must be cooled down to the correct temperature for use. In the case of sugar glass or caramels, toffees, etc. the cooling is carried out with the least possible agitation in order to avoid encouraging sugar crystallisation. It is therefore common to spread the material onto the surface of a stainless steel band or drum cooled by chilled water.

For fondants and cremes cooling is accompanied by controlled agitation in order to initiate sugar crystal formation and to control the size of the resulting crystals. Chilled water or a refrigerant may be used on the other side of the heat exchange surface.

Cooling with agitation also occurs in the 'tempering' of chocolate prior to its use. The process of tempering consists of the controlled development of cocoa

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butter crystals so that the chocolate will set in the required manner. The fluidity of the chocolate must be right for subsequent processing and the combination of crystal forms must also be correct so that the resulting article has a good colour and gloss when cooled.

Most food and confectionery processes, both heating and cooling, require a measurement of the temperature of the material in order to control the flow of heating or cooling media. Where the material is dynamically unstable it is often extremely difficult to obtain a representative measurement due to build-up on the probe and/or channelling of the main flow. Radiation pyrometry may sometimes be used to good effect.

In crystallisation processes the heat removed is a combination of sensible and latent heat, and since the latter may have little effect on temperature it is sometimes necessary to measure parameters additional to temperature in order to maintain full control of the process.

1.3.5 *Vacuum and pressure cooking*

Some processes are carried out under reduced pressure to boil off moisture at reduced temperature. This is used in jam making to achieve a fresh fruit flavour. Another example is in milk concentration where operating under partial vacuum reduces heat damage to the milk protein and at the same time enables very large savings in energy through the use of multiple effect evaporation. All these reduced pressure processes require the measurement and control of vacuum.

Conversely, some processes operate at elevated pressures. For instance, the process of pasteurisation, which is designed to kill micro-organisms with minimum damage to the flavour and nutritional value of food materials such as milk. This is achieved by raising the temperature very rapidly in a continuous process by, for instance, steam injection under pressure, holding for a closely defined time in a delay tube, and then quickly dropping the temperature by releasing the pressure through a relief valve and hence 'flashing off' the steam again. The cooling effect may be enhanced by flashing off under reduced pressure.

Pressure cooking is also used to hasten normal cooking processes in food preparation and to accelerate the Maillard reaction for flavour and colour development in caramels. Elevated pressures are also used to reduce the time cycles in sterilisation and canning processes.

1.3.6 *Variable flowrates*

The problem of varying the flowrate through continuous processes was mentioned in an earlier section. An example is that of a continuous plant where the slurry must first be taken through a preheater and held at an elevated temperature in a delay tube to induce flavour development, then passed

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through an evaporator to establish the moisture level, and finally cooled to the required temperature.

If the throughput is increased the time in the delay tube is reduced, and so the preheater temperature must be increased in compensation. In practice, when throughput was increased it was found that the preheater showed a substantial delay and some instability in responding to the extra demands of both throughput and temperature. Evaporators are generally more stable and these responded reasonably quickly. Throughput could be all too easily changed just by speeding up the pumps.

Various attempts were made to develop an acceptable ramp change in pump speed, but in the end a simple and elegant procedure was discovered which provided an optimal solution and may have more general application. Rather than ramp the throughput up or down, the slowest element, i.e. the preheater temperature, was simply set to the required temperature and the actual throughput was driven by the temperature as it climbed to the new value.

1.3.7 *Effluent*

Primary processing nearly always produces waste materials, especially in the early stages of treating the raw materials. These waste materials may be dry, such as bean husks which can be sold as fertiliser, but most will be in slurry or liquid form. To these liquid wastes must be added large volumes of washings.

Handling and processing waste of all kinds should be seen as an integral part of primary processing—putting them 'down the drain' is not good enough. Where possible an economic value may be extracted from them, for instance as animal feed or fertiliser, but where this cannot be achieved they must be treated as effluent.

It may well be that the local municipal sewage works can deal with the plant effluent, but at a cost which needs to be investigated and compared with alternatives. In the case of a large manufacturing unit it may be more economic to build a dedicated treatment plant especially where large quantities of waste arise such as in the production of instant potato granules. Symbiotic systems have been attempted where one process feeds off the waste of another, e.g. pigs fed off potato peelings.

1.3.8 *Dispensing and container handling*

Many food products are dispensed directly into tins, jars or plastic pots and containers of various kinds. They may be liquids or slurries, solid pieces in a liquid, or powder or granules.

Where precise volumetric metering is possible, the filling process is carried out at a single filling station. In some cases the container may be tare weighed

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before filling and weighed again after filling so as to provide monitoring data for manual, or automatic fine tuning of the filler.

With powders or granules, two filling stations are often used with an additional weigh station in between. The filling mechanism consists of an auger which rotates through an accurately controlled number of degrees (usually several rotations) to place in the bulk of the contents. The result is measured and the number of degrees of rotation for the second filler is calculated so to make up the balance. The result is then checked on the final weigh head and a fine adjustment made to the calculation constant if required, to compensate for changes in bulk density or other properties which may occur.

Bottling plants for soft drinks, fruit juices and beers can be made to operate at high speed, e.g. 600 per minute. A rotary multihead filler (e.g. 24 heads) is used and with carbonated drinks the bottle is filled under pressure. Filling is followed by capping and mechanical crate handling, loading and palletising. A decrater is used for returnable bottles, followed by bottle washing and drying prior to filling.

Optical fill detectors are used to check on the operation of the filler since excessive headspace not only gives short measure to the customer but with carbonated drinks represents an explosion hazard. Optical bottle inspection is a difficult operation to accomplish reliably at high speeds and methods to do so have met with only limited success. These check for chipped necks and dirt on returned bottles and glass imperfections on new ones. Plastic 'PET' bottles are competing with glass in some cases.

1.3.9 *Shaping and forming*

In chocolate, confectionery and snacks the base materials are usually formed into the shape preferred by the consumer. There are a number of processes, such as moulding for chocolate, cremes, boiled sweets and jellies. Moulding plants are often substantial machines where large plastic moulds, containing a number of impressions of the desired articles, are carried by chain systems through a series of operations. A mould heater brings the mould to the correct temperature to receive the product which is deposited into the mould by a plunger type volumetric filler, usually followed by mechanical shakers to settle the product, with lengthy cooling of up to 20 minutes. Demoulding and delivery of the product to the wrapping and packaging system follows cooling.

Demoulding of chocolate presents no problem due to the convenient property of cocoa butter in contracting when it sets. Boiled sweets are demoulded by ejector pins in the bottom of the mould impressions, whilst jellies and fondants may be moulded in rubber moulds and simply pressed out when set. Cremes and jellies can be moulded in rigid moulds with the prior application of an oily release agent and then demoulded pneumatically via small holes in the impression with compressed air applied to the back of the

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mould—the so-called starchless moulding process. Starch moulding is described in the next section, as is the shell moulding process.

Sheeting the materials onto a belt, cooling and then slitting and cross cutting is another common process. The sheeting process produces a uniform layer of material carried on a belt of, say, 700 mm width. After cooling to a precise temperature the sheet passes through slitting discs which produce a series of ropes. The ropes are spread onto a wider belt, say, 1400 mm wide, and then passed under a transverse guillotine, or 'cross cutter', which produces the individual pieces. Materials which cannot be moulded are shaped in this way. This process lends itself to layered product structures.

Extrusion through a line of dies across the width of a belt provides a method of producing ropes of simple cross-section shape, and concentric extrusions of different materials allow variety and interest. A cross cutter divides off the individual pieces as described in the preceding paragraph. Many products which have been produced by these methods are subsequently covered in chocolate by the process known as enrobing where they are carried on a wire band through a curtain of chocolate.

Biscuits are sometimes extruded and sliced off with a wire cutter and deposited onto the oven band, but the rotary moulder is the most common device. The dough is sheeted and a rotary drum with cutters shapes the biscuits, the waste web being subsequently recycled.

Cook extruders are devices developed from plastics extruders to produce expanded, cereal-based snacks. The extruder screw and barrel mix and heat the mixture of cereal grains and flour leading to a change in the protein structure and expansion due to flashing steam as it leaves the die. This results in the expanded structure found in many snack products.

1.3.10 *Example of a confectionery assortment*

Confectionery assortments provide an interesting example of the progressive automation of both primary and secondary manufacture. Many confectionery centres for assortments are made by depositing the various cremes, caramels, jellies, etc. into impressions made in trays of starch. The trays are stacked in cool rooms to allow them to set (a lengthy process) and are then tipped out so that the centres can be fed to the chocolate 'enrobing' line and the starch recycled.

This process involves handling quantities of starch, which need to be conditioned by heating to control moisture content, as well as any dust nuisance and explosion hazard; an awkward handling problem can occur at the point where the centres must be fed to the enrober. Although ingenious feeding devices have been developed, some centres must be hand fed, and labour use tends to be high.

With this style of centre production it is feasible to enrobe a number of different types of centre simultaneously so that the hand packing operatives at

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the end of the line have immediate access to a high proportion of the assortment without the need of any intermediate handling and storage. In these circumstances those centres manufactured on special purpose plants are supplied in trays drawn from an intermediate store.

Over the years an increasing proportion of assortments have employed starchless moulding techniques or have moved away from enrobing to the shell moulding process. The latter comprises three moulding plants in one very large machine. A chocolate shell is created by filling mould impressions with chocolate, shaking, inverting the mould and tipping out about 60% of the chocolate, reinverting and then cooling the remaining shell. The shell is then filled with creme (or whatever is required) and cooled if necessary. Finally the items are backed off with chocolate, cooled and demoulded as the finished product.

These more mechanical processes preclude the possibility of making a number of different centres simultaneously although they do permit a series of batches to be made. This necessitates substantial intermediate storage of trays of finished product 'units', which are held in automated stores. The packing of assortments is discussed at the end of the next section.

1.4 Secondary processing

Secondary processing is the handling and packaging of the product, following the primary processing stages. The boundary between primary and secondary processes is not always clear cut and varies with different types of product. For bagged products such as crisps and similar snacks the primary process produces the product in bulk, which is carried on conveyors for distribution to multihead weighers mounted above vertical form/fill bag filling machines. For convenience the weighers may be seen as the first stage of secondary processing.

In chocolate and confectionery manufacture the dividing line comes at the exit from the cooler where the individual items are delivered on a conveyor ready for wrapping. After wrapping the product is packed into cartons either directly or following overwrapping in groups as 'multipacks'. Similarly, the emergence of jars or cans from the exit of the cooler may be seen as the transition from the primary to secondary processing in the jam and canning industries.

The challenge to the control engineer comes at three levels: the control of handling and packaging machines which are often operating at high speeds, the coordination of many handling and packaging machines to operate as a complete system, and the monitoring and scheduling of secondary manufacture to optimise the use of machines and people in meeting the production plan. The control and coordination of packaging machines and systems must be closely integrated and these two functions will be considered in the following sections. Monitoring and scheduling are dealt with in later chapters.

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1.4.1 *Packaging systems*

Most primary manufacturing systems are capital intensive, with a strong economic incentive to keep production running without interruption. Furthermore, it is usually difficult to stop the manufacturing plant without producing significant quantities of scrap product whilst stopping and restarting. For these reasons the packaging system must be designed to deal with the full output of the plant at all times. This is in direct conflict with the tendency of packaging machines to suffer numerous small stoppages during the course of the day due to problems with the product, the packaging materials and the way these come together in the machine. For this reason it is essential to see the whole packaging operation as a system which must be capable of adapting to and overcoming problems as they arise.

The problem of accepting the full plant output whilst one or more wrapping or packaging machine is stopped is dealt with by a combination of strategies: spare machines, buffer stores before packaging, buffer stores between packaging stations or stages, the ability to store and refeed, and to recycle excess product.

The balance between these strategies depends very much on the nature of the product and the packaging operation. For instance, recycling is an acceptable and cost-effective method in the case of a simple chocolate moulding plant but is much less desirable where additional ingredients are involved. A useful buffer stock prior to packaging can readily be arranged as part of the bulk feed of a snack product to weighing/bagging but is much more difficult and costly where the product arrangement and orientation must be preserved, as in the biscuit and confectionery industries. The result is that systems have evolved around the particular requirements of each product type. This does not mean that the various sectors of the industry cannot learn from each other's experience, particularly with regard to the general technique of defining and analysing performance.

The definition of efficiency is a case in point, and whilst some companies have precise and well-understood definitions, in others it is undefined and vague. Alternative and more descriptive phrases are often preferable such as 'percentage up time'. The most common definition of operating efficiency is:

$$\frac{\text{Actual output over stated period}}{\text{Theoretical maximum output}} \times 100$$

Even this definition is open to debate as to how the theoretical maximum output is to be determined. For instance, what speed can be considered to represent the standard required and what allowance is made for loss in time at start-up whilst the plant is settling down? With more advanced machinery where data can be automatically logged some of these problems are eased. The efficiency of a wrapping leg on a confectionery plant for example can be measured on the basis of the number of rows of product which were available

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to be wrapped compared with the number of product units actually wrapped and packed.

The overall objective of the packaging system is to pack the required range of products and packings to the specified quality standard at minimum cost. Within this overall objective there are usually a range of options which need to be evaluated and questions to be answered. For example: What are the costs and benefits of flexibility? At what point is mechanisation and then automation justified for product lines of increasing annual tonnage? What are the pros and cons of pushing machine speeds ever higher? What is the best way of linking together successive stages of packaging? Is a buffer between stages cost effective?

The question of machine speeds is a frequent point of debate. Initially an increase in operating speed provides a corresponding increase in output, but as speed is further increased operating efficiency begins to fall at a rate which sharply increases beyond a certain speed. The machine output is the product of speed and efficiency and so there comes a point where a further increase in speed leads to a fall in output. The optimum speed is likely to be somewhat below this point.

In the case of machines in series the individual machine efficiencies need to be significantly higher than that which is tolerable for independent machines. This point is taken up in the next section, but the implication is that the optimum speed for machines when linked together is likely to be lower than the speed at which they can successfully be run independently.

The other key influence on machine speeds is the ability to feed the product to them in a regular and reliable way. Feeding systems which will accommodate the inevitably imperfect product supply and which will produce a steady stream of correctly orientated product, metered and synchronised with the machine, in many cases constitute the most demanding element in a packing system and determine the optimum speed.

The use of buffer stocks is another area of debate. At low speeds and with regularly shaped and easily handled products simple and reliable buffers may be designed which partially decouple the machines before and after them, thereby improving performance; but as speeds increase and/or difficult shaped products are involved, the technical complexity, size and cost of buffer systems increase and the efficiency of the buffer itself may become so low that any benefits which it should in theory contribute are removed.

This is an ideal opportunity for system simulation provided the basic performance data are available and are properly understood.

1.4.2 *Machine control and coordination*

Conventional wrapping and packaging machines consist of mechanisms linked together by chain or shaft drives: linear motions are generated by cams and links, and special gear boxes generate intermittent or cyclically varying

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rotary motions. Synchronisation of the various sections of the machine is achieved by phasing gears and the speed ratios are varied by variable speed gears. Adjustment of different size products or cartons requires manual intervention to adjust component positions or to change parts and fine tuning of adjustments is needed to achieve acceptable operating efficiencies.

Conventional machines connected in series suffer from problems of interaction; a small error in one machine may lead to the machine which follows it losing control or jamming, and a stoppage in any of the machines will halt the whole system. This is apparent in the practice of assuming that the efficiency of a system is the 'product' of the efficiencies of unit operations in series which together make up the system. This assumption in fact probably understates the problems of interaction, and attempts over the years to link wrapping and packaging machines together in order to reduce labour and permit high speed operation have usually resulted in very low operating efficiencies which have nullified many of the potential benefits.

Recent developments in high performance electric drives and digital systems have enabled machines to be developed which are much easier to change from one product or carton size to another and which, through the use of adaptive control techniques, are able to achieve both higher speed and higher efficiency. Ease of product change can be further enhanced by motorising the adjustment of guide positions and the like.

The control requirement for high-speed machines presents a different set of challenges from that provided by process control. Loop closure times down to 1 ms or less are often required, and the precise positioning of components at high speed requires the use of specially developed algorithms.

Advanced machines now available use a separate servo motor for driving each unit operation within the machine thus doing away with mechanical linkages and replacing these by software interconnections. The software approach confers two major advantages. Firstly, it enables the machine to be changed from one product to another much more easily and certainly than conventional machines, and since the motions can be defined and controlled very precisely by digital position feedback, the traditional fine tuning and running-up period after a change is eliminated. Secondly, and probably more important, it allows the introduction of algorithms enabling the machine to adapt to small changes in the product or its arrival position. This ability to adapt enables the problems of interaction to be overcome and the speed potential of the machinery to be realised with minimum loss in operating efficiency.

1.4.3 *Assembly automation*

Some food and confectionery products consist of a number of different products brought together to provide an assortment or variety pack. A similar situation arises with pre-prepared meals where the various components of the

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meal need to be assembled. Progress has been made in the automation of some of these processes. For instance, the assembly of small rectangular cereal packets is relatively straightforward, although when the total manufacturing system is considered as a whole a complex requirement for the coordination of a large number of machines emerges.

For confectionery assortment, where a dozen or more types of chocolate items must be placed in a plastic tray with additional packaging elements, the actual assembly operation is far more demanding. On the other hand, coordination of the total system is set against a longer timescale, due to the necessity of carrying larger stocks, and so automatic coordination is not easily justified.

1.4.4 *Example of confectionery assortment packing*

The trend in primary processing towards producing and storing serial batches of confectionery assortment units, described in the previous section, has been reflected in a corresponding trend towards team packing. A line of packers each adds a particular type of unit to the plastic trays which are carried past them on a conveyor belt. Each packer works from storage trays placed in front of him or her. Further down the line various packaging elements may be added and the plastic trays placed in their box, lidded and overwrapped.

The team-packing approach lends itself to automatic packing where each operative is replaced by a placing machine.

Although mechanical systems for placing units have been operating successfully for a number of years the development of robotic systems with computer vision promise very significant improvements in flexibility, efficiency and tolerance to difficult shapes.

The product units are transferred manually from their storage trays onto an infeed belt which is under the control of the machine. In mechanical systems the units must be spread out and then encouraged by a system of guides, side belts and rotating discs, into a single line, correctly orientated, so that a vacuum pick-up head with a fixed motion can take them from the end of a queue and place them into the plastic trays passing down the line on conveyor plates.

Great ingenuity is needed to get the units into a single stream and cause them to rotate to the correct orientation to form a queue, without continual problems of jamming in guides, etc. Although the operative unloading of the storage trays makes sure that they are all the correct way up, the units often have a plan shape which does not lend itself to easy orientation and are somewhat variable in size and/or shape. Some units defeat any mechanical system and in these cases manual placing must be retained.

The robotic system avoids the need for complex and ingenious guides and

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active components such as side belts and wheels, which are special to each shape. It permits a simple, universal and unjammable system where the units are spread, and then brought in random position and orientation to the pick up area. A solid state camera is used to determine the position and orientation of each unit and the robot is instructed to pick up each unit in turn, rotate it to the appropriate orientation, and place it in its correct position in the plastic tray. The computer vision system can also identify units which are oversize or badly misshapen in plan shape and leave them to fall into a waste tray. Unit shapes are 'taught' by showing the camera system a number of samples. Position and orientation in the tray are defined by entering appropriate data. Such systems must be fast enough to match the speed of a hand packer (up to 80 placings per minute) and cheap enough to be justified by the saving of only one person on three shifts.

1.4.5 *Finished goods storage and despatch*

Most companies stack their finished product on pallets of some kind which enable quite large units to be moved around on fork lift trucks or stacker trucks and stored in the warehouse. Typically the products are packed in cartons, usually designed to provide a display container for the product on the shelf of the shop or supermarket. These cartons are sometimes packed into large cardboard cases for shipment or, alternatively, they are built up directly on a pallet. Sometimes cartons built on a pallet are bound by transparent film for added security.

Automated warehouses are rapidly becoming more common and, as for raw material deliveries, bar codes can usefully be applied for finished stock.

In a fully automated system the pallet, or unit load, is delivered to the warehouse handling system which places it in a location determined by the computer. To save space, the storage locations may be stacked several high and the isles between adjacent banks of locations are kept as narrow as possible to make the best use of the volume of the building. The handling system retrieves loads under computer control in the same way as it stores them. The loads need to be dismantled in order to assemble the orders received from the shops or supermarkets.

The make-up orders are increasingly planned by computer using a direct order entry system which enables the representative visiting the shop to transfer the order directly onto the computer network. The computer then checks credit worthiness before issuing the order details to the warehouse. The physical making up of the order is like a production line where pallets move in sequence past stations where each type of product is stored, and the appropriate number of cartons stacked on manually. Made-up loads, to meet specific orders, are then loaded into vans in the correct order for the delivery round, which can be scheduled by computer to meet various constraints and to

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minimise the distance travelled. Finally, when the delivery documents come back receipted, invoices can be automatically prepared and sent to the customer.

1.5 Weighing and metering

1.5.1 *Weighing*

It is important at the earliest possible point in the development of a scheme to establish clearly with the end user the uses to which the weight data are to be put. At the finished goods end of the process product unit weights may have to meet legislative requirements. Legislation requires that certain categories of goods over a specified weight must carry a 'declared weight' printed on the wrapper. The mean of sample products taken from a production line over a period of one hour must not exceed the declared weight or 'nominal quantity'. In addition, no more than 2.5% of the products may weigh less than the 'T1' limit and no products must weigh less than the 'T2' limit, the 'T1' and 'T2' limits being defined for a series of bands of average weight.

The challenge to production management is to keep the product weights as low as possible without breaking these limits. Playing safe involves 'give away' which may be very costly, taking too great a risk may involve large quantities of the product being scrapped and eventual legal proceedings for persistent offenders. Weight control is therefore a critical issue. The weighing system used for checkweighing must be approved by the appropriate authority.

Traditionally laboratory type scales have been hand loaded and manual records kept, but data are increasingly captured automatically from such instruments and processed in a computer. Where the product is being discharged in a single stream from a packaging machine it can be carried by a belt conveyor across a 'checkweigher' which can weigh and record at speeds up to 300 per minute. Checkweighers must also be approved by the appropriate authority.

Multihead weighers for products such as snacks or wrapped sweets were mentioned in an earlier section. The problem with single weigh heads is that the addition of the last item required to achieve the desired weight may take it well above what is needed, so that even a perfect performance does not produce a perfect result. With a multihead system it can be arranged that, say, four heads are needed to make up the required weight. By choosing the best four from ten a much more accurate result is achieved.

At the receiving deck any requirements are commercial rather than legal. Deliveries from suppliers must be weighed in to confirm the quantity which must be paid for and platform scales of good accuracy are required for this purpose. The delivery vehicle is driven onto the scales and weighed before and after delivery, the difference being taken as the weight of material supplied.

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Within the process there are two principal purposes for which weights are needed; stock control and recipe control. Of these the requirements of stock control are the more difficult to meet since a very small percentage error can accumulate over time leading to big material variances which can cause consternation at the cost office. These material variances may simply represent measurement error or under or over use of ingredients or, at worst, material losses. Only by minimising instrument error can the true position be established. For this reason measurements for stock control can never, in practice, be accurate enough and a realistic compromise is necessary.

Recipe control is seldom so demanding since small variations in recipe are generally not detectable in the final product. Over a period of time, of course, under or over use of particular ingredients will become apparent, but this can be recovered during subsequent time periods. It is often the case that a recipe consists of a relatively large proportion of an inexpensive base material with additions of lesser quantities of more expensive ingredients whose presence will be crucial to the eating quality of the product.

In a well run plant there will always be a tendency for plant managers to err on the side of underusing the most expensive ingredients so as to show a positive cost variance. Whilst this may achieve cost savings it is important that it does not adversely affect quality. Ideally, weighing or metering systems should give the same percentage accuracy for all ingredients. This means a greater absolute accuracy for the smaller quantities of the more expensive ingredients. It is for this reason that special 'small additions' weigh vessels are provided even when the base ingredients are being measured by 'weight addition' to the mixer.

1.5.2 *Metering*

As was mentioned in the section on primary processes, metering is in greatest demand in continuous processes where two or more streams must be blended together. Under these circumstances what is required is a means of controlling the instantaneous flowrate of each stream.

Metering pumps were also mentioned which create a precisely controlled flowrate by straightforward mechanical means. The most accurate metering pumps are of the reciprocating plunger type with variable speed drives, variable stroke, or both. The variable stroke feature is valuable when a single drive is used for a battery of several metering pumps, the overall throughput is varied by speed, whilst adjustment to the recipe can be made by adjusting the stroke of individual pumps.

A key feature of this type of pump is the design of the inlet and outlet valves which must close precisely and without leakage. This becomes rapidly more difficult to achieve as viscosity increases and becomes impossible when solid material is present. Under these circumstances rotary positive displacement pumps must be used. Since these are not fully positive, and suffer from a degree

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of 'slip' which may vary, they must be used in combination with a meter if high accuracy is required.

Unfortunately the very circumstances which rule out the use of metering pumps, i.e. high viscosity and the presence of solid particles, also apply with the majority of meters. Positive displacement meters of the type used for water, petrol or oil are not suitable for most food and confectionery materials.

An excellent answer for water-based materials is the magnetic flowmeter. This instrument has no internal obstacle to flow and can be of the same bore as the pipe. It works on simple electromagnetic principles, the material being pumped through it forming the moving conductor of a generator, a strong magnetic field being applied at right angles to the flow and the generated e.m.f. being measured at right angles to the magnetic field. The e.m.f. is proportional to the mean velocity through the meter and hence to the flowrate. For a material of constant density this will provide the mass flowrate. In common with most flowmeters, any introduction of air bubbles, or their use in a partially filled pipeline will lead to errors.

Magnetic flowmeters will not work for materials of very low conductivity and unfortunately fat-based materials such as chocolate and peanut butter fall into this category. A suitable instrument makes use of the coriolis effect. The material is pumped through a U tube which is vibrated about an axis lying across the open end of the U, the connections being flexible. The velocity of the material travelling round the U bend is analogous to a spinning disc whilst the up and down movement of the U bend is similar to rapidly reversing precessions of the spinning disc. The resulting coriolis force causes the U to twist one way on the up movement and the opposite way on the down movement. The angle of twist is then a measure of the mass flowrate. In order to achieve a reasonable signal level fairly high flow velocities are needed which result in rather a high pressure drop across the instrument when viscous materials are used. This means that the pump used to feed this instrument cannot at the same time be expected to deliver the material down a long pipe. Since mass flowrate is measured directly, air bubbles are not such a problem as with volume measuring devices provided the bubbles are well distributed.

1.5.3 *Example of a 'loss in weight' metering system*

'Loss in weight' systems are especially useful for materials that are difficult to handle such as powders or viscous slurries. Some, such as peanut butter, are very difficult to pump due to a tendency for the oil to become separated from the fibrous material and for the latter to seize up the pump. An alternative to the pumped delivery is to drive the material through the delivery pipe by pressurising the vessel containing the peanut butter with compressed air.

Under these conditions, and provided the material has been well mixed and is at a uniform temperature, there will be an approximate relationship between

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air pressure and flowrate, but it is clearly necessary to monitor the flowrate and make continuous adjustments in order to achieve a precise result.

By mounting the holding vessel on load cells the mass flowrate can be monitored. The preferred system is for the controlling computer to establish the desired weight at successive intervals of time and for the control system to modulate the air pressure in such a way as to follow the descending weight. In this way the total product delivered over an interval of time will be very accurate even if there have been fluctuations in flowrate during each time interval. As outlined previously, the total integrated flow is generally what matters, some variation in instantaneous flowrate being tolerable.

The same principle is applicable regardless of the means used for delivering the product. Screw feeders are often used for powder, whereas for viscous liquids rotary pumps are the most common method. In the example given where compressed air was used it would be necessary to use two vessels alternately to provide continuity of flow. Where pumps or screws are used a second vessel is placed above the first, and when the primary vessel is nearly empty the pump speed is fixed whilst the vessel is quickly refilled by dumping the contents of the secondary vessel into it.

1.6 Summary

In the introduction the need for control engineers to appreciate the wider commercial context within which they are working was stressed. Subsequent sections attempted to characterise the major stages of the production process and to give a few examples of the many and varied processes employed at each stage.

Three types of the control system requirement have been identified: the control of individual machines or process elements; the coordination of groups of machines and process elements to form an effective production line; and communication facilities to allow the coordination and scheduling of the overall production system. The historical development of control systems follows these three stages in a similar order with the exception of recent developments in high performance machine control.

Automatic control has been an essential part of primary processing elements for the last forty years, especially in the control of thermal processes. The advent of PLCs allowed the handling and transfer of materials between stages to be controlled and coordinated with greater certainty and minimal effort in all the stages of production.

Computer-based control systems with interconnecting links and networks have more recently permitted the co-ordination and scheduling of machines and production lines in increasingly sophisticated ways, and have enabled management information to be made available from direct plant

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measurement. The most recent advances have been in high-speed packaging machines where the digital control of high performance servo motors and the use of adaptive control strategies have opened up new possibilities for flexibility combined with high speeds and high efficiencies. The opportunities presented by these advances have yet to be fully grasped by the industry.

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2 Total systems

JOHN HOLOWAY

2.1 Introduction

Today the result of the last ten years' investment in capital equipment by the food manufacturers can be seen in food processing plants throughout the world. Traditionally conservative by nature, they have come to realise that any investment in plant and computer equipment can be justified not only in terms of pay back or throughput, but also in market share protection and other corporate issues and strategy. During the last ten years, significant changes have occurred in the industry. These have arisen from internal requirements for modifications to management practices, changes in production methods, new alternative ingredients, to respond to the changing retail environment, distribution chain and consumer behaviour. To meet this challenge the food manufacturing industry has initially responded by investment in 'enhancing' technology, to replace or augment existing plant with newer technology and computer systems.

The widespread installation of automated process plant and supervisory systems throughout the industry is indicative of the direction taken to exercise control in the factory environment, whilst centralised systems for forecasting, budgeting and production planning are seen as the method for management control. However, this approach does not take into account the advances being made in technology, or the need for change in the future. As each new problem has arisen, the understandable reaction of applying a correspondingly new technology to the problem has been taken. The result is a collection of self-supporting plant systems, such as time and attendance, engineering or quality systems. Each system offers a solution to a particular identified problem, can be justified in terms of pay back, and can be run independently of the other systems. The negative effects have not always been identified: duplication of data entry, varied operator interfaces, validity of information held on multiple systems, uncontrolled reporting sequences.

Today, the factory management tasks can be made more achievable by removing the insulation between the management and the production process, by ensuring that the current working practices are the 'best working practices' and by allowing the plant to respond to production changes more effectively. The detailed costing information available for every step of the process can

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be used to track capital investment as well as to justify it, which allows consideration of technologies in areas that could not be supported by previous costing data.

To achieve this enhanced management support the installation of an integrated information system or total system is required. To understand the methods and needs of such a system it is necessary to examine the view of information technology (IT) systems by the food industry, the general requirements, specific industry issues and practical methods of implementation. Once these have been established the way is open to food producers to initiate system planning and integration of their systems to achieve real time control of their business.

2.2 Current systems concepts

The challenge to today's management is to be able to step back from the day-to-day and month-to-month tasks of running the business, from applying short-term solutions to specific areas of concern, and to review the total operation in compliance with the business demands placed upon it by its position in the industry, with the likely demands in the future and its competent management.

The view of manufacturing systems by the users does not necessarily coincide with those of the major system suppliers. One major reason for this divergence is the different standpoints of the IT suppliers to those of the users; the food manufacturers are focused on the food market, whilst the system suppliers' objective is to market their products across a wide range of commercial sectors, including food processing. This has led to the food manufacturers responding to the system suppliers in a predictable way, basing their purchasing decisions upon proven practices. The manufacturers have a number of valid beliefs and concepts about systems and their usage. One of these concepts concerns 'information'. Simply stated it means that:

- Information is the key to successful management and supervision.
- Information is only valid if the user requires it.
- Information is required at different levels for different purposes.
- Archiving of information is an automatic function.
- Integrity of information is paramount.

How the information gets to a particular point is not of interest: only that it is accurate and relevant. This view of an 'information' system from the food manufacturer's perspective illustrates the difference between the suppliers of a system to manipulate and control data to that of a user of 'information'.

Another concept that is foreign to the IT systems supplier, but favoured by many food manufacturers, is the principle that 'people make products—not machines'. Although the food makers wish to remove the vagaries of

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manufacture from their plant floor, they still want to retain the human control. This results in requirements for systems to reduce operator errors, but which allow the supervisors the final judgement.

Following on is the concept that 'computer integrated manufacturing' (CIM) does not just integrate islands of automation, but takes control away from the operators of the discrete systems and hands it over to the total system, removing the authority from the human operator. In fact this can happen if the system is not designed to interface with the workforce, and is not built to reflect the food manufacturer's business and process strategy.

2.3 General requirements

The view taken by management of their individual production processes can be extremely diverse. This is due to the varied nature of the products and their position in the market. A supplier of high volume, low margin, long shelf life items may identify conversion factors, plant utilisation and production targets as critical success factors, whereas a producer of higher margin chilled food may focus more on raw material quality control and distribution as particular areas of interest.

Despite the different emphases placed by food producers upon areas of information technology, a number of general requirements are prevalent across the industry.

2.3.1 *The pragmatic approach*

The adoption of practical and proven methods of problem resolution and implementation is pre-eminent. This approach, however, does not facilitate the 'critical' leaps that may be required in some sectors to prevent a decline in the market share due to a changing market place.

2.3.2 *Utilise existing technology*

The utilisation of existing technologies is preferred to innovative techniques. In the main this is a sound approach, especially as the information and control systems will probably be upgraded every three to five years, allowing the use of proven, newer technology in phases. The downside of this tactic is the potential loss of benefits accrued through the use of specific leading edge technologies such as expert schedulers or product formulation systems.

2.3.3 *Identify measurable benefits*

The capital investment cycle normally includes budget planning and approval steps. Any potential system must satisfy the approving authority that the proposed investment will bring identifiable and measurable benefits to the

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organisation that implements it. In addition a payback period of between twelve to eighteen months is typical. The selection of system components that do not fall neatly into easily identified return on investment patterns may demand a different approach, or an act of faith on the part of management.

2.3.4 *Commonality of use*

A typical problem being encountered by production workers and management is the diverse user interfaces and methods of operation of the installed systems. To overcome this issue the users are now demanding common standards of interaction and operation from the system suppliers. The IT industry is responding with open system standards, but the level of compliance to these developing standards varies from supplier to supplier and product to product.

2.3.5 *Transfer of information*

Many systems have been installed as stand-alone units. Transfer of information between them is now recognised as a standard requirement for future systems. The reason for the move towards totally integrated information systems lies in the need for enhanced control over the business and its component activities, which can only be achieved through the access of information by all levels of staff for operational or decision-making purposes.

2.3.6 *Utilise a modular platform*

Due to the range and scope of IT supplier products, and the ever-changing technical environment, modularity is seen as a hedge against evolving products, and as a method of incremental installation. The building block approach satisfies many of the criteria for investment protection and also provides a basis for gradual deployment of an overall IT strategy.

2.3.7 *Resilience*

Modern information systems are expected to have high availability for the users, and architectures tolerant of system- or operator-induced faults. The storage of information in each data base is assumed to be error free, as is the integrity of transferred information. The systems have to be supplied in the knowledge that sub-systems may not be available for data transfer for operational or maintenance reasons, and that the transition between operational states should be 'seamless' to the operators. The maximum resilience for an architecture comprised of component systems is only achieved by the careful definition of hardware and software to exclude single points of failure, and the pragmatic integration of the functional units.

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2.3.8 *Adaptibility and expandibility*

Any system supplied should be capable of a 50% expansion in capacity without extensive hardware re-configuration, and should allow transfer of information, via standard interfaces, to other systems. In addition, simple evolution of the systems, in terms of screen displays, reports and data stores, should be catered for in the design or selection of the software.

2.3.9 *Use industry-recognised vendors*

The approved vendor lists for the hardware and software components should be limited to those vendors having a strong industry presence, proven technology track record and a known capacity relative to the proposed system. The latest trend is for formal alliances and partnerships between vendors to provide complementary skills, with one partner acting as the prime contractor.

2.3.10 *Maintainability*

The ability for all vendors to supply maintenance services, both in the short and long term, is paramount. Also, the day-to-day remedial and housekeeping overhead is required to be minimal, as this is carried out by the food manufacturer's operating staff.

2.3.11 *Allow for external factors*

These include electronic data interchange and wide area networks. The wider implications of communication between the enterprises in the supply chain can provide a host of conflicting requirements. The current view of most food producers is to adopt an EDI standard to use in communicating transactions with their major suppliers and retail clients, but to ignore other messaging formats for wider purposes.

2.4 Food processing industry issues

There are a number of issues that affect the use and implementation of IT within the food industry. Each sector has its own specific requirements, and these are catered for in the functionality of the supplied systems, but overall there are some issues that cross all boundaries.

These issues are relevant to senior management as well as process line operators; they can be strategic or tactical. They revolve around factors that are faced on a daily basis, and occur year in and year out. Also, changes in technology and consumer expectations are bringing about the need for new

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ways to meet the continuing challenge. Examples of changing requirements include:

- aseptic processing;
- ionising radiation (EC products);
- natural ingredients;
- BS 5750.

The following issues cross many boundaries, and have implications for many functions within the manufacturing enterprise.

2.4.1 *Conversion factors*

The plant manager will monitor performance, and be judged on such performance against plan. The ability to draw information from all areas of the facility for planning and supervision is facilitated by the installation of integrated systems, and fine tuning of the process is possible at all levels. Control is also exercised by:

- driving production by authorised recipes;
- control/specification of raw materials;
- economic batching.

2.4.2 *Quality*

The ability to plan and design-in quality rather than introduce it later in the process by inspection and sampling, assists in the overall management of quality. The modelling of process operations before the production run and the real time QA feedback can lead to greatly improved standards. In addition the facility for full batch recording and archiving of information allows analysis of any discrete or pipeline process to bring about improvements of any line.

2.4.3 *Safety*

The safety of food products has been much in the news over the last few years, as has been the safety of the process operators. The degree to which stand-alone systems can assist in the promotion of safe working practices and safe food products is limited to the functions built into each system. A total system can offer the potential of increasing the safety margins by:

- control of working practices;
- less mobility required of workforce;
- greater supervisory environment;
- removal of human errors;
- planned maintenance;

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- security;
- product quality;
- identification of faults.

2.4.4 *Cost*

The identification of specific production costs and correct allocation has always been problematic in process industries. The main factor missing from the overall equations has been the accurate recording of data for the entire process. Discrete systems can record information within their control, but combining this with other data has not always proved effective because of synchronisation or interfacing. An integrated recording system can provide:

- increased capacity for finite modelling;
- tighter budgeting;
- identification of line/process cost;
- true allocation of waste;
- process gain/loss adjustments;
- interaction with corporate forecasting/ledger systems.

2.4.5 *Repeatability*

The control of multiple production processes using essentially natural or variable raw materials is not an easy task. To gain a consistent product batch and be able to repeat it on plan is essential to achieve the performance factors demanded by the modern business environment. The total system provides:

- control of a greater number of factors;
- identification of deviations;
- options for action;
- identification of best working practices;
- comparison between lines/plants.

2.5 Manufacturing process system

The implementation of a total system in the manufacturing process involves all areas from pre- to post-production, and should provide continuous supervision of, and detailed information from, the actual plant. As the system is comprised of component blocks it is possible to introduce newer technologies in stages to upgrade the functionality as long as the future is planned in total system terms. The stages can include any stand-alone operation as a means of verification prior to full integration.

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2.5.1 *Pre-production issues*

The interaction of functions in this stage allows the full range of information to be used for management and planning purposes. The information comes from a number of sources such as ledger and financial modelling systems, simulation, production planning and sales and marketing systems. The facilities include:

- budgeting;
- product formulation;
- product modelling;
- product costing;
- resource modelling;
- material requirements;
- stock planning;
- sales account management.

2.5.2 *Production issues*

During the production process the interactive supervision relies on information for decision making. The source of such information may be from a time and attendance, planned maintenance or process control system. The large number of functions involved in the production process means that total supervision of a production environment can only be satisfactorily achieved by integrating the discrete systems together into a coherent unit, capable of operation by all levels of staff, and resilient enough to operate in a true factory environment. The facilities provided to the operators and management by an integrated system are:

- production performance measurement;
- cost allocation;
- quality auditing;
- batch tracking;
- time and attendance;
- manpower resourcing;
- line performance;
- engineering/maintenance;
- material acquisition;
- delivery quality monitoring;
- waste allocation/management.

2.5.3 *Post-production issues*

After the product has been realised and distributed to the food producer's outlets, the real time data are stored to provide management with the information about performance.

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Reconciliations can now take place with actual data from the production floor reporting against the targets that were originally planned. The ability to compare and analyse information across the whole range of activities provides a sound basis for management reporting. The systems used in this phase include:

- costing/specification;
- conversion factors;
- integration of production information to ledger systems;
- capital project reporting;
- inventory management.

The degree of integration between each component system, and the look of the overall system depends upon the needs of the manufacturing enterprise. Once the decision has been taken to implement such a system a plan can be devised that allows a gradual or accelerated take up. This is discussed in the next section.

2.6 Total systems

To provide a practical system that extends across the entire manufacturing enterprise, a number of factors are taken into consideration to ensure that the resultant system not only fits the production operating requirements, but also management practices. The factors include:

- production information flow;
- logistics information flow;
- interaction of people and systems.

By ensuring that the production commands and process feedback operate in a coherent loop, matching the materials handling/logistics information to the manufacturing process, the system becomes an interactive tool for accurate supervision, a window on the enterprise for executive management and an integrated planning and reporting mechanism for production management. Interaction between the users and the system should be based on actual requirements and can be via normal dialogue on standard or graphics terminals, single-way traffic using keyboards or teletext screens or hands-free communication by speech recognition systems. If components of the overall system are obtained from a number of different suppliers, who do not share identical user interface standards, a common approach can be developed using the most suitable 'open' system from amongst the major hardware, software or network vendors.

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2.6.1 *Functional blocks*

Once the functional requirements of the system are established, it is practical to consider separating the individual functions such as 'goods in', 'quality test' or 'wrapping' into clusters of functional blocks. By determining logical blocks of functions it is possible to build up a model showing the grouping of related work activities. This type of model can be used to identify islands or packages of functionality suitable for stand-alone implementation in a phased approach.

2.6.2 *Method of implementation*

There are two main approaches that can be taken to realise the total system. One method is to obtain a bespoke solution from a major software supplier, and the other is to identify application packages to provide a large percentage of the solution and bespoke modules, interfaced to the packages which supply the remaining functionality. The pragmatic approach employed by most food manufacturers in systems implementation is to acknowledge that any solution to be considered will have to employ existing operational units installed over the last few years. This leads to a focus on packaged solutions rather than total bespoke, but can result in severe integration issues, as some major food producers have found to their cost.

2.6.3 *Benefits of total systems*

The benefits that accrue from total systems, rather than component systems, are those derived from the enhanced information flow, control of data and interactive operation of the systems. For example, it is possible to plan for the manufacture of products in a number of streams or pipelines using stand-alone functional units. The real time control of such a series of concurrent events, however, when the operation extends from the receipt of multiple consignments of raw materials, through the complex processes of manufacture, to packaging, warehousing and distribution is the major source of problems for production management. Coupled with enterprise-wide systems such as sales order processing, ledger and research/development, the problems of reporting and transferring valid information at the right time, and in the right sequence, can be exhaustive in resource and prone to error. The benefits of an integrated system in a manufacturing operation typically include:

- Control of the process by authorised recipes, including best working practices.
- Total flowstream batch recording.
- Repeatability.
- Efficient tuning of resources shared between flowstreams.

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- Real time quality control.
- Realistic plant utilisation data.

The full capabilities of any integrated system are not limited to the scope of any of the component units, and can be enhanced by the addition of newer technology systems in phases, with the additional systems being commissioned in functional steps, until full integration is achieved.

2.6.4 *Engineering the facility*

The methodology for installing an integrated information system within a manufacturing enterprise follows a practical path. It is rare that the site is a green field one, so the existing systems and operational needs are among the first factors to be taken into consideration. A simple plan for the introduction of a total system would include headings such as:

- Information/production requirements.
- Functional architecture.
- Solution architecture.
- User interfacing.
- Interaction of systems.
- Data ownership.
- Resilience.
- Criticality of systems.
- Project management.

The implementation of such varied systems is complex, and not to be taken lightly. It is recommended that a project team be set up to manage the scheme from the start. The team should include users as well as technical staff, and should report to senior management. The reason for this is that many of the issues will cross divisional and operational boundaries, as well as contractual ones with suppliers; senior management support is therefore essential.

2.6.5 *Training and education*

The implementation of advanced process and management systems relies on the ability of the management and workforce to competently operate and understand the systems and their purpose. The interaction of systems and the users is made more effective by the introduction of structured training and education, and can, in some cases, be the deciding factor in achieving the required success.

This is not an element to be left to chance, or until the changes have been implemented, or compromised by lack of commitment. The whole philosophy of total systems is to take into account *all* aspects of the development and this

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must include training and education. It should therefore be considered as an integral part of the 'integration philosophy' and not just at the end of the proposed development.

2.7 Examples of total systems approach

The diverse products and manufacturing facilities within the food industry provide additional challenges for those implementing total systems. Each producer has its own priorities, and preferred method of approach, which incorporate the operating staff as well as information requirements. To show the different tactics generally employed, a number of examples are shown here that follow the outline plan described in the previous section. These show a different stage for each manufacturing example from the inception of the project to the final stages of integration, and highlight the methods and potential achievements of such systems. For simplicity the stages have been condensed into three phases: design, planning, and implementation. Each of the following examples will show one phase of the total cycle.

2.7.1 *Example 1: the design phase*

A poultry processing company, specialising in high volume oven-ready carcasses and pieces was chosen. The output is direct to retailers, and chilled, not frozen. 'Own-brand' products account for 40% of output. The plant is a single location with hatching and distribution facilities close at hand. The objective of the system is to provide control of the entire process from sales orders to dispatch, with particular regard to matching orders with processed carcasses. The system is to be comprised of a number of systems, both new and existing, with current plant equipment being augmented with new data capture and storage facilities. It is not intended to reduce staff overheads, but to increase throughput and reduce prime meat waste.

The design phase is initiated by the definition of the executive strategy for the poultry process plant, which outlines the parameters within which the plant is required to operate, and the production operating theory produced as the guide for operations (see Figure 2.1). These are combined to produce the overall system philosophy and the integration philosophy, which serve as the basic design guidelines for the total system. These documents will embody both the particular objectives such as the process supervision and matching of sales orders to processed materials, and the integration desired by the executive and production management. After review for compliance the functional requirements for executive, production and user levels can be established, and published in the system approach. This includes any integration requirements falling across the boundaries of the other areas. Finally, the information requirements and functional architecture documents

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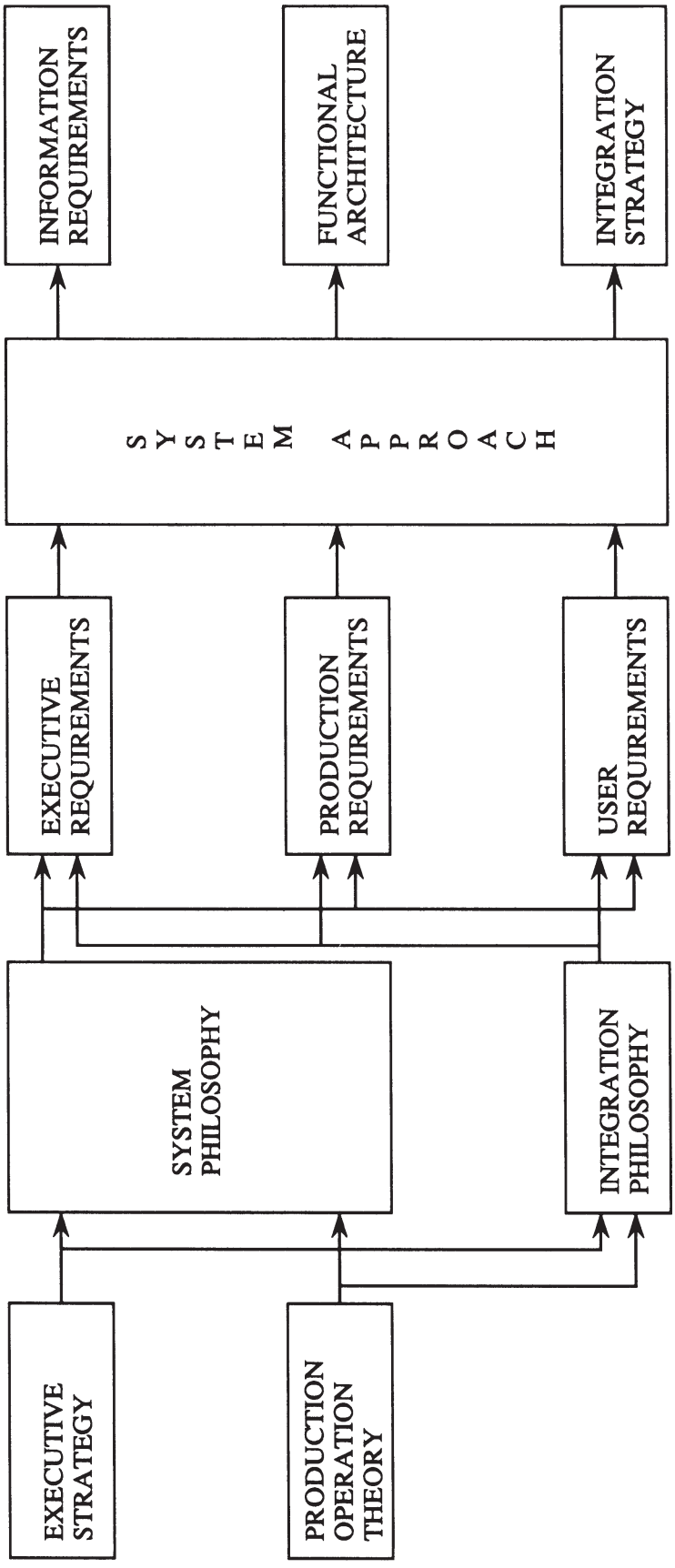


Figure 2.1 Design phase

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are produced and signed off, by senior management, and complemented by the approved integration strategy for the system.

2.7.2 *Example 2: the planning phase*

This manufacturer has a number of sites throughout the UK, and produces a high volume, low-margin food product with a shelf life measured in weeks. The products can be manufactured at a number of sites, depending upon demand and availability of plant, and the variations of product due to 'own brand' versus 'famous name' leads to a product range numbering thousands. Certain of the brands account for a large percentage of the total output. The objective for this food producer is to establish coherent control over the varied plants, by means of centralised recipe management, production pipeline management and enhanced production planning. The system has to take into account varied working practices, provide autonomous local management with supervisory and control facilities and be capable of implementation in several stages. The benefits are expected to include: more effective plant utilisation, less waste, enhanced quality control and better reaction times to retailer demand variations. Although the producer has corporate systems, much of the total system is to be implemented from new. The decision as to the timing and priority will be greatly influenced by the payback that each individual system can provide.

The multisite manufacturer has a number of additional problems to those of the single site poultry processor. Firstly, the process resources are split and duplicated over a number of UK sites. Secondly, the product lines encompass many different products, and multiple variations upon each single product. To plan for the development and integration of a total system to manage this business leads on from the activities path that the other producer took, but with particular regard for the increase in system to system communication, data storage and validation, and coherence in production processes.

Information requirements and functional architecture form the key blocks of the specification for procurement, with integration strategy providing the cement between the component units (see Figure 2.2). Inclusion of integration requirements in the procurement process is essential, as it ensures that the vendors are fully aware of the interfacing and testing stratagems that will be applied to the total system during its development and commissioning. During the drafting of the procurement specifications, the integration plan is generated for issue to the vendors.

The integration plan takes in all phases from procurement to field acceptance, and includes systems standards on screen layout, keyboard usage, system access, data storage and the expected resilience of systems. The standards can be graded into mandatory, advisable and desirable. They form an important part of the processing that the vendors will go through in establishing their approach to the system solution. In this example it is likely

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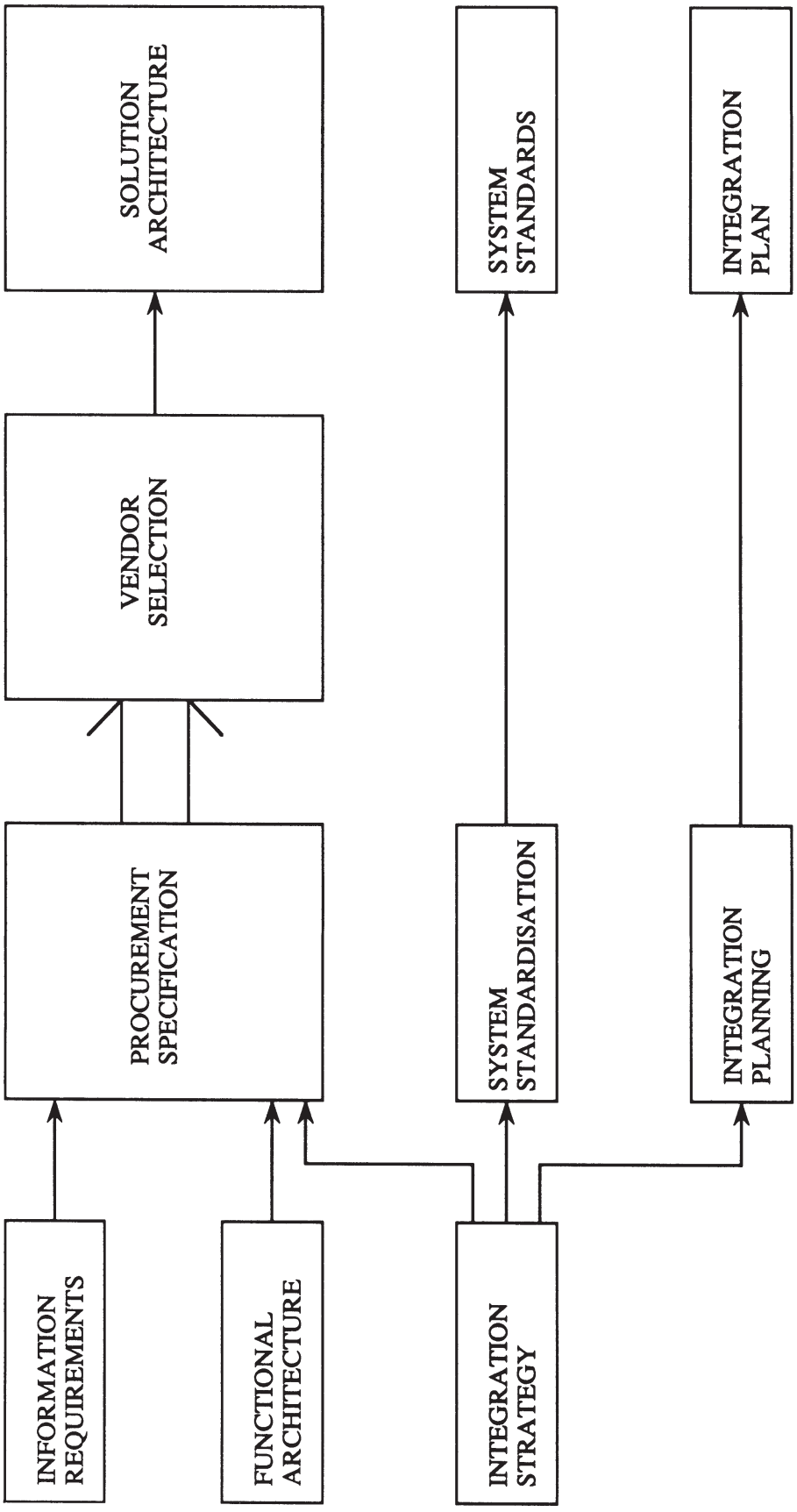


Figure 2.2 Planning phase

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that the manufacturer will implement the total system in stages. To achieve a consistent response from the vendors, and an efficient end result, it will be necessary to provide as much information about the total requirements from the first procurement cycle. The vendors would be assessed upon their ability to provide a solution that suits the multiple sites and varied systems needed to support the manufacturing process. As it is likely that several vendors would be involved, conformance to the integration requirements is paramount. Following the selection of the vendors, and their component solutions, the results are combined to produce the solution architecture. This is matched against the information requirements and functional architecture that drove the procurement process. Anomalies and errors can be highlighted and removed at this stage.

2.7.3 *Example 3: the implementation phase*

This manufacturer produces a wide product range of canned and bottled goods. In addition to this wide range, some of the products have a complex series of processes incorporated in the recipe. More than one plant is located in the UK, but each facility is expected to be autonomous. The output is directed to both wholesale and retail units, with some product exported. This manufacturer concentrates on its own 'famous label' products and is implementing a total system with the view to reducing overheads, enhancing supervision of the processes and driving production by controlled recipes. The expected benefit is an increase in margin, through reduced costs, and an increase in availability of product on the retail shelves. The main thrust of the system installation is through the implementation of Supervisory Control And Data Acquisition (SCADA) systems and MRP II, with interfacing to the corporate systems running ledger and scheduling activities.

The success of this phase rests not just with the management of the implementation teams, but also with the strength and commitment that has been applied to the first two phases. Significant changes at this stage are far more costly and are the root cause of project over-runs. The producer of canned and bottled goods has specified the system components, but now has to manage the implementation. The integration of these systems is particularly important as the end result should be capable of running an entire facility as an integrated unit, and not as a series of stand alone units requiring hands-on supervision for every function. The main components of the solution architecture, in this instance, are a SCADA system to direct the process activities, including the downloading of recipe instructions, and a Manufacturing Resource Planning (MRP II) system to provide production planning and control. Communication to corporate systems is also managed by the MRP II system (see Figure 2.3).

The vendors will initiate the systems development and system configuration, based upon the definitions contained within the solution architecture

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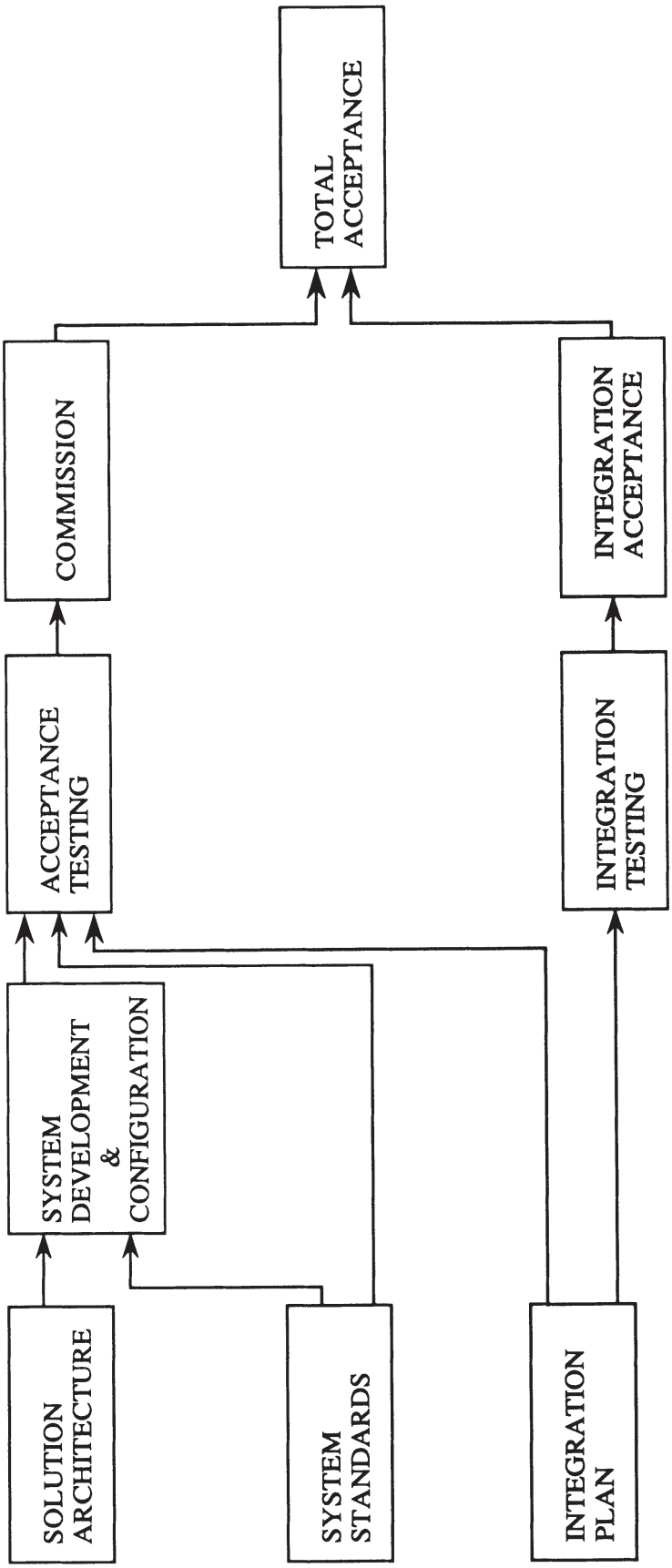


Figure 2.3 Implementation phase

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and system standards. Concurrently, the integration plan is developed and implemented. This requires that the system vendors adhere to integration testing at module and system level during the development cycle. The normal vendor acceptance tests are augmented by integration testing prior to sign off. After acceptance at the vendor premises, the systems are moved to the factory sites and commissioned in the usual way. The full system can now go through the final tests for integration acceptance. In reality, the commissioning is followed by a period of stand-alone operation to prove and validate the systems operations. During this time the final, but minor, configuration changes can be made before the phased integration is achieved. Even during the stand alone period the enhanced control of the process, and increased productivity, begins to produce a payback, in line with the organisation's objectives.

2.8 Summary

In the final judgement, total systems are essential if food manufacturing enterprises are to realise the full potential of their capital investment in plant and information technology. The extent to which the benefits will accrue will depend upon the approach taken by the implementors and the degree of commitment to the projects by the manufacturer's senior management. The systems will provide a level of control to protect margins, enable shorter product launches and to enter new markets. The ability to manage changes in the environment, whether in raw materials, demographic or competition, can be used to gain the business advantage.

The pragmatic implementation of total systems includes selection of hardware and software architectures, identification of functional blocks and the priority phased commissioning of the total system. The overall integrity is achieved by use of a structured test and integration strategy.

The timing of the decision to move towards a total systems environment depends on the investment cycle of the enterprise, but the actual decision itself may, in fact, be strongly influenced by factors external to the organisation.

(i) *Cost* The costs of certain components may appear to be reducing, but in the long term a system will cost considerably more to implement in three to five years' time. Therefore an installation within the next twelve months will reduce the overall costs.
(ii) *Technology* Today's leading edge technology is next year's proven technology. If a system is designed to take advantage of the advanced technology available now, it will be tried and tested by the time it is implemented in twelve to eighteen months.
(iii) *Competition* The competition, in general, can be expected to be implementing new systems now. Planning to adopt total systems as soon as possible will ensure that the business advantage is maintained or achieved.

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(iv) *Planning* The inclusion of provision for total systems in the next budget and business plan should be effected. Final approval and phasing can be made as a business decision depending upon company performance.

The key factors in a successful systems implementation range from forward planning over a three- to five-year period to determine global requirements, creation of a realistic action plan, identification of likely places for errors to creep into the project, managing the errors and obtaining executive commitment to the project from the inception. It is recommended that a study be carried out to investigate the feasibility, benefits and likely solutions to provide an overall strategy document to initiate the process.

The future for the food industry has never looked better for those organisations geared for change. The evolution in consumer tastes and the tools to assist the food producers means that the food producers have the resource to match demand. The adoption of total systems will make their job easier, achieving greater consistency in performance, and with the ability to change more readily in the future.

Further reading

Mike Gifkins and David Hitchcock, *Trading in the 1990s*, Blenheim Online Publications, 1988.

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3 Integrated factory systems

MAURO NOVARESIO

3.1 Introduction

The concept of integration needs some clarification because of the different meanings of the term 'integration' according to its applications. With information systems this concept is strictly related to the computer integrated manufacturing (CIM) philosophy; everybody has heard the words CIM, several people know its meaning, though only few have real experience of it. In this chapter we intend to describe integration as 'how we can run a computerised industrial process'.

The purpose of the integration is, in general:

- resources optimisation;
- monitoring and tuning;
- scheduling and planning;
- linkage between the process control and the factory management information system.

In the following paragraphs a practical approach to the problems that may arise during the project's life, either suddenly or unexpectedly is outlined.

3.2 Integration objectives

In handling the subject of computer integrated manufacturing, we have to differentiate between the goal of integration from the means used to achieve it, i.e. the computer. Whenever dealing with a corporate issue, we must separate the 'what', i.e. the integration, from 'how' this is to be achieved.

This brief theoretical outline is a reminder of one the most frequent mistakes made in integration issues: the incorrect separation of responsibilities between who is to deal with the problem—the manager, and who is in charge of solving it—the integrator. Often a manufacturer wants to 'push' through a particular solution without a thorough investigation.

The leading goals of the manufacturer and consequently of integration in general are:

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- Efficiency.
- Flexibility.

The manufacturer spends to improve production while reducing costs; he spends to earn more. He thus improves the efficiency (and subsequently the profit) of the different production steps, adding value to each of them.

Meanwhile, he must watch the market changes and promptly tune his organisation to them. The process must be flexible enough to meet the new market demand—even be ahead of it. It is therefore essential to improve communication at all corporate levels. Besides being a milestone in achieving efficiency, this will also provide a great incentive to the cooperation between all the different departments.

Nevertheless, this will be as nothing unless the whole company is involved. Although the automation of the production processes and the implementation of a corporate network are the actual groundwork of the integration, two other main aspects must also not be disregarded:

(i) *Finance* The financial aspects are to be taken into account both during study and implementation in order to avoid the risk of generating a 'non-profitable integration'.

(ii) *Personnel* The integration and subsequent automation bring about radical changes in the corporate organisation. This results in management problems which have to be solved in order to avoid any 'rejections'. There is but one way to tackle this issue: either the managers accept with enthusiasm the new organisation or there is no room left for them in the company.

3.3 Integration phases

The first requirement for integrating any system is a sound knowledge of the problem; the more we are familiar with the task the less we will lay ourselves open to the risk of a wrong implementation. The manufacturer has therefore to define the system concepts and functional requirements of the facility to which the CIM philosophy is to be applied.

Generally, any analysis of the system deals with the following:

- material flow;
- production process;
- information flow.

It is advisable to employ simulation instruments provided with graphic interfaces to carry out the analysis, using the most expert complex system simulation. The graphics are not a mere matter of appearance: they can be used to verify immediately the solutions as they are entered into the model.

Simulation is also recommended because it forces the engineers who design

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the model to enter coherent data, otherwise it will not 'run'. The simulator will thus caution that the data are inconsistent or that information is missing.

The simulation will then find out the best (not necessarily most complex) strategies to achieve the required throughput. Generally speaking, simulation is a highly reliable decision-making support, which has proven to be useful to schedule activities even in conventional operating conditions.

The corporate logical data base is defined upon completion of the analysis stage. This logic data base is the kernel of the forthcoming corporate data base. It has to be provided with all the key data; the *relations* between the data and the relevant *attributes* which may come to light while proceeding with the detailed analysis. In this case, the data refer to the product and the relevant production means. Other data concern the various organisation and accounting aspects required to run a company.

Before we move any further, let us examine a generic CIM architecture, which can be applied to food processing, as shown in Figure 3.1. This scheme is based on the assumption that the product has already been defined.

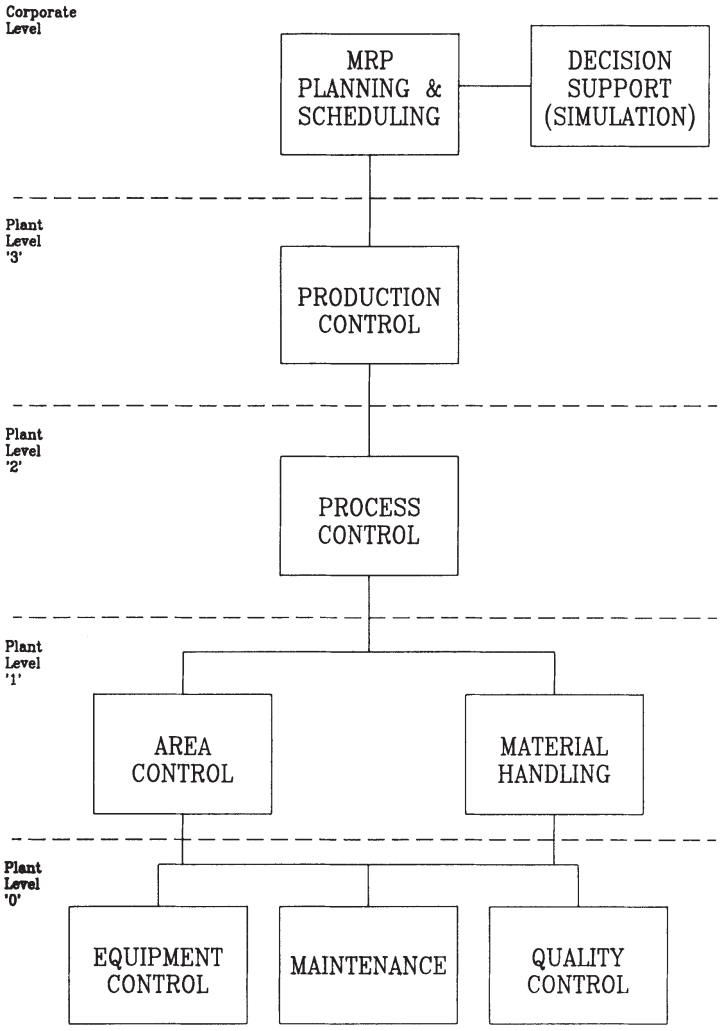


Figure 3.1 General computer integrated manufacture solution

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The proposed CIM solution is only logic; it deals with 'what' has to be done. It shows the information flow and classifies it hierarchically into the different functions summarised below:

Equipment control. The logic sub-system which manages the production equipment.

Maintenance. The logic sub-system allocated to keep track of functionality of the whole production equipment; it can operate on its own (routine maintenance) and/or receive inputs from the process system (corrective maintenance).

Quality control. This logic sub-system supplies information about the quality of the products at the end of each production stage.

Area control. This sub-system manages a specific working stage, which may involve several machines.

Material handling. This sub-system is allocated to control the material handling and the relevant tracking; it also controls the AS/RS systems. This is the sub-system which manages the physical flow and its tracking.

Process control. This coordinates the activity related to production without making any strategical decision; its task is to optimise the resources of the production system. The process control receives instructions from the production level and returns status information relevant to orders (carried out, to be carried out, pending, etc.) and components (equipment, etc.).

Production. This level handles the detailed scheduling; that is, it makes decisions according to the system status it receives from the process level in connection with the master schedule. Its functions include the monitoring of the production system: it is one of the inputs of the decision-making system both at production and planning and scheduling levels.

The corporate decision-making level is MRP (material requirements planning), or MRP II (manufacturing resource planning) planning and scheduling. This level already exists in almost all companies, even if it is not yet integrated into the lower levels of the CIM architecture. The logistics described above are the first step of the integration process. The second step is the search for the base solution, which analyses the most suitable applications, their relevant costs and investment return.

The aim of this step is finding out how to implement the integration. In order to make the most appropriate decision, we have to keep in mind that the objectives of the manufacturer are efficiency and flexibility, which can only be achieved through process automation. This will cut down costs and increase the flexibility and efficiency of the production process. Automation also shows the factory status in real time; the reaction time is subsequently faster and will vouchsafe lower management costs.

The computer is the tool which enables automation and integration to be accomplished; manufacturing automation and information systems are the supports upon which integration is based. The corporate information system manages the aforementioned logic data base. It is based on a computer by its

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own definition and is logically and physically connected to the manufacturing automation computers.

Once we have established the production process to be automated, the next step is selection, i.e. the choice of the following:

Process technologies. All the equipment allocated to carry out the treatments, handling, etc. It is worth remembering here that the hardware to be used for material handling (e.g. the AGV trucks) has to be interfaced to the one allocated to the work stations and—consequently—the selection must be aimed at achieving a non-complex, inexpensive interface.

Control hardware. All the hardware components which control the process equipment. i.e. PLCs, PCs, mini/micro computers, main frames. When selecting this equipment, we must find out which type of link will enable the final integration of the systems. Networks such as Ethernet, Token Ring, Serial Lines and suchlike are usually preferred.

Base software. The hardware and base software are selected at the same time due to the importance of their connection; the choice of a distributed data base rather than a centralised one directly influences the selection of the hardware as well as that of interfaces and protocols which enable the flow of information between the different components.

Recovery procedures. These issues are extremely critical in process control and should be considered for all the functions of an integrated system: redundancy can be provided wherever failures may be fatal, e.g. if the process hardware can be duplicated, but this may not be the case with the production equipment. Nevertheless, control and maintenance procedures of the machinery should still be defined and automated.

At the end of the selection stage, a budget cost for the automation and integration process is generally identified. It is well known that nowadays the actual costs always exceed the planned ones. The manufacturers are aware of this and in order to avoid any risk tend to select a step-by-step approach, whose completion shall be the integration of all the corporate sub-systems which have been automated in the meantime. This allows them to keep track of the selections which have been made up to then and how they match the preliminary project. There will therefore be room to intervene and alter the design of the sub-systems which are still to be implemented.

No matter what implementation strategy is selected (progressive or parallel), the sub-systems must be tested one by one and allowed to function as self-sufficient devices.

3.4 Process control and factory automation

Generally, the first investments are aimed at the automation of the different production processes. Material handling is automated in parallel to give way

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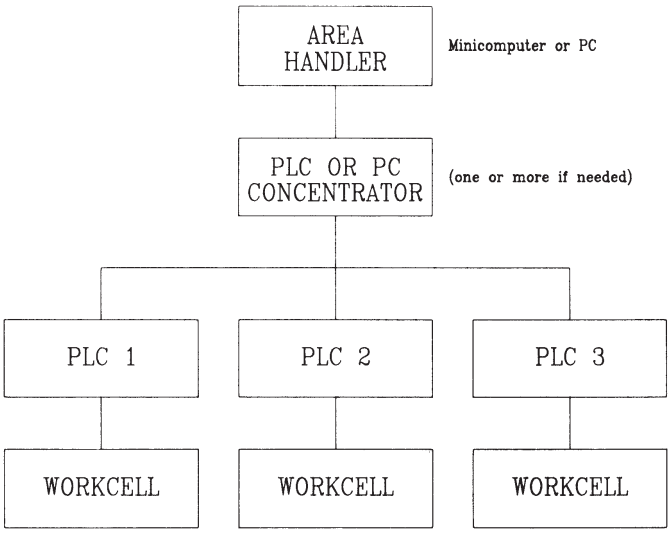


Figure 3.2 Area control subsystem architecture

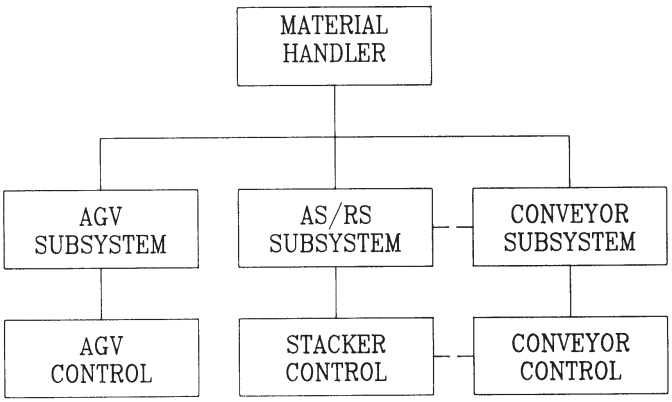


Figure 3.3 Material handling subsystem architecture

to the optimisation of the production flow with the facility to know at any moment 'what is present' and 'where it is'.

Provisions for the various activities related to the integration are to be made from this stage: each working tool is to have its specific record for monitoring, quality control and maintenance. In other words, the logic data base is to be defined. Furthermore, we shall identify the standard for collecting the data and sending it to the functional levels involved. The hardware devices which control the equipment are generally PLCs; the resulting architecture is shown in Figure 3.2. The typical areas of food processing are, for example, packaging and finished goods warehouse, plus all the areas where the raw materials are processed.

An applicable architecture for material handling is shown in Figure 3.3, whilst Figure 3.4 shows a viable solution for food processing automation. This example shows the hierarchy of functions and information levels. It can be used to define a hardware architecture where the links between the different levels are managed by standard RS232 serial lines.

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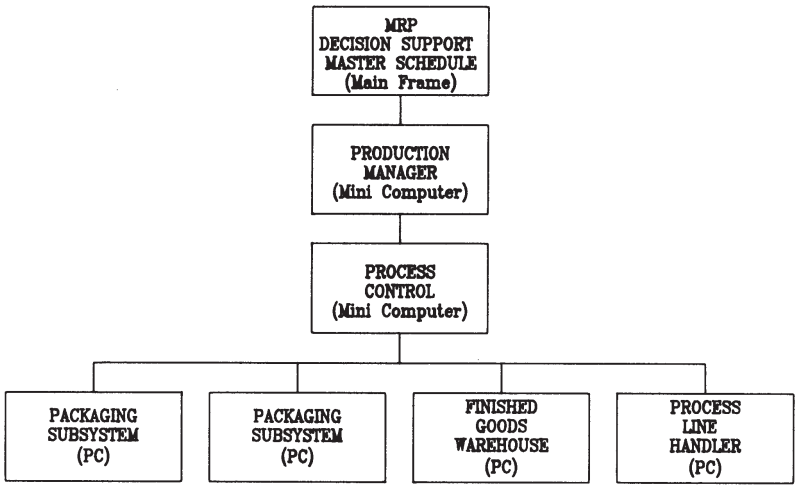


Figure 3.4 Typical food processing automation architecture

Figure 3.5 shows an alternative hardware solution based on a token ring network. The set of information contained on all the computers constitutes the corporate data base. A redundancy of information is generally set up at the different levels and some information is therefore repeated in the local data structure; the same data can be 'keys' at some levels and 'attributes' elsewhere, according to usage. The supplier code, for example, is an attribute of the units being handled in the 'handling' sub-system, but is a key field in 'production'.

The map of an automatic storage/retrieval system (AS/RS) is a data base kernel of the handling sub-system. It is none the less advisable to save it into the production system, which can perform a down-load should it be lost by 'handling'. The analysis stage shall also identify which data are to be stored on several systems, as well as the recovery procedures.

Let us see now how the process functions can be interfaced to the corporate ones. In particular, our aim shall be supplying the production level with

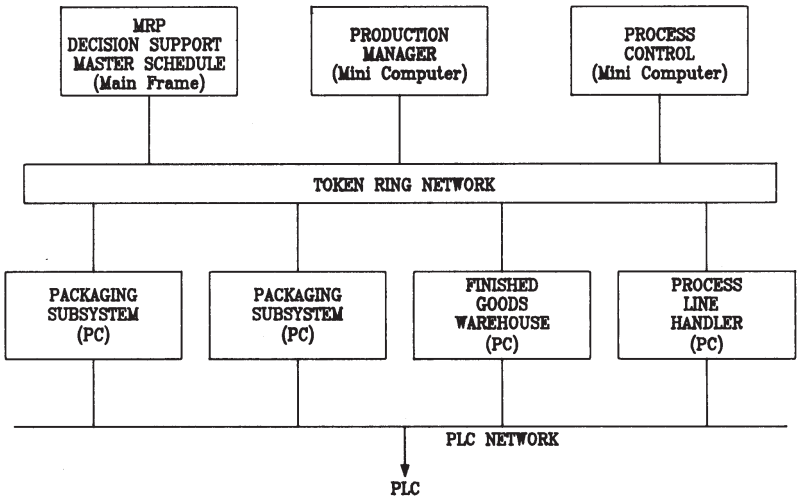


Figure 3.5 Token-ring solution

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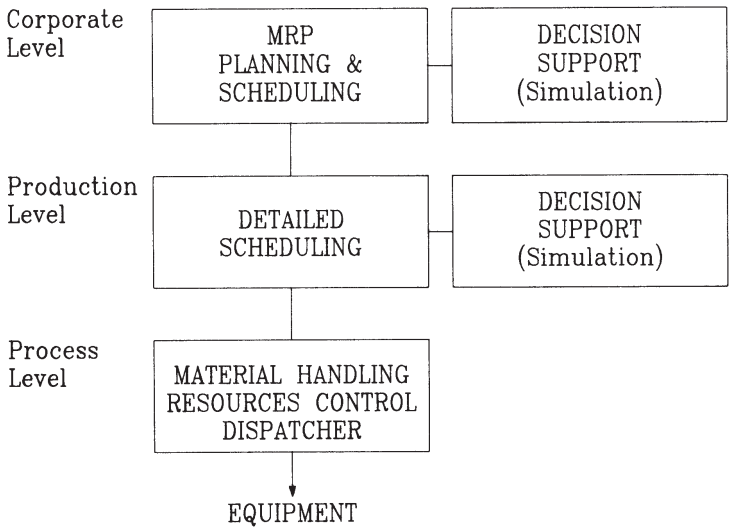


Figure 3.6 Scheduling system logical flow

medium-term instructions which can be derived from the corporate planning.

A practical example is shown in Figure 3.6.

The corporate information system generates the master schedule and the capacity planning, resorting to all the decision-making tools which are required for this purpose. The master schedule and capacity planning generate the inputs for the following:

- Procurement for materials requirement plan (MRP).
- Production for the generation of the detailed scheduling.

The detailed scheduling acknowledges the current plant status and generates all the activities required to comply with the master schedule; those activities may concern both the automated and manual processes.

The detailed scheduling is continuously updated with the status changes which occur at plant level, such as:

- equipment failures;
- manpower non available (strikes, etc.);
- changes in quality control parameters.

Figure 3.7 shows the data flow relevant to the scheduling function.

What we have described above is not fully computerised at the beginning, nor it is bound to be so in the future.

In all decision-making stages, the manager shall evaluate whether or not the schedule (master or detailed) is valid. This implies that the editing function is extended to the processing levels. Part of the maintenance and quality control functions are managed manually, i.e. the inputs coming from the equipment are integrated with those entered by the manager. The critical decisions are left to human appraisal and confirmation.

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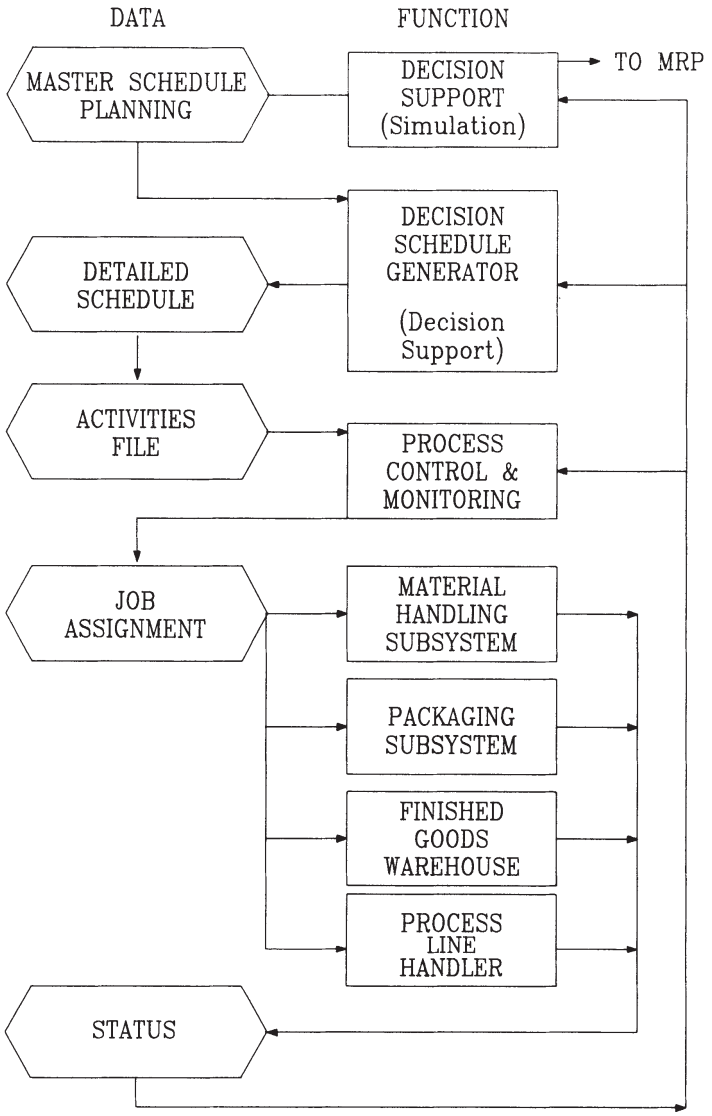


Figure 3.7 Scheduling system data flow

The main data contained in the data base of the process level are those relevant to:

- lay-out;
- tools;
- parts being handled;
- AS/RS maps;
- materials infeed to the plant;
- materials outfeed from the plant;
- production statistics;
- work in progress.

The production statistics are the 'decision support' elements; they are used by the process level to decide, for example, the work load distribution on the stacker cranes, or to request a routine maintenance intervention. The production data and in general the historical data are fundamental com-

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ponents in the process systems since they are often the only ones which can identify the causes of anomalous events due to wrong decisions made in the past.

The historical data base is generally not on-line and is asynchronously updated with the evolution of the conditions. The data it contains concern the mechanisms which are to be set up to supply statistical data, even if these same data are only used as a further step on the way to the integration process.

The historical data base is included in the corporate data base and is part of the 'inferential motor' inputs of a knowledge-based expert system used for 'decision support'.

3.5 Human interface

The human interaction is present at all levels, though to different extents. Man/machine interfaces are therefore to be established for:

- Quality control.
- Maintenance.
- Updating the physical data base to align the data to the physical conditions. This operation is particularly useful in the 'material handling' sub-system, since the parts are often being handled manually when the information is available.

The importance of effective human interfaces is dealt with in greater depth in a later chapter.

3.6 Summary

We have highlighted that the need to integrate elements effectively is driven by the business needs of the company. It is essential therefore that the company's aspirations, objectives and methods are taken into account properly.

To apply the CIM philosophy, there are two other elements which must not be overlooked:

(i) *Financial issues.* The manufacturer aims to reduce the production cost per product unit; to achieve this an exhaustive knowledge of the products is required.

(ii) *Human factor.* This aspect, though often neglected, is indispensable for a successful outcome of the integration process. We often wonder what is wrong in a company whose different sectors seem to be integrated yet do not achieve their best: the answer is usually found in the human element. Integration requires a revision of functions within the company, and this has to be accepted by the whole managerial staff.

A computer is the tool which makes the integration operative and efficient;

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however, procuring powerful computers and scattering them around the company does not mean that system integration has been achieved at all. Computers have a tremendous potential when wisely used, otherwise they are nothing but an expensive, dangerous collection of hardware. What matters is that the logic behind their use and the manner in which they are introduced is properly conceived and implemented.

Further reading

Bertrain and Leonard, *CIM Implementation Guide*, 2nd edition, Extracts from CIM reviews nos. 1, 2 and 3.

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4 Specification for success

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4.1 Introduction

In an ideal world, the control system software would arrive on time, be within the agreed budget cost and would do what you wanted it to do. How often have we experienced the complete opposite? The control system, and in particular the software, is often late, over-budget and it is not what is required by the end user.

So how can we who are responsible for food industry projects improve on this rather dismal picture?

For the purpose of this chapter, the control system shall mean the computer hardware and software used to provide the automation of the plant, the operator interfaces consisting of visual display units and keyboards or keypads, and all the equipment including programming terminals, printers, external data storage and, lastly, the documentation that provides the user with the instructions on how the system is designed and how to operate the system.

The documentation is a very important aspect of the overall system and forms an essential element to ensure a successful project. It can be neglected in the overall specification and, if so, this will lead to problems during engineering testing, commissioning and subsequent plant operation and maintenance.

A typical control system including most of the above elements is shown in Figure 4.1. The remaining systems which make up the overall electrical, control and instrument elements of the plant are outside the scope of this chapter and will be left to others to detail how the specifications for these elements are prepared.

Having defined the scope of the control system, we shall look into how such a system can be specified and what the criteria are for the specification during the various stages of the project.

4.2 Control system concepts

Before the specification for the control system hardware and software can begin, the overall automation requirements for the plant have to be

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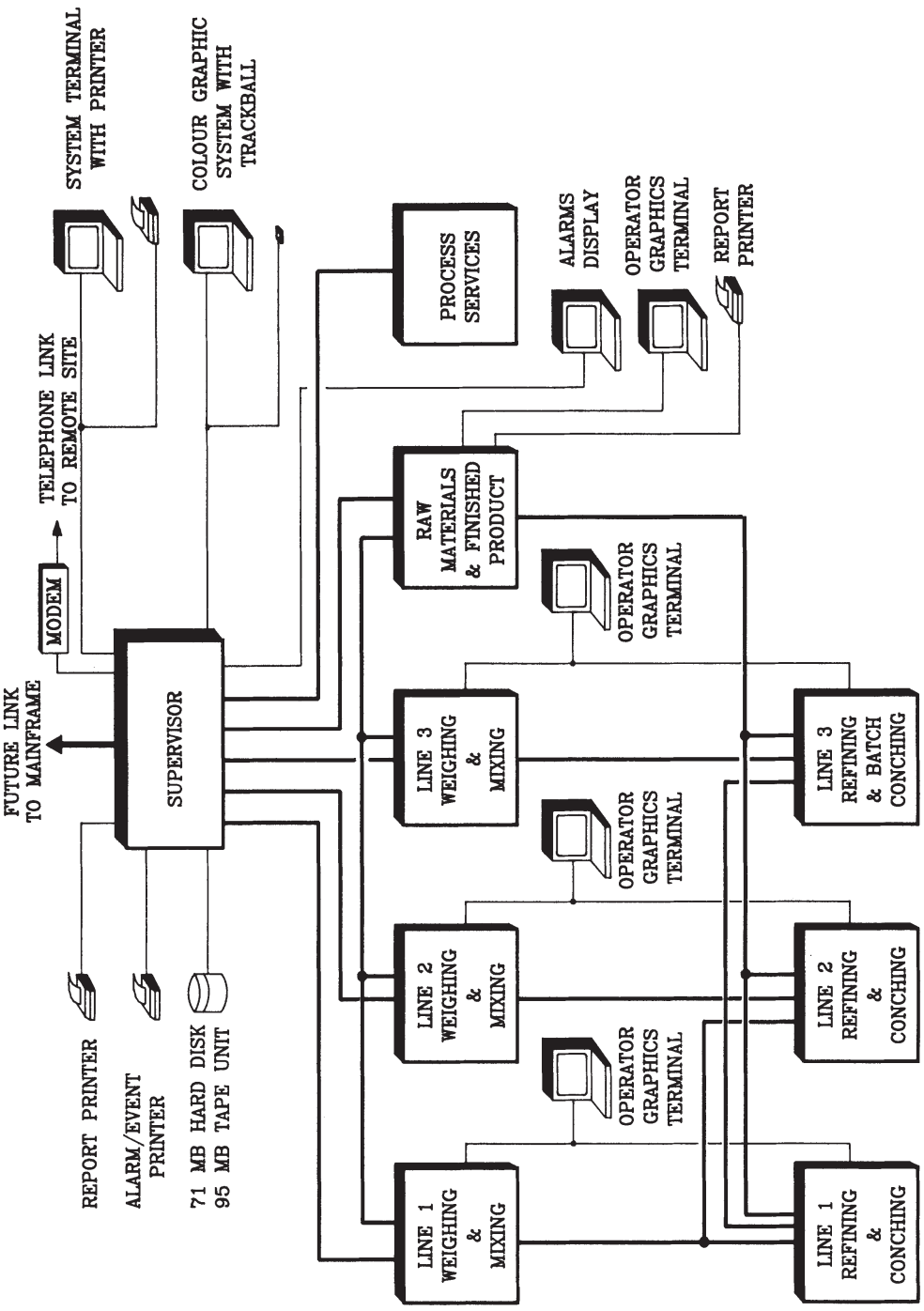


Figure 4.1 Typical control system hierarchy

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determined. Here the project team has to decide on the level of automation required. Decisions are required at an early stage on such matters as the number of operators required to run the plant and how the operators will interface initially to the mechanical equipment and then to the control system, which operations are to be totally manual, which are to be fully automated or to be a mixture of the two, as well as the planned maintenance requirements of the plant. Furthermore, what prompts are required from the control system to the operator to tell him or her which manual operations are required and at what time during process. The above questions all have to be addressed by the project team, with the control engineer taking the lead in determining the answers.

During this early stage it is possible to provide a framework from which the control system engineer can develop the overall control system strategy. This framework could well take the form of a number of options on the degree of automation required. Typically a list of these levels may be drawn up as follows:

- fully automatic operation;
- semi-automatic operation;
- manual operation.

This list of options should be fully analysed by the project team and the consequences of adopting a particular strategy should be fully explained to the project team and if possible to the end users of the system.

Typically, the question should be raised against each of the options as to the desirability and the impact on the overall project timescale and costs if it were adopted. If the fully automated route were used, would this be beneficial to the operators and would they still be required to do other tasks anyway? With a semi-automated system, are there dangers of the operators adding the wrong ingredients? How is the plant manager going to run the plant in the event of a control system failure or is the decision to be taken that if the control system fails, production has to stop? These and many more aspects have to be explored at this stage to enable the current strategy to be developed.

An interesting outcome that is worthwhile considering, when deciding on the fully automated route, is that operators will find the time, now that they are no longer required to perform the manual tasks, to increase their understanding of the process through the information that modern control systems offer. Hence they will be able to maximise the plant efficiency through operation of the plant variables that are available via the control system. The use of this generally un-tapped resource can be a powerful argument in favour of automating plants and one which should not be overlooked when obtaining capital authority for the project.

The questions posed by the project team on the required degree of automation and the general discussion on how the plant is to be operated should of course take place as early as possible within the project. Preferably

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the control system strategy should be finalised during the feasibility stage of the project.

Having agreed the level of automation, the project team can now begin to define the overall requirements of the control system.

Assuming the project follows the traditional stages of feasibility study, front-end design, detail design, implementation, engineering testing and commissioning, then at each of these stages the control system requirements can be progressively defined and specifications prepared.

Initially, the specifications for the first three stages will be considered: the feasibility study, the front-end design and detail design. It is convenient to consider these stages because not only can the technical requirements be outlined at each stage, but also the project cost can be defined to greater degrees of accuracy at each stage. The specifications that are prepared at these stages can form the basis on which capital cost of the control system can be determined.

Having made the fundamental decisions at the feasibility study stage, the control system engineer can prepare the initial control system strategy. This will consist of the proposed hardware configuration of how this hardware relates to the process together with a written description of how the system relates to the operators, what the main functions required from the system are, and whether there is a requirement for the system to interface to the other systems on the site. For example, is there a need to transmit production data from the control system to a central computer for record purposes, or more important, is there a site-wide computer network which operates a computer integrated manufacture system that will send the production requirements to the control system? In particular, if a computer integrated manufacture (CIM) system is to be employed in addition to the hardware configuration, the software architecture should be determined in outline at this stage to allow CIM to be implemented. It is important to identify these needs as early as possible to enable the correct control system configuration to be developed.

It is vital when developing this configuration that the control system is designed to suit the process requirements, and not the other way round. It is very easy in the early stages of a project to limit its success by imposing particular limitations, such as using a specific supplier's equipment. Whilst there may well be a preference, or indeed a need, to stay with one supplier it is essential that the concepts are defined without this limitation. Then when they are made clear it is easier to evaluate whether the use of this equipment is appropriate.

When considering those requirements which will form the basis for the specification, it is useful to follow the procedure as laid out within the *Starts Purchaser Handbook* [1] which advises that two levels of specification should be prepared. These levels can be related to the project requirements, to which a third level can been added which will involve the control system supplier as well as the project team. The project stages are as follows:

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Feasibility study/front-end design—Level one.
Detail design/implementation—Level two.

In general *Starts* defines the specifications prepared during level one as the 'overview', and level two as the 'detailed specification'. All together these form the 'requirement specification'.

We shall look more specifically at what is required for each level later. Firstly, let us develop the requirements necessary for the hardware.

4.3 Hardware requirements

From the discussions which take place at the feasibility stage, the control system engineer will draw up the hardware requirements. It is sometimes the case that the hardware requirements are already known in the very early stages of the project. This may be because the project is an extension of an existing facility and the control system hardware is to be extended in conjunction with other hardware on the site which would lessen the spares holding or training requirements of personnel. As stated earlier, this must be considered carefully, and must not prejudice the decision-making steps.

Let us assume that we have a green-field site in this case and the hardware that best suits the requirements is the most suitable one to use. This immediately puts a great onus on the hardware specification in that it should be written to enable competitive bids to be sought from a number of control system suppliers.

There are a large number of potential suppliers of control systems offering a variety of computer-based solutions, but generally the system used within the food industry falls into two categories—a distributed control system (DCS) or a programmable logic controller system (PLC). It is advantageous at the earliest stage for the project team to have made the decision as to which of these two major categories best meet the requirements of the plant.

In order for the control system engineer to arrive at the typical configuration shown in Figure 4.1, he will need to know the major elements of the process, how they are to be controlled and the number of operators required.

Initially, a block diagram could be prepared. The blocks are used to show the control system hardware and the process description of what is to be controlled is shown within the block.

For a typical food-based project, each block could contain the following:

- Ingredients in-take.
- Weighing.
- Blending.
- Storage.
- Ingredients off-take.

Within each of the blocks, an allowance is made to accommodate the required

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process services for each of the operations. Above the blocks of control the supervising system or data logger or main operator interface may be placed, depending upon the system requirement. This being a computer-based system it could include the interface to other systems if required.

From each of the main blocks, specific operator interfaces would be shown. From this initial drawing, an appreciation of the hardware can then be obtained. In parallel with the control system, the process line diagrams (PLDs) will be developed by the process engineers. During the preparation of the PLDs the control system engineer has an important role to play in adding to the PLDs the automation requirements. From the process line diagrams, the control system engineer will be able to obtain all the input/output requirements for the control system. This input/output requirement represents the number of control elements the control system has to interface with and it enables the control system engineer to quantify the size of the input/output requirements of the hardware.

The input/output counts will determine the size of the control system required for each of the blocks and it is important that a balanced view is taken as to the logical split of the control system. This may be the same split as applied by the process engineer when he is developing the process line diagram but care should be taken by the control system engineer that this split may not be the most appropriate for the control system.

Consideration should be given to the overall redundancy requirements of the system; for example, in the event of a failure of any mechanical part or of the control system which parts of the production process can be maintained.

The control engineer, having established the outline computer hierarchy, can start to develop the hardware specification. The control system hardware, for a typical food related project, will consist of the following components:

- The computer hardware which, depending upon the final selection taken, will consist of a main processor, memory cards, input/output cards, power supplies.
- The panels to house the computer hardware detailed above and the control power supplies, the field terminals, protection units including uninterruptable power supplies.
- The peripheral equipment including printers and associated paper feed mechanism, operator keyboards and graphic display units, engineers' terminals.
- The plant level operator terminals, with suitably designed enclosures.
- Hardware documentation.

The above defines the scope of the control system hardware. In addition, and depending upon the configuration, details of the data highway and standard software package that are required should be specified. Having defined the scope required, the control engineer should specify the standards to which the

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equipment should be constructed and the particular details required by the project, for example, the control system voltage levels.

For food-related projects, the environmental condition of the control system is of utmost importance. The impact of the environmental conditions on the equipment will result in the panels and operator interfaces conforming to the hygiene requirements of the plant.

The specification should include a statement on the hygiene requirements for the project. In particular, the required finish of the panels—stainless steel or painted should be specified. The location of the control panels will depend upon the standard of finish, material of construction and the required enclosure rating of the panels. The enclosure rating should be defined as specified within BS5490 and will reflect the proposed location of the panels. With the ever higher hygiene standards being applied to food production plants, it is recommended that the minimum amount of the control system hardware is located within the production areas. The concept of panel rooms and a central control room is now well known within the food industry. This type of approach is recommended to minimise the panel equipment that has to be located in the plant areas.

When specifying the panel configurations required, due regard should be made to ensure that the correct size of panel is allowed for to suit the equipment enclosed and the location within the building. In addition, consideration should be given to the internal layout of the panels to ensure that the initial cable installation can be carried easily and accurately and that the panels can be subsequently maintained. Therefore, there should always be sufficient space for cable terminals and access to components contained within the panels.

For the control system equipment that is to be located within the central control room, consideration should be given to the ergonomics of the desk layouts, the correct position of the visual display units and the location of the operators' keyboards; this is vital to allow for ease of operation. The materials of construction and finish of the central desk should reflect the importance of the control room to the overall operation of the plant. Care should be given to lighting levels and the finish and colour of the materials used in the construction of the control room. The correct environmental conditions should be specified not only for the operator but for the hardware as well. As with any area where operators will spend a significant time, the central control room has to be aesthetically, as well as practically and ergonomically, correct.

Having dealt with panel design, required finish and materials of construction, the hardware specification should address the specific needs of the control system. Depending upon the concepts determined during the early stage of the project, the hardware attributes may well be fixed; for example, if the programmable logic controller route has been decided upon the possible hardware configuration may then be limited. But it is important to specify the areas that are common between differing systems and a well written

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specification should enable the control system supplier, when tendering, to put forward the configuration and type of system that best suits the application. Consideration should be given within the specification to the following points:

(i) *Hardware expandability.* What is the maximum system configuration and how much of this expandability will be used to meet the needs of the current project requirement?
(ii) *System modularity, distribution and redundancy.* What are the requirements of the process in the event of one section of the control system failing, whether this is a single card failure or complete failure of the control system? Is the hardware proposed modular in its approach so that the failure of one component will not affect the operation of another?
(iii) *Reliability.* If figures for the 'mean time between failures' are available then these should be specified within the specification. A better understanding of the reliability of hardware can be obtained from direct experience of existing users of similar hardware.
(iv) *I/O interfaces.* When specifying the input/output requirements of the system, in addition to the requirements of the type of I/O digital or analogue, the communications links of the system should be specified.
(v) *Expansion.* Specify the current needs of the system, but pose the question 'Can the memory be expanded, and to what value can the number of operator stations be increased; can the I/O be increased and how easily?'

In dealing with these matters relating to hardware and the subsequent section dealing with software, a useful tool when assessing the varying systems is to incorporate into the specification a questionnaire that the potential supplier completes at the tender stage so that a fair assessment of the merits of the system can be evaluated by the control engineer.

A typical questionnaire would have the following main headings:

- Hardware.
- Software.
- System integrity
- Testing.
- Project management/organisation structure.
- Maintenance and support.

Further details on developing this type of questionnaire are in reference [2].

4.4 Software requirements

We now move to software specification, which often gives rise to the most difficulties.

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Following the project route, feasibility study, front end and detail design, as defined earlier, it is proposed that at each stage a control system software specification is prepared. The nomenclature of the various stages varies depending upon approach, but for the purpose of this book the format outlined within the *Starts Purchaser Handbook* is used. The title used for the total document is the 'requirement specification'. The documents used at each stage of the project are as follows:

- Level one: Overview: feasibility/front end design.
- Level two: Detailed Requirement Specification: detail design.

A third level is also identified. This is the 'software specification', which is prepared by the control system supplier and details the design parameters used to write the software.

The above approach has many advantages. It ensures that the end users' requirements are fully specified at all stages of the project and provides a clear and precise specification for the project team; the basis of the technical documentation for the tender to the control system supply; the basis on which the control system will be tested and its subsequent performance will be judged; the basis for plant operational manuals and is a useful training document for the plant operators. Future maintenance and up-dates of the system will be easier. This being so, it is imperative that each of the stages are carried at the appropriate time within the overall project programme.

For examples of preparation, and what should be included within the various sections the reader should review [1] and [3]. In particular, the IEE Guidelines referred to in [3] give a very clear definition of the contents of each of the specifications including the fourth level specification prepared by the control system supplier. Whilst the essential features of the specification documentation are given within these references, it is worthwhile defining in general terms the information required at each of the levels.

Level one: overview At this stage of the project, the team will know the degree of automation required from the control system. These can be summarised as follows:

(i) *Fully automatic plant.* The plant will start from a single command and will continue to operate until stopped by the operator or the process conditions force the plant to stop.

(ii) *Semi-automatic plant.* The plant will start from a single command, carry out a number of sequences and processes, and then halt, waiting for further operator input. With this type of control, an important feature will be the required operator interfaces.

(iii) *Manual operation.* The operator has total control of the individual pieces of plant. The control system checks that the sequences selected do not cause a safety hazard.

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It is usual within a food processing operation that the control system will incorporate all three of the above degrees of automation for various elements of the process plant.

Level two: detail requirements specification The general principles outlined for level one are developed within the detailed requirements specification. This should contain the process description as prepared by the process engineer and also the requirements of the plant and equipment operation.

It is at this level that the general requirements which have been stated within the introduction are developed. The style and format of the information required for the detailed requirements specification will vary from project to project, and indeed for different elements of the project itself, but if level one has been correctly approached the framework for the detailed requirements specification has already been established.

The process description will form the basis of the detailed requirements specification. Broadly this document should address itself to the following areas:

- safety requirements;
- operational requirements;
- operator interfaces.

The safety requirements are fundamental to plant operation and the control system must always, under all conditions, control the plant in a safe manner. Particular attention should be given to start-ups, shut-downs, emergency shut-downs and plant failure, including control system failures.

One area to be reviewed in this section which is often overlooked is that of recovery back to normal operations after a plant shut-down.

The operational requirements of the plant should be embodied within the process description and the flow sheets, but clarification may be required; for example, the overall accuracy required by the process should be stated. The required operator interfaces, what the operator expects to see on the screens (and what he does not!) or what keys have to be operated, have to be developed in conjunction with plant management. In addition, any requirements on data storage or report formats should be specified in outline at this stage.

In order to provide a better understanding of the requirements, flow-charts and tables should be used as much as possible. For example, in applications that require valve sequencing charts should be used to show route combinations. Flow-charts should be used initially to provide an overall sequence of events and, secondly, to indicate individual operations and sequences within the complete scheme. A typical example of a flow-chart is shown in Figure 4.2.

Level three: software specification Having produced the detailed requirements specification, this is issued either as part of the tender documentation to

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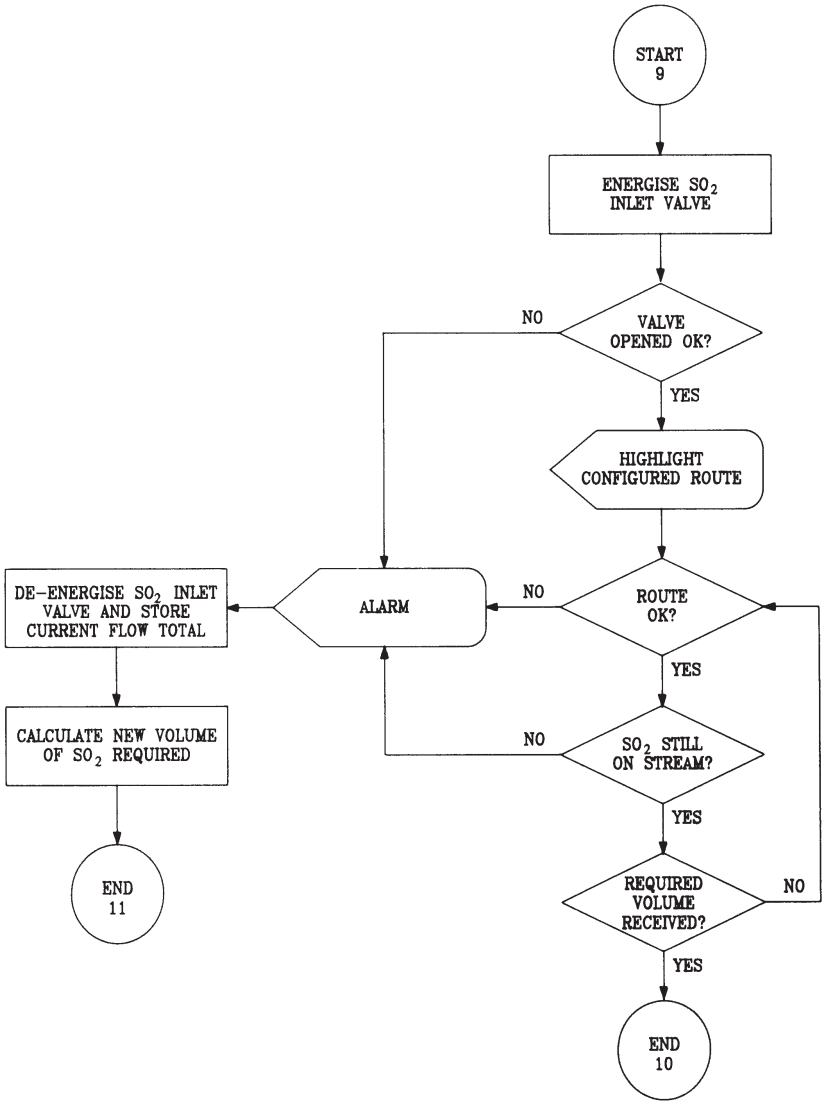


Figure 4.2 Typical control sequence flow chart

the control system supplier or is prepared in conjunction with the selected control system supplier, depending upon the contractual arrangements between the purchaser and the supplier. The software specification should be prepared by the control system supplier himself.

The detailed requirements of this specification are contained within IEE *Guidelines for Documentation of Software* (see [3]). The functions of this specification can be summarised as follows:

- To provide a specification for the software writers to design and develop the system.
- To provide the basis on which future developments on the system can be implemented.
- To provide a document that can be checked against the detailed requirements specification before the control system company produces the software and therefore prevent costly changes at the later stage of the project.

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Indeed, the point of checking each level of documentation against each other is a very important advantage of the overall approach. It provides a means of ensuring that the original requirements of the system as defined within level one are being met throughout the development of the control system software.

This checking procedure is taken through to the testing of the system when it is normal practice for the control system supplier to produce a factory acceptance test specification which will detail the tests the supplier will carry out on the completed system before delivery to site. It is recommended that the factory acceptance tests are checked against the detailed requirements specification and not the software specification, to ensure that the original intent of the systems is met. In fact the software specification may not be fully intelligible to anyone other than personnel with software writing expertise.

4.5 Case studies

To provide case studies of the application of specifications that have been used successfully within food-related projects two examples are included. These relate to projects requiring a high degree of automation and hence the need to provide clear and unambiguous specifications was of paramount importance to the overall success of the project.

In providing detailed case studies of the contents of the specifications, the examples relate to the preparation of the requirement specification for the control system software. The methods of obtaining information for inclusion within the specification will vary from project to project. This depends upon the client's personnel, the specifiers' team and the available process knowledge within the two teams.

4.5.1 *Soft drinks plant*

The first case study relates to a new plant for the production of soft drinks. From the onset of the project the client was fully committed to providing a totally automated plant.

The hardware selected for the project consisted of a distributed programmable logical controller (PLC) based system together with two supervisory computers providing the main operator interface and management information system. The hardware system being based on PLCs, required the majority of the software to be written specifically for the project. The two supervisory computer systems were based on standard products and required configuration software to be implemented.

The main task of the requirement specification was therefore to provide a detailed description of the control system function to meet the needs of the

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process at PLC level. With this main objective in mind a detailed functional specification was prepared defining the requirements for the various PLCs controlling each process area. From this detailed functional specification the control system supplier, who in the case of this project was responsible for providing the hardware and software, carried out the design and the subsequent writing and testing of the software.

With the proposed distributed system each of the PLCs controlled a specific process area and a functional specification was prepared for each of the PLCs and hence for each of the process areas. The format for each functional specification was planned prior to commencing the writing of the specification. By way of an example, a process area functional specification will be examined in detail. The contents for this section of the functional specification are shown below, together with a brief description of these contents.

Introduction. The introduction included background information, such as relationships with other areas, and the current revision of each of the drawings.

Plant description. This states what the function of the equipment is in relation to the process.

Definition of systems. This details what plant items are contained within the sub-systems of the specific process area; for example, the automated valves and pumps are listed.

Product coding/tank identification. This details the codes and abbreviations applicable to each of the materials used. Tank identification relates the tank number to the material being held in the tank. For this particular process the duty of the tank in relation to the material varied for different aspects of the process. It was a requirement of the control system to be able to identify what material is held in which tank.

QC sampling. This described the required operator action and how the operator enters the data into the control system.

Detailed operations. Within this section the process operations were outlined within the plant description and described in detail. Considerable use was made of graphical presentation to support and explain the various functional requirements. Typically the graphical information consisted of:

- Process flow diagrams;
- Operator interfaces video page diagrams;
- Route definitions;
- Logic flow-charts.

In addition to the textual description extensive use was made of logic charts and video page formats, the latter showing what the operator would see on the control system terminals and what actions were required to continue on to the next stage of the process. It was within this section that the areas of start-up, shut-down and failure modes were described.

Alarms and events. For this project a particular policy was established as to how the control system handles alarms. This was used to derive the required

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information at PLC level. Within this section the alarms are identified in terms of the input to the system; for example, motor and valve failures and operational alarms. The events to be recorded and logged are also defined in this section, and a common policy was adopted.

Tank agitation. A common approach was used for the control of the starting and stopping of each of the agitators within this process area, the control being dependent upon liquid levels within the tanks.

By adopting this modular approach to the production of functional specifications what initially looked to be a daunting task became manageable and resulted in a high standard of specification. This was used successfully by the control system supplier to provide the software without the need of further fundamental questions on process design.

4.5.2. *Edible oil plant*

For this case study an example is drawn from a major refurbishment of an edible oil process plant. The project was based on two phases; this case study relates to phase one of the project. To be sure of the ultimate success of the scheme, the impact of the second phase on the control system had to be considered during the development of phase one.

The control system for the plant was based on a distributed control system, and Fisher Controls were responsible for the supply of the hardware and software.

To meet the needs of the project and provide Fisher Controls with a definitive specification upon which the software could be designed and the system configuration carried out, the project team wrote a 'user requirement specification' for the control system. From this user requirements specification Fisher prepared a combined functional specification and software design specification. Subsequently the testing specification was prepared and the completed control system tested at the supplier's premises for conformity with the user requirements specification. On completion of the tests the software was installed into the hardware on the client site for engineering testing and commissioning leading to the successful completion of the project.

The user requirement specification was prepared and written by the control engineer working for the main contractor responsible for the overall project design. He worked closely with the client's process team to understand the process requirements and to convert these into a specification that could be understood by the control system supplier. In addition to providing the main technical description of the process and control system requirements, the specification provided the commercial basis on which the software costs were based.

The initial phase of the project was concerned with the offloading, storage and distribution of oils at the client's refinery. The process equipment was a mixture of new, refurbished and existing plant. The control system together with the field instrumentation was all new equipment.

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The main objectives of the control system were clearly identified in the specification and are summarised as follows:

- the ability to receive oils from road tankers;
- the storage of oils in a closely controlled environment;
- the distribution of accurately measured quantities of oils;
- overall management of the storage system including the maintenance of a stock rotation scheme.

In addition to the main process objectives listed above the control system was required to:

- enable operators to deal effectively with abnormal occurrences;
- facilitate safe working practices;
- provide production management data;
- provide alarm monitoring and logging systems.

Together with these a number of objectives clearly stated the detailed plant operation under normal, abnormal, start-up and shut-down conditions, all of which were fully described within the specification.

With the requirement of the specification to convey the process requirements to the control system supplier extensive use was made of graphical information. These included:

- detailed input/output schedules describing the function of each point wired into the control system;
- timing diagrams for each of the product routes;
- route definition tables indicating the required position of each of the valves within the route to be defined;
- detailed drawings of the required video graphics displays.

The benefits derived by the client from this particular user requirement specification can be summarised as follows:

- It provided a clear definition of the process and control system requirements which all parties could understand and conform to.
- It provided a firm commercial basis on which to engage the control system supplier.
- It provided a training document for the final plant operation.
- It provided a specification with which to measure the completed control system against the original requirements of the client.
- It provided a working platform for which future developments of the system, including the second phase could be made.

4.6 Summary

The approach for the preparation of the control system specification can be used on all projects requiring software, no matter what the size. By adopting

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this systematic approach to the preparation of the specification the problems highlighted within the introduction will be overcome. As with all documentation that has to be prepared by engineers, the engineer may find difficulties in meeting the criteria of any specification, which should be clear, precise and unambiguous; by following the guidelines available to him the objectives will be met.

The approach described for the preparation of the control system specification has been used successfully on many projects within the food industry. Because of this success, it is anticipated that it will become adopted throughout the food industry. However, the impetus must come from the industry itself, so that the designers, main contractors and the control system supplier will all recognise the approach, which will be of major benefit in providing quality software to the agreed programme within the accepted costs.

The two case studies demonstrate that the time spent at the specification stage to define fully the control system software is time well spent for the successful completion of complex, highly automated projects. In environments such as the food industry where the process requirements and methods, and the aspirations of the engineers, production and management personnel are not always fully understood such documentation is essential.

References

[1] *The Starts Purchasers Handbook.* Prepared by the Starts Purchasers Group. Published by NCC Publications. Second edition, 1989.
[2] Brian Roffel and Patrick Chin, *Computer Control in the Process Industries.* Lewis, 1987.
[3] *Guidelines for the Documentation of Software in Industrial Computer Systems.* The Institution of Electrical Engineers, 1986.

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5 Computers in control

DEREK MACK

5.1 Introduction

The term 'computer' is now used in a very general and often confusing way to refer to any item of equipment containing a microprocessor and ranges from very simple instruments to very large data processing installations. It is therefore worthwhile establishing exactly what is meant by the various types of computers used in industrial applications. This chapter considers the different types of computer which can be employed, firstly as general purpose machines then refers to equipment designed to fulfil specific purposes. It reviews how more accurate control of a process can be achieved using closed loop three-term systems, and what this means in practice.

The physical arrangements for computer systems in terms of the geographical layout of the equipment and the methods of providing redundancy of some or all of the computer equipment are considered and, finally, the various levels of operator and maintenance controls that can be provided are summarised.

5.2 Types of computer

5.2.1 *Programmable controller*

The programmable controller is often referred to as a 'PLC'* (programmable logic controller), and sometimes as a 'PC' (programmable controller). This latter term can be confused with 'PC', also being used for personal computer!

Programmable controllers range in size from a unit capable of accepting 12 inputs and providing 8 outputs, all digital with no analogue capability at all and having 1K bytes of memory, up to a machine capable of accepting over 16,000 digital signals and 400 analogue signals with over 1.5 M bytes of memory and a variety of bulk data storage devices and graphical display units.

Figure 5.1 shows a typical arrangement or architecture of the various parts of a programmable controller. Programmable controllers are designed to

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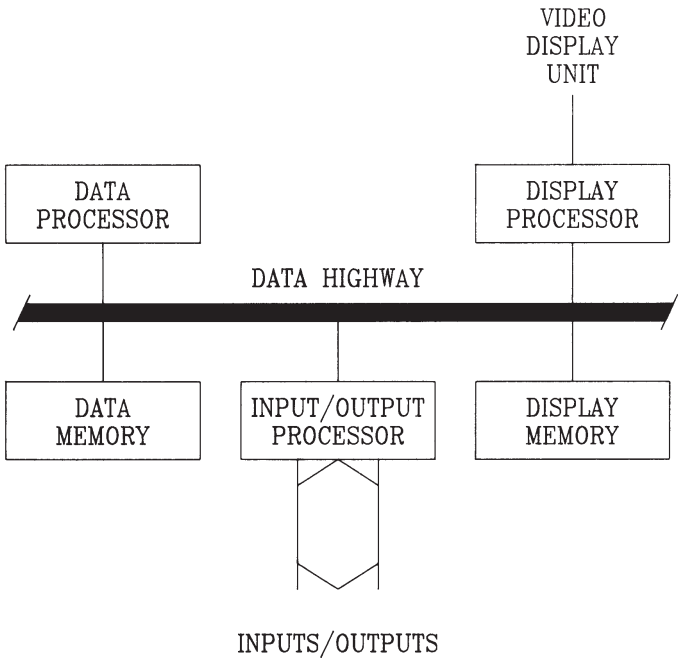


Figure 5.1 Typical programmable controller architecture

accept large numbers of digital or analogue inputs and condition these to produce the appropriate output, again either digital or analogue.

Digital inputs are ON or OFF signals fed from the plant, e.g. pressure switches, high and low level switches, auxiliary contacts of circuit breakers and contactors. Digital outputs operate plant equipment, e.g. bin slides, motor starter contactors and on/off valves. Analogue inputs are variable signals taken from the plant, e.g. temperature, pressure, flow or level. Analogue outputs are variable signals fed to the plant to control, for example, the speed of a pump to adjust flow or the opening of a control valve to control temperature.

The digital inputs and outputs are connected to the plant by input and output modules. These modules accept or send out d.c. or a.c. voltages from 5 V up to 250 V or more with outputs up to 2 amps, and are able to withstand the levels of electromagnetic interference (EMI) which are present to a greater or lesser degree in all process plants. These modules provide the required isolation between the plant and the microprocessor level signals used in the I/O processor. The analogue inputs and outputs utilise analogue modules suitable for a variety of ranges such as 4–20 mA, 1–5 V, $\pm$ 10 V. Interfacing analogue signals to a digital computer requires them to be converted, which is done with analogue to digital (for inputs), and digital to analogue (for outputs) converters. These have a limited accuracy, commonly 8 bits (1 in 256) or 12 bits (1 in 4096).

Programming languages have been developed to provide both sequencing and analogue control. The most familiar form is known as ladder diagram programming, although other forms are now available. Figure 5.2 shows an

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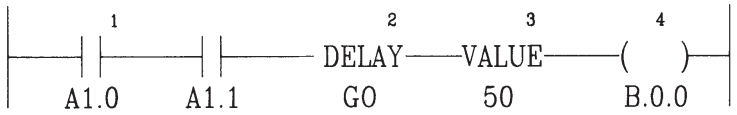


Figure 5.2 Typical ladder diagram program format. Key: 1, Input contact ref. A1.0 and A1.1. 2, Timed delay command calculated in location G0. 3, Delay period of 50 (= 5 seconds). 4, Output contact BO.O.

```
1. IN A1.0
2. AND A1.1
3. DELAY 50
4. OUT B0.0
```

Figure 5.3 Typical mnemonic language format. Key: 1, Input contact ref. A1.0. 2, 'AND' result with A1.1. 3, Time delay of 50. 4, Output result to BO.O.

example of a simple motor starter circuit with time delayed start as it would be seen in ladder diagrams.

Although the larger systems can now support storage devices such as hard disc drives and tape streamers the ladder diagram programming language makes the processing of data rather difficult. It is, however, very effective for real time plant and sequence control. Some of the alternative languages have addressed this problem and generally provide better data handling facilities, but at the expense of the simplicity which ladder diagrams can offer. Figure 5.3 shows the same problem as Figure 5.2 but solved using an alternative, mnemonic type language.

5.2.2 *Personal computers*

The personal computer uses the same family of microprocessors as the programmable controller, commonly from the '80' series of the major chip manufacturers, e.g. Intel 8086, 80286 and 80386.

IBM became a market leader with their XT, AT and PS/2 desk top computers models. Most models which arrived later (and there is now a vast range of models) have been obliged to maintain this compatibility with IBM models.

Personal computers have a very limited capacity for accepting plant inputs and outputs but very good facilities for data processing and storage. Virtually all models now available have a built-in hard disc and at least one other disc drive either of 5.25 inch or 3.5 inch size. They do not have any particular programming language included but have an operating set called DOS (disc operating system) which establishes the way in which the computer will respond, i.e. it sets up the system environment.

Many programming languages are available for personal computers, such as BASIC, PASCAL and FORTRAN. In addition there are many proprietary programs for manipulating information, such as spreadsheets and word-

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processors. Some or all of these may be appropriate for inclusion into a real time control system but care must be taken as to how this is done if the intended results are to be achieved.

5.2.3 *Mini and mainframe computers*

Computers are sometimes referred to as mini- or mainframe, and are different from personal computers, not only in that the computer itself is usually a fixed installation, often in a specially designed room with air conditioning and fire protection equipment, but also in the way the internal architecture is arranged. They are normally very well protected against interference, provide automatic back up systems and so on.

Personal computers are designed to stand alone, although they are sometimes connected into a network. As a rule they only have one operator able to access them at one time. Mini- and mainframe computers often have many numbers of operator stations and peripheral devices. Each operator has his or her own area of memory and files and other operators cannot have access to these files.

The number of workstations that can be connected depends on the size of the computer. In large installations the terminals are connected via a high speed local area network (LAN) of such type as Ethernet and in this way the terminals can be distributed around the factory. The computer bulk storage medium is also by hard disc, but these are often removable, and are installed into the computer in packs, rather than having just one fixed disc inside the

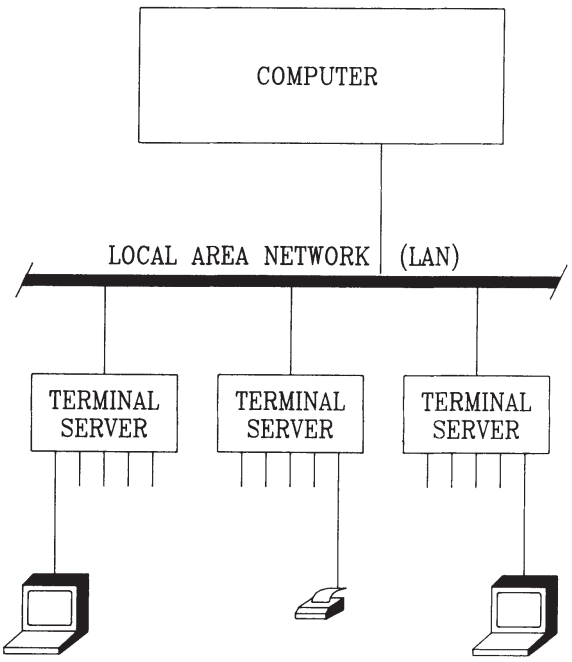


Figure 5.4 Layout using local area network

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machine. The number of users who can have simultaneous access is again limited by the size of the machine.

The response of each terminal will become slower as the number of users increases. Note that it is the number of terminals actually connected, rather than the maximum that can be connected which causes the response to slow down. It is common for the practical limit of number of terminals to be much less than the maximum number that can be physically connected.

5.2.4 *Summary of computer types*

A programmable controller uses computer components to control large quantities of external devices. A personal computer is a portable or semi-portable device intended to be accessed by only one person at a time, usually seated at it. A computer is a fixed device and has many people located remote from it, but accessing it simultaneously.

5.3 SCADA and DCS systems

SCADA is an acronym for 'sequence control and data aquisition'; DCS for distributed control system. Both these types of systems are special applications of computers. The programs which are running in the computers are written in a high level language, but are not able to be modified by the user. The usual method for the user to input information is via a menu and 'fill in the boxes' style of programming.

5.3.1 *SCADA system*

The main purpose of any SCADA system is to gather information, log the data and present it to the user in an understandable form. Because of its special purpose, it is designed to connect to a reasonably large number of digital and analogue inputs but with few outputs. The number of outputs is determined by the amount of sequencing capacity included.

The system will have a fixed capacity for inputs, whether digital or analogue, usually referred to as channels, and this capacity can usually not be exceeded or increased. The user programme is often limited to the following type of function:

- Identifying a particular channel by process tag number or mnemonic.
- Specify printer message to be output.
- If the channel is analogue what alarm levels are required? Usually four are provided, two for high values and two for low values, designated high (H), very high (HH), low (L), and very low (LL). Sometimes additional alarms are available, for example 'rate of change'.
- Sample interval for analogue inputs.

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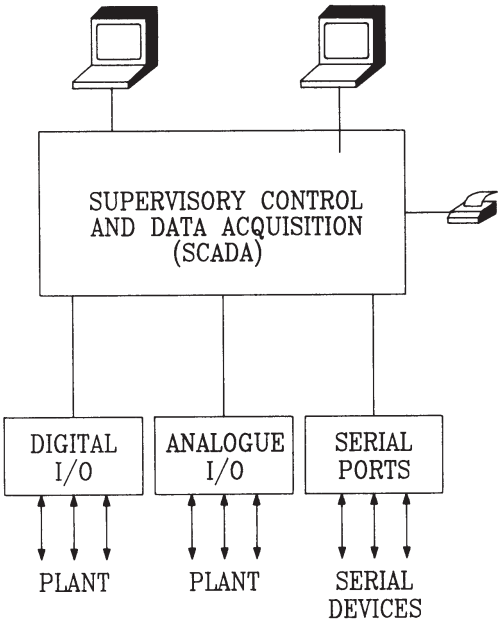


Figure 5.5 Typical SCADA layout

- Whether a trend display is required, and what time interval of trend is required.

The system will contain a real time clock so that events can be time tagged for logging purposes. The resolution of tagging is often not better than one second unless particularly specified. SCADA systems also have additional serial ports which allow them to communicate with other intelligent devices, such as programmable controllers. The necessary protocols are included in the software library of each SCADA and are part of the configuration information specified for the plant. Figure 5.5 shows a typical block diagram for a SCADA system.

The serial connections allow the SCADA system to access data that is held in the other devices so that any duplication of inputs is avoided for the information may have already been partially processed. For example, a thermocouple input may already have been linearised and calibrated so that the temperature value may be read directly to the SCADA system without further signal processing. Alternatively, digital signals may be collected together so that one bit of data passed to the SCADA system is the result of some logical deduction at the programmable controller. In this way the SCADA system can be used more effectively.

5.3.2 *DCS equipment*

Distributed control systems equipment (DCS), as its name implies, is designed to provide process control functions, usually with special emphasis on

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analogue control. The programming performed by the user is achieved by filling in boxes on VDU displays with values. Special displays are provided to allow control loops to be configured. This display is often referred to as a 'faceplate' display, since it emulates the information and set up method used on a single point, three term, controller instrument.

This method of programming does not easily lend itself to the execution of digital sequencing tasks, so that DCS systems are not usually employed where most of the work is sequencing rather than analogue. There are usually more VDUs and keyboards available with DCSs than SCADA systems and the level of access available at each workstation can be varied from access to monitor only, through to full access, allowing parameter reconfiguration to be carried out.

5.4 Stand alone controllers

The SCADA and DCS systems described above are able to control a number of activities simultaneously, including analogue control, digital sequencing and interlocking: Stand alone or single point controllers control only one analogue control loop, or a small simple sequence with typically eight I/O points.

Single point controllers are used in situations where the process is required to continue or can continue, even when another part of the system has failed. If a DCS or programmable controller was used and failed then all control carried out by it would be lost, and the process would have to be taken automatically to the safe shutdown state. If single point controllers are used then even if the programmable controller which is controlling the sequence fails, control of the process may be able to continue.

Consider the example of a furnace which has a number of temperature zones giving a temperature profile through the furnace, but where the product only needs to be transferred from one zone to the next over a number of hours.

If a single programmable controller was used for the transfer sequencing and also for the temperature control of each zone, the failure of the controller would cause failure of the total process. If the programmable controller was used only for the transfer sequence, and single point controllers were used for the individual zone temperature controls then failure of any one device would allow the process to continue with possibly only one burner group or the transfer system being lost until repairs could be carried out. The disadvantage of this type of configuration is that the cost is usually greater, since the programmable controller is already present and a single point controller is more expensive than fitting an analogue input and output for each control loop to the programmable controller.

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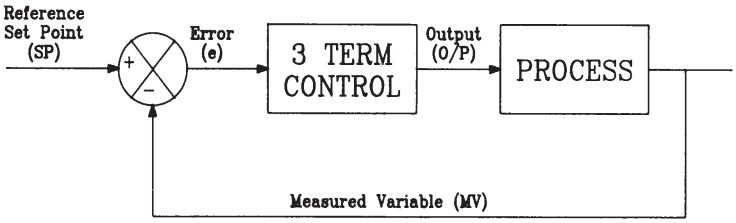


Figure 5.6 Simple block diagram three term controller

5.5 Three term control

Three term control, or PID control as it is sometimes called, can be achieved by any of the types of equipment previously discussed. PID refers to the 'proportional', 'integral' and 'differential' control factors that can be included in the analogue control loop.

If a computer-based system is used, then PID control can be effected by means of an algorithm included in the program. If stand-alone controllers are used the PID control may be effected either by means of an algorithim as before, or by utilising analogue electronic circuitry designed specially for the purpose. A simple block diagram of a PID control loop is shown in Figure 5.6.

5.5.1 *The purpose of three term control*

The purpose of the three term controller is to ensure that the process variable under control remains at the required value within the process despite other influences upon it. The control actions achieved by computer-based systems can be as effective as with pure analogue systems but care has to be taken to ensure that the delay introduced by the digital system does not significantly change the control. The delay is caused by the fact that a digital system is inherently a sampling system where the variable under control is only read at certain time intervals rather than continuously.

Consider a temperature control system as shown in Figure 5.7 which is required to maintain liquid at a constant temperature in a vessel by passing hot water through a coil inside the tank very similar to a domestic hot water system. If the control valve is fixed at one position, the temperature of the water inside the tank will vary if any of the surrounding conditions change, such as:

- the temperature of the heating water;
- the pressure of the heating water (this changes the rate of flow of the heating water);
- the temperature of the air around the tank;
- if any water is drawn from the tank and replaced by cold water.

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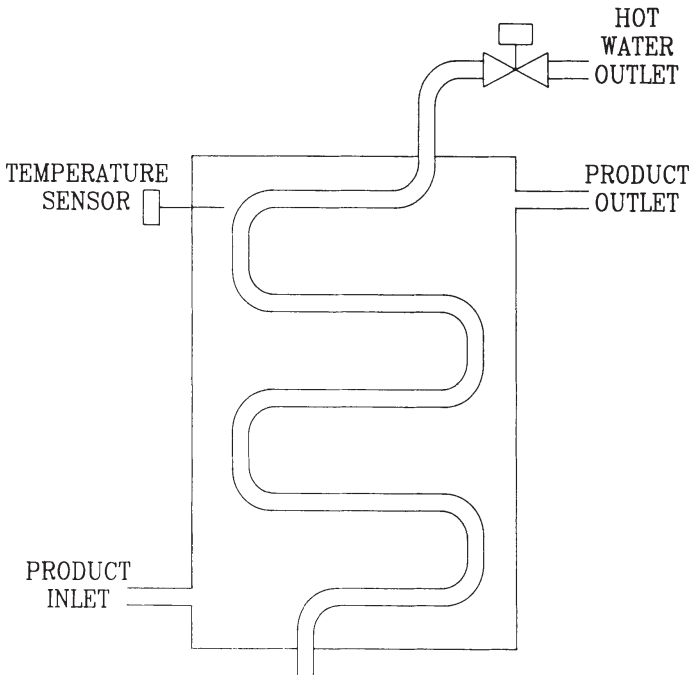


Figure 5.7 Water heating system

If we can make the opening of the control valve vary as the water temperature varies so that as the water becomes hotter it will close more, reducing the flow, and if colder, open more, to increase the flow, then better control of the temperature is possible.

The desired temperature of the water is called the set point or reference. The actual temperature, as seen by the temperature probe, is the measured value, and the opening of the valve is the output. For this example we assume that the valve opening is directly proportional to the control signal applied, so if the control signal range is 0–10 V, then at 0 V the valve is fully closed, at 10 V it is fully open and at 5 V it is 50% open. So, if we now extend Figure 5.7 to include the various parts of the system, it would look like Figure 5.8.

To decide how much to open the valve, we subtract the measured value from the reference to obtain the error; from the size of the error we decide on the

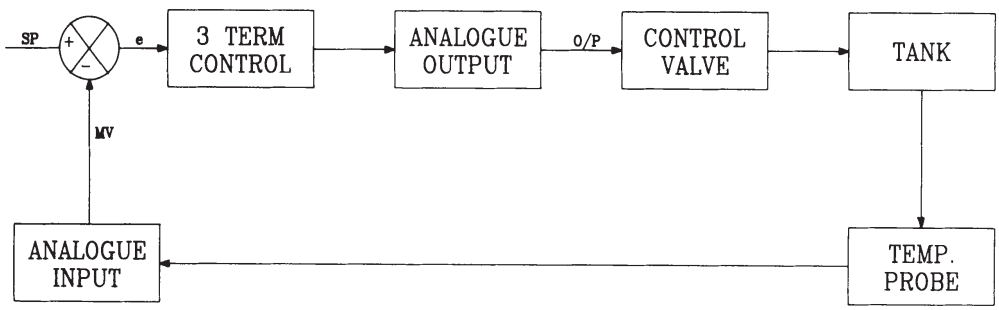
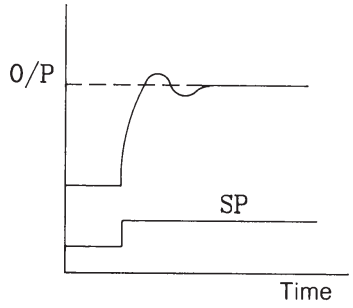


Figure 5.8 Control loop block diagram for water tank heating

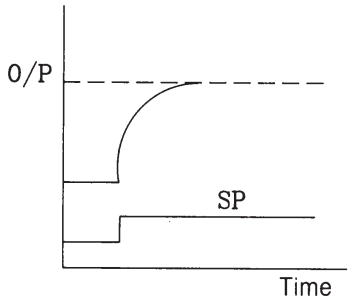
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opening required. The amount that the valve opens for a certain error is called the 'gain' or 'proportional band' of the controller, and is the 'P' term of 'PID'.

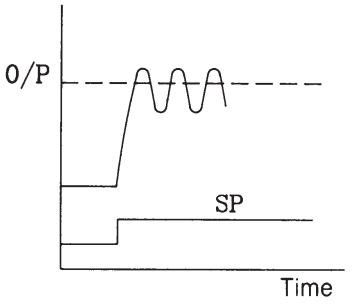
The larger the gain, the more sensitive is the control, but if the gain is too large, the valve will be continuously changing from large to small opening, rather than settle to a steady value. In this condition the system is said to be unstable. An error must be present to provide any signal at all to the valve, so with this arrangement the set point and measured value can never be equal. The difference between them is called the steady state error. The greater the required output the larger will be the error. The integral action of a PID controller causes the output to rise for a fixed error. The greater the error, the faster the O/P changes and also the larger the integral term the faster the change. So now, if we add some integral control to our proportional control, we can make a system which has no steady state error. The control is now called 'P&I' and for very many applications this is sufficient. The third term



(a) CRITICALLY DAMPED



(b) OVER DAMPED



(c) UNDER DAMPED

Figure 5.9 Step response of control system

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can be introduced to improve stability or dynamic response (the response to changes in the system). This derivative term, 'D', provides an output which varies as the rate of change of the error varies, so the faster the error changes, the larger is the output value.

By varying the proportions of the terms, the response of the process to change can be varied and the best possible result achieved. Figure 5.9 shows three different types of response to a step change of input. Figure 5.9(a) provides the fastest response, provided that the slight overshoot can be tolerated, if not then Figure 5.9(b) is used. Figure 5.9(c) is rarely used, as the system tends to be unstable and any slight change may cause it to become totally unstable.

Analysis of the control system can be undertaken mathematically using a variety of techniques, but these are complex and outside the scope of this book. A number of textbooks exist which deal with the formal aspects of control systems theory, and the reader should consult these if he or she requires more information.

5.5.2 *Algorithm-based three term control*

In applying PID control by computer the mathematical model is contained in the computer system and only simple analogue input and output modules are used. There may be a maximum number of loops that can be included in any one computer-based system, or the algorithm may be able to be called with different settings as many times as required, limited only by the maximum memory size of the system. The operation of this form of PID controller can normally be treated as a 'black box' as the routines are designed to operate effectively. However, as mentioned earlier the system is one which only samples data, and relies on the computer's own scan time to achieve a regular, uniform timing.

If this is not stable, then the algorithm will be implemented on inaccurate data, and the resulting control will also be inaccurate. At best this may result in ineffective control; at worst the control loop may become totally unstable.

5.5.3 *Auto tuning*

If the P, I and D settings are fixed then they will only be correct for one set of conditions and if the conditions change then the perfomance of the controller will change. Consider the above example shown in Figure 5.7 again. If the controller has been tuned when the heating water was at a certain temperature and that temperature is reduced by 25%, then in order to provide the same amount of heat the flow may need to be increased by 33%. So for a given temperature error the valve would need to be open a greater amount, that is, the proportional gain would need to increase and the other terms would also need to change.

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If the range of change is small, then it is possible to find a compromise setting that provides an acceptable response over the range, but where the range is large, a fixed setting would not provide very good control at any point on the operating curve.

To overcome the problem, systems are now available which adjust the P, I and D terms to provide the best control at the particular operating point. This is called auto tuning. A crude but simple form for auto tuning has a number of settings which are selected depending upon the operating point, but more sophisticated systems have continuously variable settings which are adjusted for the best response. Two methods are used, one assesses the performance each time a change of output occurs, and mathematically calculates the required PID values. The second applies a small step change itself at regular intervals and adjusts the parameters based upon the response to achieve the optimum performance.

5.6 Hardware configuration

The physical distribution of the control equipment depends upon the method of control required and the geography of the process. This section highlights some of the possible configurations to consider.

5.6.1 *Single system*

In this arrangement all the equipment is located in one suite of cubicles (see Figure 5.10). All the field devices and operator controls are cabled to the single set of equipment. Control for the whole process is effected by the one computer

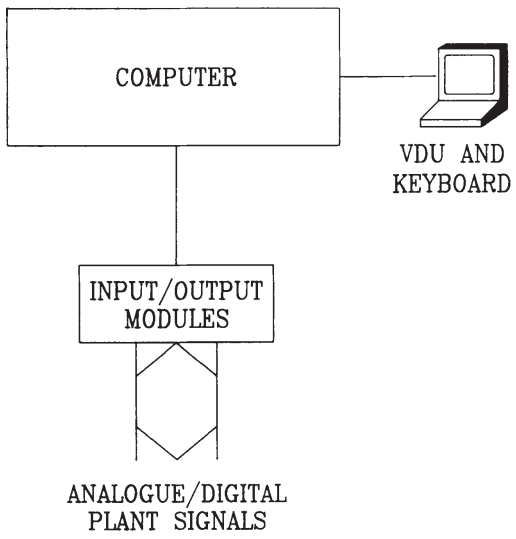


Figure 5.10 Single channel hardware

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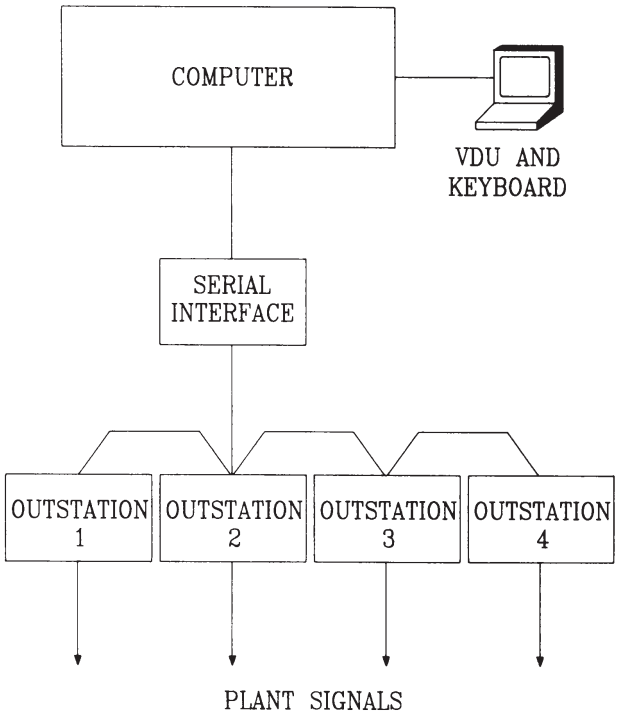


Figure 5.11 Single controller with remote I/O

system. This configuration is used where the number of inputs and outputs is fairly small or are all within a small area.

5.6.2 *Single controller with remote I/O*

In this arrangement one single controller effects control of the whole process, but the I/O is distributed around the process and connected to the controller via a serial link (see Figure 5.11). Each outstation may have as little as 16 I/O points or as many as 2000, depending on the process requirements. The number of outstations possible varies, depending on whether outstations are required to have small or large numbers of I/O at each one.

If the required number is small but the locations are many, then an I/O system like the GEM 80 GEMSMART* equipment can be used. With this system, each input/output module is self contained and obtains its power and communication from the same single pair cable. Where larger numbers of I/O are required at each location, then remote I/O interfaces are used which are able to house the same range of modules as are mounted locally, making the stocking of spares simpler.

5.6.3 *Hierarchical system*

In this configuration the control of the process is distributed in a number of controllers with a central supervisory system overseeing them (see

*GEM 80 GEMSMART is a product of GEC Industrial Controls.

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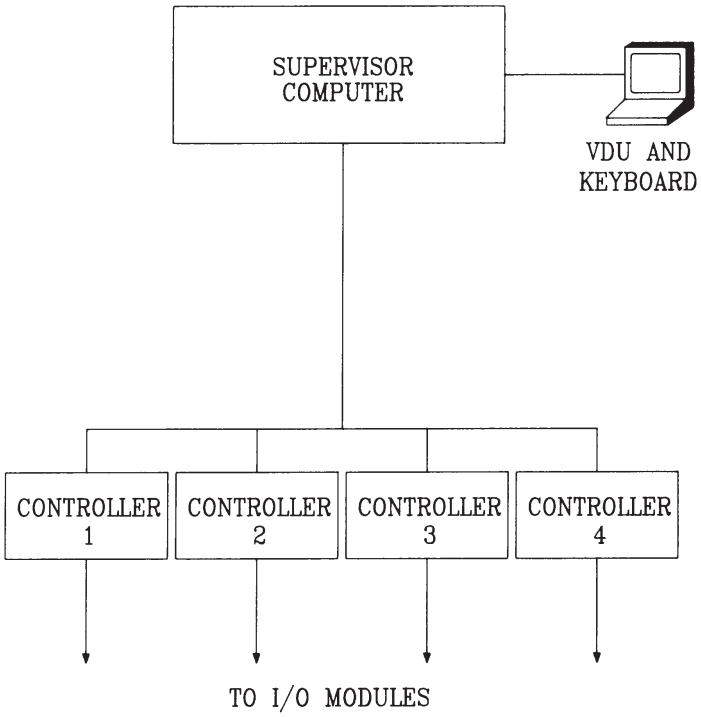


Figure 5.12 Hierarchical control

Figure 5.12). The supervisory system may be called a cell controller or area controller and is able to send and receive information from each of the outstation controllers. In some processes control may be exercised directly by the cell controller, through the outstation controller, with the same graphics displays and control keyboards being available at both locations.

In other processes local operators control the process being undertaken by each outstation, but with the cell controller being used for gathering data and giving management and maintenance information, directing assistance quickly to where it is needed in the event of problems occurring.

The supervisory system or cell controller may be a similar type of machine to that of the outstation controllers. Programmable controllers may be used for both functions, or the machines may be different with possibly programmable controllers performing the outstation control and a personal computer-based system acting as the cell controller. Many such units are available with the necessary software included, which can communicate to the major supplier's programmable controllers. Again, where larger supervising systems are needed, large computers may be used such as DEC Microvax 2* or similar. The data transfer uses some type of local area network, either the proprietary one of the particular manufacturer or one of the standards based on either Ethernet or MAP and using some or all of the ISO seven layer communications model.

*DEC Microvax is a registered trade mark of the Digital Equipment Corporation.

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5.6.4 *Intelligent field sensors*

A special case of the hierarchical structure which is growing in importance uses intelligent field sensors connected to a central data gatherer by means of a serial link, employing a particular communications protocol. The advantage claimed for this type of system is that sensors of different manufacturers may be used for obtaining the process information and, provided that they conform to the protocol, they will communicate on the network satisfactorily. Unfortunately, at the present time, different communications networks are available which are not compatible with each other, so that sensors are not interchangeable between the two systems.

5.7 Secure system configurations

The control activities described in this chapter to date have not taken account of failures within the computer system.

Although electronic hardware is very reliable, usually much more than the plant sensors and actuators, a failure can render the total system inoperative. This is not usually so with stand-alone controllers, because only one parameter is being controlled so failure does not usually render the whole system inoperative but for all of the other types of system this can happen.

Where very high availability of the plant is required, or where failure of the control can lead to dangerous situations, then consideration must be given to duplication of some or all of the control system to provide a 'secure system'.

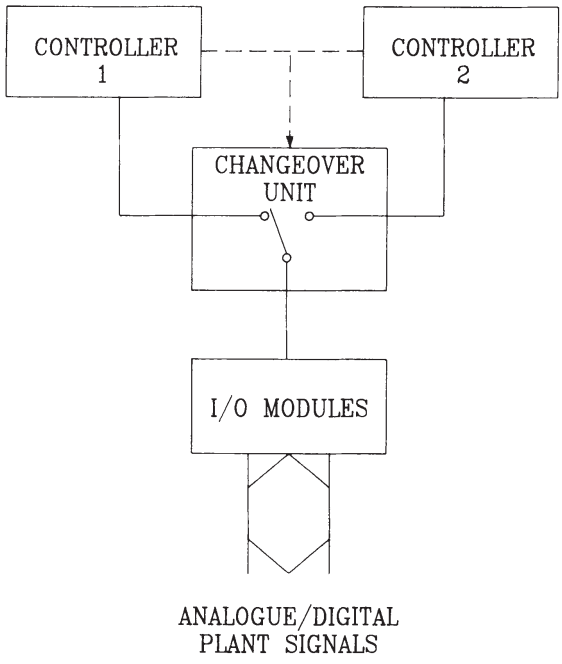


Figure 5.13 Dual processor single I/O system

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5.7.1 *Dual processor single I/O*

In this configuration only one set of I/O is used, but the processor system is duplicated (see Figure 5.13). This configuration is useful where the quantity of the inputs or outputs which are critical is small. Two separate inputs can be used for each of the critical plant sensors with two outputs provided for plant actuators. The disadvantage of this configuration is that the changeover unit which transfers the control of the outputs from one controller to the other becomes a common cause failure (CCF) point, that is its failure may cause a complete system failure.

5.7.2 *Dual channel*

In a dual channel system both the I/O and the processor system are duplicated, so that failure of any one part cannot render the system inoperative (see Figure 5.14). In a dual channel configuration two modes of operation are possible.

- One-out-of-two (1002) operation gives control action if either controller decides that action is required. This configuration is not usually employed in normal control situations, as it may give rise to spurious stoppages. It is used in situations with a very high hazard, for example, as part of an emergency shutdown system for an off-shore oil rig.
- Two-out-of-two (2002) operation means that control action is initiated only when both channels agree that action is required.

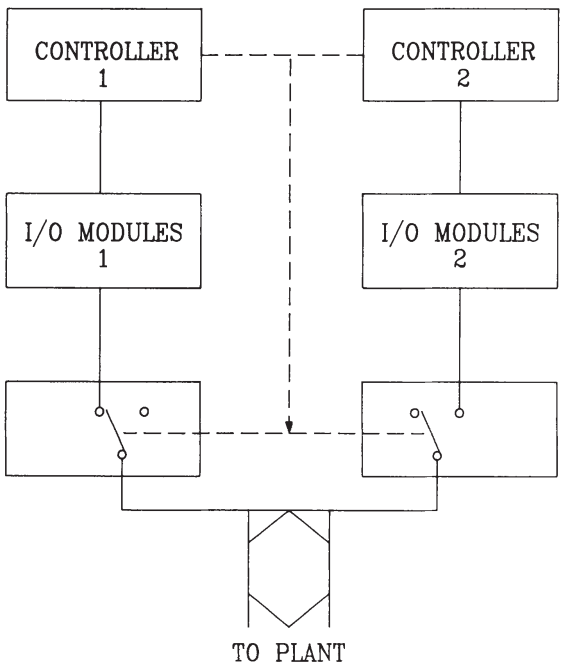
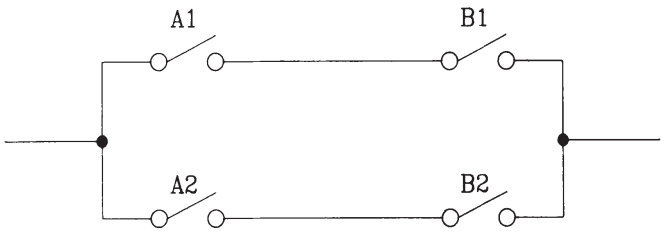
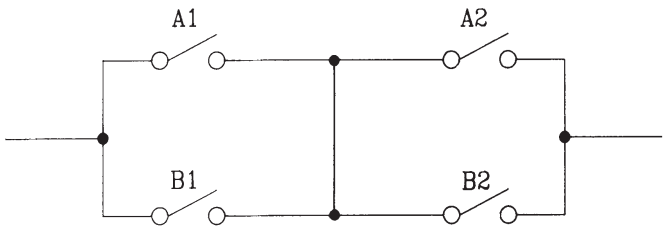


Figure 5.14 Dual processor dual I/O system

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(A) (A1 AND B1) OR (A2 AND B2)



(B) (A1 OR B1) AND (A2 OR B2)

Figure 5.15 Output configurations—dual channel system

Two outputs are necessary from each channel to ensure correct action takes place. The method of interconnecting the outputs varies depending on the required guaranteed action, the two options normally employed being either:

(A1 *and* B1) or (A2 *and* B2)
or (A1 *or* B1) and (A2 *or* B2)

This is expressed in electrical terms in Figure 5.15.

5.7.3 *Triple (or more) channels*

In areas of extreme hazard where failure may cause serious loss of life, then three or possibly more channels are used to provide the very highest level of safety. These levels are typically used in 'fly by wire' aircraft systems but are unlikely to be found in food processing, so are not considered in detail here.

5.7.4 *Single channel with non-computer back-up*

This configuration is used where there are safety considerations, for example to ensure that a safety gate is closed before a mixer or cutter can start. In most food processing situations the actual number of interlocks necessary for these safety interlocks will be small and so can easily be achieved by means of hard wired interlocks where the safety devices operate directly into the power circuits. All such devices are fed to the computer system so that it too can take appropriate action as a back-up and provide information as to what has stopped the process.

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5.7.5 *Safety considerations*

With any process it is necessary to consider all possible situations which could be hazardous to people either directly involved in the process, or who may be injured as a result of a failure within the process. It does not matter whether the process is controlled by a computer-based system or by some other control system: it is a requirement under the Health and Safety at Work Act that the work place is safe for all people who may have cause to be there.

When the control system includes a computer-based unit, the various types of failure that can occur in the computer need to be considered. Any single point controllers which are microprocessor based must also be included in the consideration.

In any computer-based system there are two types of failure:

- Random failure.
- Systematic failure.

Random failure occurs in the hardware only, and component manufacturers provide guide figures for the failure rate of their devices. From this data the equipment manufacturer can calculate the theoretical failure rate for the complete equipment. Alternatively, where the equipment supplier has a recognised quality control system approved to BS5750 or AQAP-1, then it is possible to produce field based data which will normally show a significant improvement over the calculated figures.

Failure data are usually expressed as failures per million hours of operation and typical figures and equations are given in the HSE Guidelines PES1 and PES2*.

Systematic failure can occur in either the hardware or software of a computer system. Hardware failure can occur due to bad design resulting in, for example, components overheating or being susceptible to external electromagnetic interference such as may be generated by a variable speed motor drive. Software failures may occur due to faulty programming or inadequate or misleading specifications.

Random hardware failures can be overcome by providing some alternative means of control such as a duplicate channel, using the same model of controllers first, but no amount of similar hardware will overcome a systematic failure, which will affect all the equipment in exactly the same way. In systems which require duplication for safety purposes consideration must be given to the use of diverse hardware and software. Different models of controller can be used for different processes and firmware and the application software can be written by two different teams of engineers working separately from the same specification.

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* Programmable Electronic System in Safety Related Applications is published by The Health and Safety Executive.

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5.7.6 *Reboot and auto synchronising*

Whenever two or more channels of hardware are used, special consideration has to be given to returning a channel to service following its failure and repair.

Consider a dual-channel system operating a cooking process which may take many hours to complete, but which requires a varying temperature time profile and various additions of ingredients throughout the cycle.

If one of the channels has failed and has to be repaired, when it is brought back into service part of its start-up cycle must be to obtain all the necessary information from the running machine to say what step in the process cycle has been reached and the time into the step. This is usually known as the 'reboot' and must be achieved before the incoming controller can be considered to be available on line. When the machines are then operating together cross checks are made between them to ensure that they are still in step especially where operator keyboard inputs are used. This action is often referred to as auto synchronising with the reboot and auto synchronising programme progressing continuously as a background activity in the controllers, so that whenever changeover occurs the controllers are at the same stage in the process.

5.8 Operator interfaces and maintenance aids

Operator interfaces are considered in more detail in a later chapter but are mentioned here as an integral part of the computer control system.

5.8.1 *Operator interfaces*

These range from very simple devices such as pushbutton through to full operator workstations. The overriding principle must be that the controls should be as simple and as unambiguous as possible.

The type of controls will be governed by the actions required of the operator. If the process is fully automatic but requires a selection from a limited number of options then a number of dedicated pushbuttons, one for each variant, may be sufficient. The operator would select the required variant and a light would be illuminated, either in the pushbutton itself, or close to it to indicate the selection was accepted. The operator would then operate the start button and a run-lamp would flash. When the start sequence is complete, the lamp then becomes steady, indicating the process selected is running. A stop pushbutton would shut down the process and all lights are extinguished when the shutdown sequence is complete.

In this system the operator has no control over any of the process parameters to make any slight adjustments. The controls can be extended by the inclusion of thumbwheel switches and either liquid crystal displays (LCD) or light emitting diode displays (LED) whereby the operator can select a parameter and value using, say, a six decade thumbwheel and check what

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values are set by the LED. A pushbutton enters new values when the operator is satisfied with the setting.

Using such a six decade thumbwheel the first two wheels can be used to select a parameter and the next four to set the value. In this way up to ninety-nine parameters can be set with any four-digit number. This type of control could be used where a blending process has to cater for different raw material conditions, for example, moisture or sugar content of raw cane sugar in a refinery.

Simple controls like this are satisfactory providing no faults occur but when the process stops or the start sequence fails there is no indication as to the cause of the failure. This deficiency has, in the past, been overcome using large numbers of alarms facias to give an indication of the faults. However, today much clearer information is available using an alpha numeric display. Such a unit has a number of lines of characters, usually between one and six, and around forty characters per line. The text messages can be displayed in much the same way as the advertising message displays used in shops and airport check-in desks.

The displays can either be programmed to store the messages and display a particular one when its number is received by the unit or it will display a complete message sent to it by the host controller. The same serial message format is used as for printers, known as ASCII (American Standard Code for Information Interchange). In ASCII code each letter, number and control character has a fixed number value so that if the bit pattern corresponding to the number is transmitted, then the particular character is displayed.

It is possible to include real data in the messages so that essential parameters can also be displayed. However, the number of lines available for the display is limited so that where more lines are needed some other device must be used. The next stage up is to use a monochrome VDU.

Text messages along with information on the required screen position are sent from the host controller to the unit and are displayed on the screen at the specified position. By this means a complete screen of information can be displayed and the dynamic parts of it updated rather than continuously updating the whole screen. This allows for recipe and menu type displays to be shown which the operator can then modify within certain prescribed limits.

At this level of display sophistication it is necessary to provide a more versatile operator input facility by means of a keyboard. Two versions may be used, one dedicated to the process using high level commands such as single keys for OPEN, CLOSE, RAISE and LOWER, or the conventional typewriter layout keyboard where single letter commands or command words are used to give the process commands.

A further level of information can be provided by the use of full colour graphics systems. In addition to text type information process mimics showing the complete dynamic state of the plant can be displayed. Positions of valves, levels in tanks, temperatures, pressures and flows etc. can be included. Any alarms present can be shown and historical information such as trends are of

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great benefit in identifying slowly failing plant. Hard copy records of all the plant status and alarms can be provided by printers but here care is needed as to what items are provided to avoid generating great volumes of paper which no one has the time or inclination to read.

5.8.2 *Maintenance data*

Much of the display information described in the previous section can also provide the maintenance department with useful information. A printer, housed in the maintenance areas, giving messages of failed devices, can instruct the maintenance engineer to go to the correct area of the plant with the required spare part ready rather than have to identify by inspection what has caused the stoppage then return for a replacement part.

A VDU terminal allows maintenance to view trends of such items as motor current or vibration which can give early indication of bearing failure allowing planned maintenance rather than breakdown replacement. The computer can be used to provide a log of operating hours which again can be shown on the maintenance screen and allow appropriate preventive maintenance. All of these display systems are, however, only possible because the computer control system is able to collect and process the relevant data. They are not usually intelligent devices themselves.

5.9 Summary

Computers find many uses in industrial situations but different applications require different attributes to be employed.

The basic hardware used for the central processing unit (CPU) is likely to be the same across very many applications but the peripheral devices will be arranged to suit the particular application. In the office environment, or for data collection, the emphasis is on the man/machine interface, archive and storage devices so VDUs, printers and disc units will be much in evidence.

In sequencing and control situations where a programmable controller or DCS type of computer is used then the emphasis is on the interface to the plant. Large numbers of digital and analogue input and output devices occupy considerably more space than the CPU system, but they are essential for the reliable working of the system.

The DCS systems tend to have both plant I/O and operator VDUs and printers since the processes they control are usually both large and complex.

The use of computer control in process applications leads to very many benefits associated with better, more consistent control and the provision of reliable data on which decisions can be made for changes to the process. Diagnostics of faults and statistics of mechanical activities allow for better planned maintenance.

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6 Operator interfaces

HÅKAN MORÄN

6.1 Introduction

Control of any process, automated or not, involves obtaining information, making decisions about actions to be performed and issuing commands to implement decisions so that actions are in fact carried out. The equipment used to obtain information and perform actions is known as the process control system. The equipment used to present information and issue commands is known as the operator interface system, or operator system. An example of a simple, non-automated operator system is shown in Figure 6.1.

It is obvious that making and implementing decisions is vital for the outcome of the process, and it is equally obvious that the way information is presented and perceived is vital for decision-making. The relationship between the operator, the control system and the process in an automated food plant is shown in Figure 6.2.

As in other sectors, automation in the food industry generally involves a shift from personnel-intensive production based on relatively small units to large, centralised production systems that are supervised and controlled by a few operators. This means that each individual operator has greater responsibility, so that the performance of the operator system becomes more important than ever.

Operator systems may be installed at three different levels in a food processing plant. Level 1 is devoted to control of individual components or machines. Level 2 is devoted to centralised control of complete production

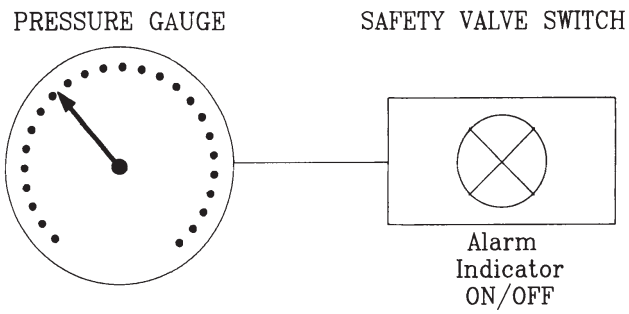


Figure 6.1 Simple operator interface

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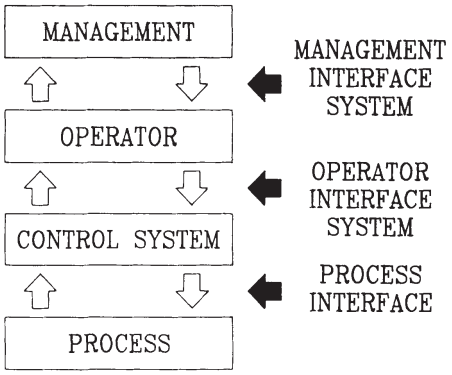


Figure 6.2 The operator in relation to other activities

units and/or sub-units such as CIP systems or tank farms. Level 3 provides an interface for management for overall supervision and coordination of production. The reader may be surprised to learn that managers are also operators!

Historically, automation came to the food industry at level 1. Early operator systems consisted of lamps, pushbuttons and simple instrumentation, usually located at strategic positions in the production area. These systems gave the operator a limited and rigid picture of what was going on, and he or she was expected to supplement it by using their senses.

As process control systems became more powerful, operator systems became more centralised, and with the advent of cheaper micro- and mini-computer systems in the 1970s and 1980s operator systems on levels 2 and 3 were introduced.

The equipment available today includes mimic diagrams etched on metal or matrix panels fitted with lights and buzzers. The operator issues commands from a console fitted with buttons or a keyboard, or both. Operator systems also include VDUs (visual display units), both monochrome and colour, and there is a clear trend to powerful graphic displays that feature flow charts as well as pictures of individual components.

There is a good reason for this trend. In a modern automated food plant, one of the key problems to be solved by an operator system is the need for both an overview and detailed information about specific parts of the process. This means that the system must have a capability for shifting quickly between different types of presentations when required. The system should also enable the presentation of information to be structured so that the operator has the optimal quantity of information in front of him, i.e. no more than what he needs to know.

In this connection it should be noted that the choice of equipment for display of information and entry of commands should be based on an analysis of what the operator actually has to do and not on theoretical calculations of what technology has to offer.

An operator system must nevertheless satisfy a number of basic criteria.

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First of all, it should be easy to use. It should enable the operator to concentrate on the process. It should provide access to information at various levels and in varying degrees of detail. It should show alarms in a clearly understandable manner. It should be capable of modification at acceptable expense as changes are made in the production system.

Acquisition of an operator system that will enable a maximum return on investment in an automation system requires active participation by the buyer. Plant personnel from managers to operators must be consulted at an early stage, as they must be in close contact with the supplier when the operator system is configured. This applies especially to modern colour-graphic systems, in which pictures and diagrams can be economically tailored to meet precisely defined user requirements.

6.2 Operator functions

In an automated plant, the operator is the link between management and the production process. It is now widely accepted that as the number of operators is reduced through automation, the individual operator's production expertise takes on crucial importance. The operator system must provide the operator with support for decision-making and action, instead of locking him into a rigid pattern of response. The three levels of operators are:

- production manager;
- process operator, normally in a central control room;
- machine operator, e.g. a packaging machine.

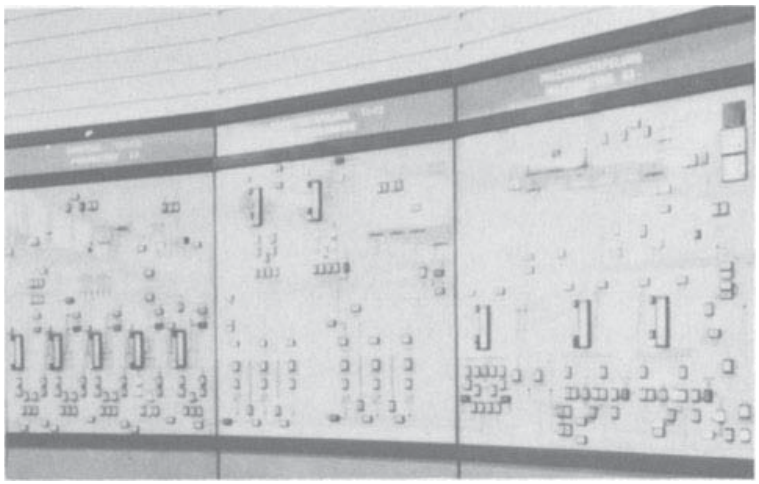


Figure 6.3 Process overview by mimic diagram

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Figure 6.4 Overview of control room

Irrespective of the level, a number of functions can be defined:

- supervision/alarm handling;
- process overview;
- production control;
- maintenance.

This section comprises a description of the ways in which an operator system can support these functions. Figures 6.3 and 6.4 show examples of operator control facilities.

6.2.1 *Supervision and alarm handling*

Alarms have traditionally been indicated by various arrangements of lamps and buzzers. For simpler processes, there is often no need for more sophisticated methods. It is worth keeping these methods in mind when considering state-of-the-art solutions, as they are still very effective and simple. Printers are used to provide detailed descriptions of alarms and to log them for future reference and analysis. In modern colour-graphic systems, alarms can be given on a VDU in virtually any shape and colour, e.g. a fault in a pump can be shown on the screen as a blinking red triangle. A major

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advantage of these systems is that the software enables the user to modify the presentation, e.g. the blinking red triangle could be replaced by a solid orange triangle or another geometric figure if that were considered appropriate. Advanced colour graphics also enable zooming the screen display to any detail in a process.

In conventional operator systems, there is no facility for logging alarms except by printing them out as they occur. The problem is that someone must see to it that there is paper in the printer, properly inserted, and that the printer is actually on-line. Systems are now available with built-in data bases, so that alarms can be given on a screen, described on-screen and/or in a printout and simultaneously stored for subsequent retrieval and analysis. A manager can thus at any time request a printout of all alarms for a given piece of equipment on a specific date or dates.

6.2.2 *Process overview*

The two principal means of showing a process overview are mimic presentations or colour-graphic displays on VDUs, as shown below in Figures 6.5 and 6.6. It is sometimes possible to combine these two methods, depending on the

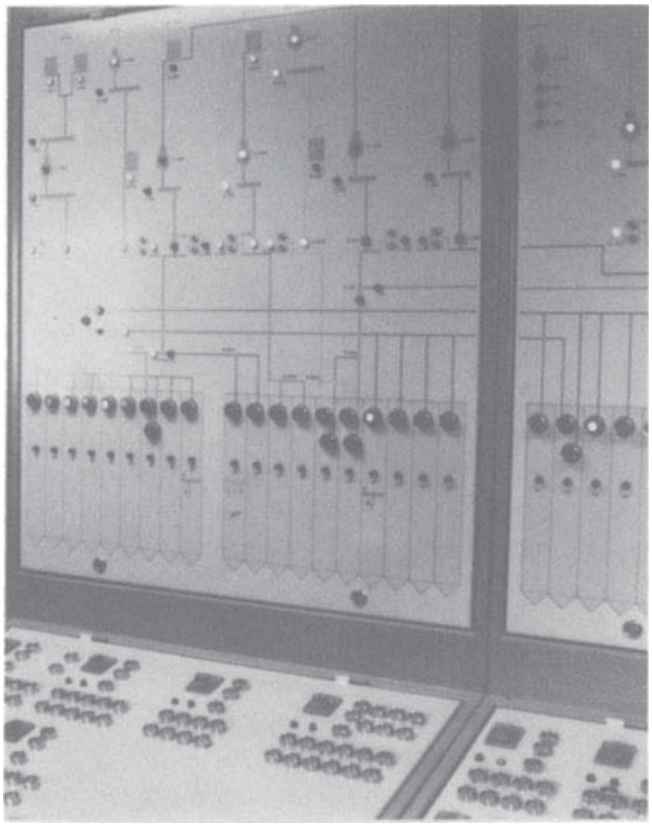


Figure 6.5 Typical mimic diagram installation

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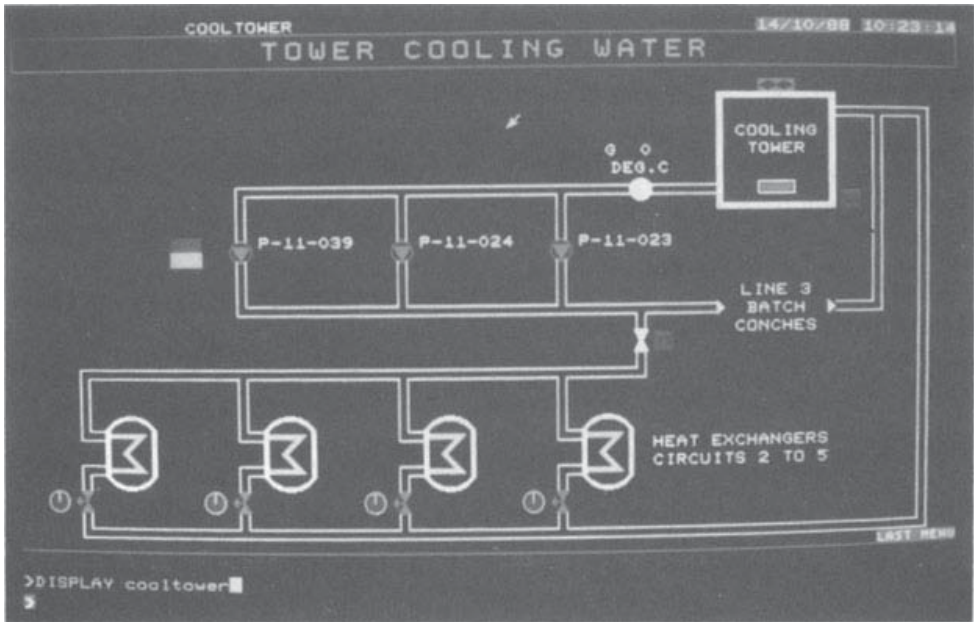


Figure 6.6 Process overview by mimic diagram

size and configuration of the production system. Mimic systems can be appropriate for small sub-processes, while colour-graphic systems are more suitable for complex large-scale processes.

The main advantages of a mimic presentation such as a wall-mounted diagram can be described as follows. A mimic provides information at a glance. It gives an experienced operator split vision, as he or she can see different parts of the process at the same time. The mimic can also be used by more than one operator at a time, and details can be inspected by simply moving from one point in the room to another. New operators can learn to use a mimic diagram in a relatively short time.

A mimic presentation is static, however. It cannot show dynamic information such as trend curves. There is a limit to the degree of complexity that can be represented, as a complicated diagram is not easy to understand. This is a restraint on the amount of information that can be stored in a mimic presentation.

Another disadvantage is that a mimic presentation is expensive to produce. If changes are made in the configuration of the production line it is normally very expensive to make changes in the mimic and in fact may not be physically possible. A mimic presentation also takes up a good deal of space. Once it is in position, it cannot be moved to another location in the plant.

VDU-based colour-graphic systems have the advantage of combining a process overview in the form of a diagram with access to detailed information on a virtually infinite scale. All and any information relative to the process can be stored in the system in a 'suppressed' form until it is needed, when the operator can call it on to the screen. Information can be supplied dynamically

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in the form of trend curves, bar graphs, etc. The ability to select information at will enables the operator to keep up to date with the process. Some systems have zoom and window features that give the operator accelerated and easy access to details. Colour-graphic systems are cost-effective, as the amount of information they provide is very high in relation to the cost of the system. Presentations can be easily and economically changed to meet the needs of the operator.

A recent development is the 'object-oriented' graphic system, in which any information can be tied to graphic symbols that can represent any component or unit. Presentations can be tailored by manipulating the symbols without additional time-consuming programming or re-entry of master data. Once information such as flow-rate has been tied to a symbol representing a pipe, it will accompany the pipe automatically as the drawing symbol is used in various pictures, at any level and for any purpose. All the symbols are stored in a library and can be used as building blocks for presentations on screen. These presentations can easily be changed to match changes in the production line, which means that in contrast to a mimic presentation an object-oriented system does not become obsolete. The speed with which presentation can be modified is illustrated by the SattGraph system, in which, for example, a new tank can be added to a process diagram in about 10 minutes, while installing the actual tank in the production system can take up to 6 weeks.

A disadvantage of colour-graphic systems is that a VDU cannot easily be used by more than one operator at a time. Although overviews and details can be stored in the system, it cannot show them simultaneously unless windowing techniques are available. Operators of object-oriented systems require thorough training, so that it takes more time for new personnel to learn how to use the system. On the other hand, training time is not very great if it is measured in relation to the power and functions of the system. The operator of an object-oriented system has more knowledge of the process and more responsibility—and has a much more powerful tool for process control.

6.2.3 *Production control*

Production control can involve production planning and administration of production orders at the managerial level, or process control from a control room.

It is now a commonplace that administrative systems should be based on VDUs, which provide managers with fast, easily comprehensible information. However, it is not always recognised that the system available to the production manager should be integrated with the operator system used for process control.

Integration enables decisions made in production planning to be transmitted automatically to the system for process control, perhaps as production orders or instructions for recipe handling. The system also records actions

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taken at the process control level and reports outcomes automatically to production planning. These reports can be transmitted on-line and can also be stored for subsequent retrieval. An integrated system thus becomes a tool for implementation of managerial decisions and ensures interaction between planning and process control.

In this connection it should be mentioned that integration between the operator systems for process control and control of individual machines is a prerequisite for effective automation of a food-processing plant. Operator systems for production planning and administration are often menu-driven and based on VDUs with monochrome screens.

6.2.4 *Maintenance*

At any level, object-oriented colour-graphic systems deliver major benefits for both planned and unscheduled maintenance. The fact that information can be tied to objects makes these systems extremely flexible, as data for planned maintenance can be built into an object such as a pump. The operator can simply call up the pump on the screen and request information on maintenance, and can also enter information relating to unscheduled maintenance. If the system includes a database, searches can be requested on the basis of various parameters. For example, an operator can request information as to which pumps are scheduled for maintenance on a specific date and compare it with production orders for the same date.

These systems can also provide valuable data for investment decisions. In an installation at a large fruit-juice producer, the system accumulates error reports for specific machines. These reports are transmitted by the operator system to a central computer where they are analysed and correlated with output statistics.

6.2.5 *Which system?*

In the final analysis, all the equipment and systems in a food-processing plant exist to serve a market. The nature of the market determines the design of the production system and the systems used for supervision, control and maintenance.

There seems to be general agreement that current trends will continue in the retail food market of the 1990s. The number of products on retail shelves is growing. Product lifetimes are shorter, and product launches more frequent. Quality—in every sense of the word—has become a vital component for marketing success. Improving the utilisation of capital has become more important than ever, and the concept of just-in-time deliveries is being applied throughout the food industry.

This scenario accentuates the need for precise, reliable control systems with maximum flexibility. For local supervision and control, a modern local panel

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with integrated PLC functions is superior to the conventional mimic presentation.

For centralised control, object-oriented colour-graphic operator systems provide a plant manager with the best means of extracting the greatest benefit from his production system. Fortunately, these colour-graphic systems are becoming steadily more attractive in terms of the price/performance ratio.

6.3 Serving the person behind the machine

6.3.1 *Ergonomics*

Just as the performance of an operator system is decisive for obtaining maximum benefits from automation, the ergonomics of the system depends on the ability and in many cases the willingness of the operator to use it. Not least because the introduction of an automated system often entails a major change in the operator's working environment.

Ergonomics involves much more than designing attractive keyboards and comfortable armchairs. The goal of ergonomics is to optimise the function of a system by adapting it to the natural needs and capabilities of human beings. It is of interest to note that personnel tend to take much better care of systems which are professionally packaged. Ergonomics is particularly important for VDU-based systems, as the information and pictures on the screen must be immediately comprehensible.

Although there are suppliers who deliver operator systems with screen displays that are more or less standard, the most effective systems are developed from discussions between the supplier and the plant personnel who will be using the system. These discussions should be based on concrete proposals from the supplier. Active participation by plant personnel ensures a long service life for the system and helps eliminate possible resistance to automation. In this connection, it is important for the supplier to have developed practical guidelines for the prospective user with regard to ergonomics and picture structure.

Bottom-up, top-down and look-ahead operator systems in particular and automation systems in general are frequently set up by specialists who have expertise in sub-processes but do not have an overall grasp of the entire installation. The total solution is formed by combining a number of solutions for sub-processes. This is known as the bottom-up principle. The advantage of the bottom-up method is that it generates an optimal solution for each sub-process but often does not provide a clear overview.

Application of the top-down principle involves starting from a general view and determining what is needed to detect errors and initiate action at each successive level of operations. Applying the top-down method enables equipment to be limited to that which is absolutely necessary from the operator's point of view.

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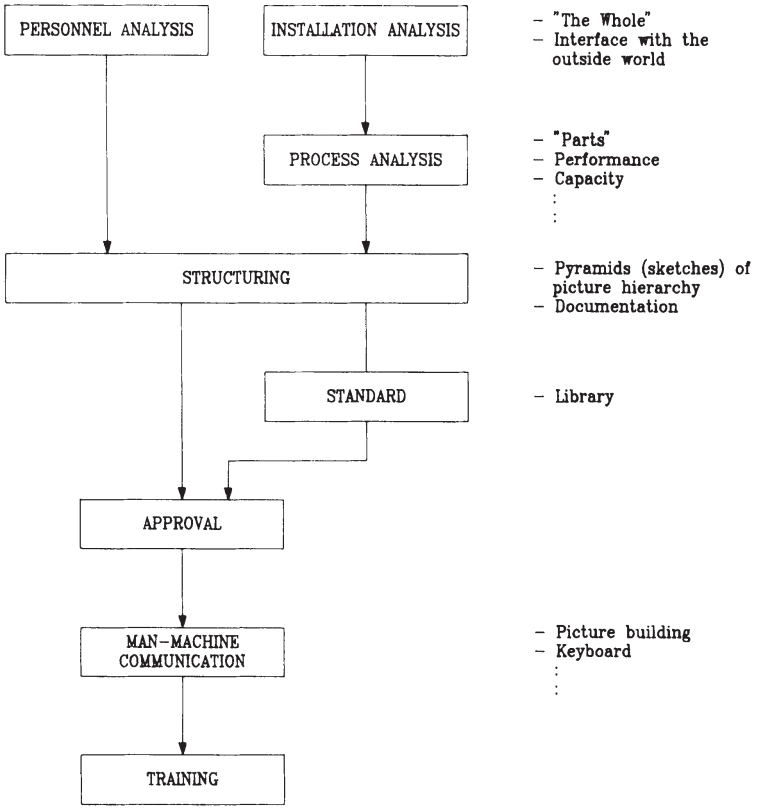


Figure 6.7 Planning operator interfaces by the top-down process

The look-ahead principle can be applied together with the top-down. Look-ahead involves analysis down to the smallest level of detail as a regular element in the design process. A supplier who combines top-down with look-ahead generates an operator system that combines a meaningful overview with access to the details of every sub-process. A schematic illustration of the top-down process is shown in Figure 6.7.

6.3.2 *Picture hierarchy*

The pictures in a VDU-based operator system should be organised in a hierarchy, or tree. The tree structure should reflect the actual structure of the production process, and be designed to reflect the levels of information required by the operator. A typical definition of information levels is shown in Table 6.1 and illustrated in Figure 6.8.

6.3.3 *The need to know and the need for speed*

Each picture on the screen should contain only the amount of information that is absolutely necessary at a given level. A flexible object-oriented operator system makes it easier to design pictures that show the operator exactly what he or she needs to know—and no more. Each picture can be composed from a

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Table 6.1 Definition of information level

Level	Types of information
System	Process Alarm list Terminal emulator Composite pictures (not tied to linear production process) Presentation of process function
Function	Key values in process (e.g. pressure, temperature) Function alarm Controls for process status
Object	Presentation of objects (e.g. pumps, valves) Alarms for each object How each object is controlled
Signal	Presentation of circuit signals (e.g. limiters, controllers, trend curves)

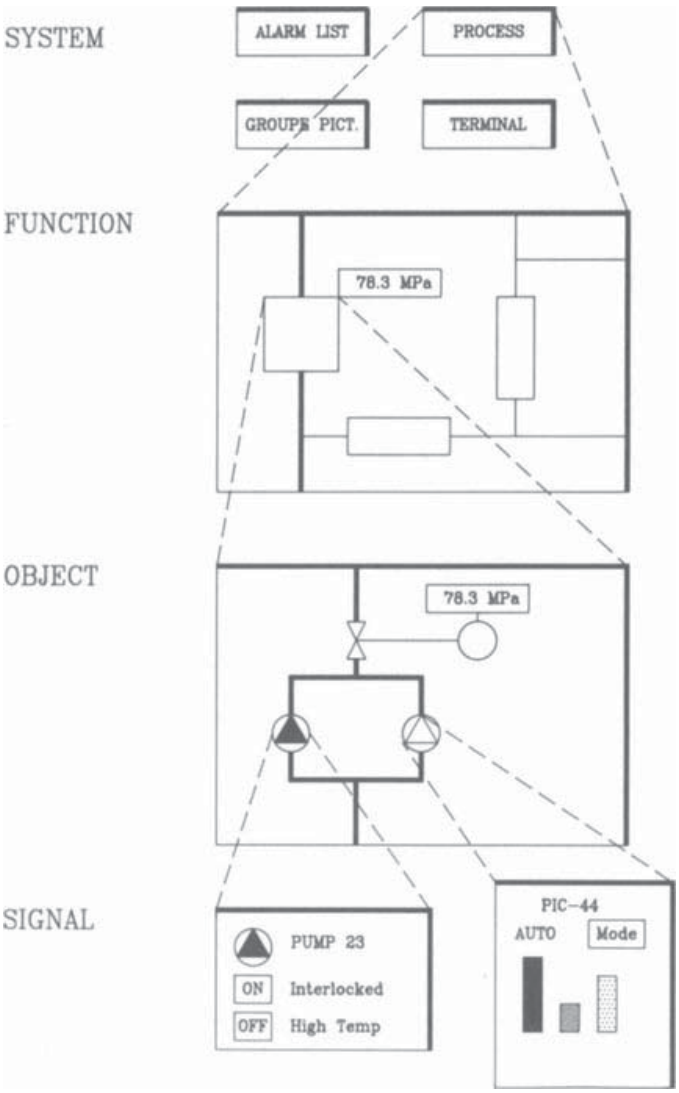


Figure 6.8 Hierarchy of picture information

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library of standard graphic building blocks, which includes geometric elements as well as conventional symbols for valves, pumps, etc. These can be scaled, coloured and manipulated at will to build a picture which can quickly and easily be modified to respond to changes in production and/or to operator needs.

A vital aspect of picture building refers to the speed with which the operator can switch pictures. Experience shows that 3 seconds is the maximum permissible time for replacing a picture, as longer intervals are normally interpreted by operators as too slow. In many systems, the need for speed is a constraint on the amount of information which can be shown, as changing to a detailed picture can take time.

Some operator systems employ zooming and windowing techniques to solve this problem. Detailed information is hidden or suppressed in the system in such a way that the operator does not have to switch entire screen pictures. Instead, he positions the cursor on the part of the picture for which he wants greater detail and then zooms in using a mouse or a keyboard button, which gives much the same impression as a dynamic closeup with a film camera. Alternatively, he defines a window on the screen and then calls up the required information into the window, while the rest of the picture on the screen remains in place.

6.3.4 *How much information?*

If the quantity of information shown in a specific screen area exceeds a certain limit, the performance of the operator will be affected. On the other hand, experienced operators normally want as much information on the screen as possible, in order to avoid changing pictures. Operators with less experience may find it difficult to use pictures containing a great deal of information, and may not be able to handle a production breakdown if there are many things happening on the screen at the same time. In real life, the operators in a plant have varying degrees of experience, which underlines the need for an operator system with windowing capabilities and enough flexibility to give an operator the option of determining the amount of information that is on the screen.

Another aspect of the quantity of information is related to the category of staff who are using the display. In centralised systems, one and the same terminal may be used by process operators, process engineers and service personnel. The structure of pictures should ensure that information for different staff categories is never mixed in one and the same picture. The reason is obvious—irrelevant information degrades operator performance.

6.3.5 *Alternatives to keyboards*

In general, control and input functions should be implemented if possible using only one type of input device. As in microcomputer systems, the choice is

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normally between a keyboard or mouse, trackball, light pen or touch screen. All of these alternatives allow an operator to 'point' at an area or symbol on the screen to activate some command. In the case of the touch screen options this pointing is literal.

This choice is not purely subjective. For certain types of graphic displays, a mouse is definitely easier and faster to use. However, if the operator has to input numbers or make selections from a large menu a keyboard is often more convenient. Mice run into problems at operator stations on the machine level, as the device requires a relatively large surface to roll about on, and the surface must be free of dust, oil and dirt in order to maintain life in the ball in the bottom of the mouse. It is therefore often necessary to accept a trade-off between mice and keyboards.

Many of the practical problems associated with mice can be solved by using a 'track ball' instead. This operates like an upside-down mouse with the operator turning the ball directly. The result is a static device which allows the operator to 'point' on the screen and which can be permanently mounted on the control desk. A light pen is used to touch the screen at the appropriate point to effect control. A sensor in the pen itself detects the light from the screen and this is decoded within the computer to identify which particular location was pinpointed.

In touch screen systems the operator actually touches the VDU screen to point at the information required. These have not won universal acclaim for a number of reasons. They tend to be expensive, and pointing is limited to a large area of the screen (perhaps 25 mm square). If used with pull down menus, windows and the like this is made more difficult. They also tend to be specific to particular manufacturer's systems and this specification again has limited their introduction. And of course you can end up with dirty fingerprints on the screen!

6.3.6 *Control-room design*

In centralised systems, the control room is where the process operator spends most of his or her time. The design of the control room has a direct effect on operator performance. Direct lighting from the ceiling or from spotlights should be avoided. Diffused lighting that is reflected from the ceiling gives enough light to prevent stress and eliminates reflections on VDU screens.

Dry air is unpleasant to work in and may also contribute to build-up of static electricity. Humidity should not be allowed to drop below 35%. Proper humidity can be ensured by installation of a humidifier. The cost of such a unit is usually very small in relation to the total investment in automation and generates a very large return.

Static electricity is a threat to all computer installations. Humidifiers are part of the solution to this problem. In addition, seat coverings and overalls should not be made of synthetic materials as far as possible. Shoes should be

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made of conducting materials. Plates or grips should be installed on which the operator can discharge static electricity before using the operator system.

6.4 The right system on the right level

In the ideal food-processing plant, a single pushbutton and two lamps, one green and one red, would be sufficient for supervision and control of the entire production process. In the real world, different types of equipment are needed for operator systems at different levels in the plant.

- The local operator interface is normally positioned at the process level for supervision and control of individual sub-processes, machines and sensors.
- The centralised operator interface is normally located in a control room and is devoted to a complete production unit or to smaller production units such as CIP processes or tank farms.
- The operator interface for management may be in a central control room or in an office, and is used for coordination of all production activities as well as for administration.

The main factor governing choice of equipment is still the traditional price-performance concept and will probably remain so for some years to come, until the price of hardware is low enough to justify a single type of standard terminal at all three levels.

6.4.1 *The local operator interface*

In most food-processing plants, there are more units for the local operator system than for either of the other two levels. It is therefore interesting to note how much more time, energy and money are usually devoted to selecting both hardware and software for the central control room. The design and layout of local operator interfaces are presumably not as glamorous, for some reason, but the fact is that a relatively small additional effort at the local level can generate significant increases in production quality and substantial reductions in downtime.

When it comes to calculating the cost of a local operator station, some suppliers are inclined to indicate the purchase cost per component exclusive of design and installation. It cannot be repeated too often that the cost of a local operator station is the cost fully installed and ready to run.

Another aspect that is sometimes overlooked is the fact that ensuring effective local operator performance requires a clear definition of the relevant functions of the process with which the operator will be dealing. The reader would be surprised to learn how often local operator stations include control functions for an unrelated section of the process in a distant part of the plant.

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The operator's need to know does not actually extend beyond machines or sub-processes that are directly related to his or her area of responsibility.

Four capabilities are required of a local operator interface:

- Information display.
- Action following operator input.
- Preprogrammed action.
- Communication with other units in the automation system.

At the local level, ease of use is more important than ever. The panel should give a clear and immediately comprehensible indication of process status. Keyboards are often superfluous at this level, and ease of use is very dependent on having pushbuttons and instruments that are large enough for maximum convenience.

A single lamp is often sufficient for an overview of the process, i.e. things are either going well or going wrong. For quick indication of process values, analogue instruments (dials) are usually the best, but demands for accuracy may require digital readouts as well. Simple text displays are also helpful in many cases, particularly in connection with events or situations that do not occur often in the normal course of production.

It is not easy to make a general statement about requirements to withstand difficult environments in terms of dust, grease and other substances but food factories demand hygienic solutions and in practice a *minimum* protection class of IP54 should be combined with smooth surfaces with few or no crevices to create dirt traps.

The concept of 'future-proof' should be one of the main criteria for selection of a local operator system. Almost all machines or processes are subject to modification in the course of their service lives. A hardware-oriented operator system may seem a bargain at the beginning, but the cost of rewiring, testing and adjusting every time the machine or process is modified will sooner or later become apparent. The best way to avoid these headaches is to ensure that the operator system is software-driven, so that changes can be made quickly and easily.

The four basic types of control interfaces are:

- Conventional panels.
- Message displays.
- Modular control panels.
- Intelligent control panels.

The conventional panels with lamps and pushbuttons, as mentioned previously, need no further discussion, except perhaps to point out that as the need for information grows the basic inflexibility of the panel becomes apparent; larger panels are also relatively expensive.

Message displays have become increasingly popular in recent years because information can be provided in plain English. These displays are usually

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combined with conventional panels. Many of them require computers or PLCs for control of output via serial connections. Some can be run with digital signals from relays. The main advantage of message displays is that there is almost always a display available in the right size and with the right type of lettering.

Modular control panels can best be described as a sort of fixed framework in which various types of equipment and fittings can be mounted, somewhat like the panel in a modern passenger car. These panels accept everything from numeric key pads, pushbuttons and signal lamps to message displays and voice-activated controls. They normally communicate serially with a host computer or a PLC, and herein lies the biggest advantage of a modular panel. The fact that communication is based on a simple pair of wires means that the cost of cables and installation can be substantially reduced. The other main advantage is of course flexibility, as the fittings can easily be changed and new ones added.

The logical development of the modular panel is the intelligent one. A control panel is intelligent if it includes some sort of memory for storing text or other data. Like the modular panel, it normally communicates serially with a PLC or a computer. A recent development of intelligent panels combines the functions of a small PLC and an operator panel. Moving a PLC into the same unit as the operator panel provides dramatic savings in the cost of installation and programming, and also saves a good deal of space. This unit offers maximum flexibility in terms of cost-efficient capability for modifications to meet changes in the production system.

6.4.2 *Centralised operator interface systems*

There are three main criteria for the centralised operator system.

- It should provide powerful features for displaying and entering text.
- It should enable the operator to define and manipulate graphic objects.
- It should provide a means of interaction, such as a keyboard or a mouse.

At the centralised level, the quantity of information needed by the operator is normally too great for the type of panels or displays that are used locally. Graphic information is often needed, but one of the main differences is the demand for trend data, i.e. for information that clearly tells the operator how the process has been running in order for him to be able to draw relevant conclusions. In addition, the central operator is expected to control a large process, to change production strategies when necessary and to supervise several different production units as well. The need to change production strategies is illustrated by the situation in a dairy, where the mix of milk, yoghurt, cream and other products may change from day to day in response to market demands. The varied and complex demands on the operator in a central control room make it difficult to work without a keyboard and some

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sort of VDU, either monochrome or colour graphic. The advantages of colour-graphic terminals for information display have been described earlier.

The overriding general requirements for the equipment in the central control room are speed and flexibility, which means that both hardware and software must be truly high performance.

6.4.3 *Mimic panels*

A typical mimic panel was shown earlier in Figure 6.5. In a sense, a mimic panel is a modular local control panel that has been upgraded to the central level and thus comprises what can be a bewildering array of lamps, instruments, displays and switches. A carefully designed mimic panel can give a good overview of a total process.

However, showing the details of a process or controlling single process units from a mimic panel requires a good deal of space. This means that such panels are in practice limited to overviews and to plants in which changes are not expected on the general level of production, as changes in mimic presentations are very expensive. In modern food plants, they are almost always used in combination with VDU-based systems.

6.4.4 *Monochrome VDUs*

As long as the need for information is limited to forms, lists or numerical values, a monochrome (black/white, black/green or black/orange) display screen is sufficient. If the monitor has a keyboard, the operator can interact with the system, i.e. he can enter information and request new listings.

The use of forms has several drawbacks. The software that generates the display of the form is normally part of the central computer system, and changing the layout of the form is almost always expensive. This is related to another disadvantage, which is that the amount of information available is limited by the number of rows and columns that can be shown on the screen. In addition, a form has to be read sequentially. Even an experienced operator can get lost in the different fields that comprise the form, so that the possibility of error is never far away. However, this is becoming easier as spreadsheets are being embedded into control systems, and people become familiar with their proper use.

6.4.5 *Printers*

In older systems, attempts were made to use printers as dynamic parts of operator systems, i.e. it was expected that the operator could exercise control of the process on the basis of quick reactions to information in printouts. There is no question that printers are necessary, but they cannot be relied on as an element in an automated supervision and control system, mainly because too

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much time is required for the operator to react to information in a printout and then initiate appropriate action.

The use of printers should be restricted to documenting information in the form of listings of alarms, events and status checks which can be used for analysis of the production system. A very wide range of printers is available on the market. The main criteria for selection of a printer are:

- minimum printing speed, 120 characters/second;
- maximum noise level 55 dB;
- easy to change cassettes for ribbons;
- simple service and maintenance.

6.4.6 *Interaction devices*

As discussed earlier these may consist of keyboards, mice, trackballs, joy sticks, light pens and touch screens.

A keyboard should always include function keys as well as alphanumerical keys. Flexible software can greatly enhance efficiency by enabling the functions assigned to the function keys to be easily redefined.

Mice and trackballs should be used in combination with a keyboard to obtain the greatest benefits from graphic systems. Modern mice are normally fitted with two or three function keys.

Joysticks and light pens have similarly never won favour in industrial applications, probably because of the greater success of the previous two options.

Touch screens have been in and out of favour in recent years, but they are not recommended. In the first place, the operator has to sit at arm's length from the screen. In the second place, acquisition of a touch screen is always accompanied by the necessity of large quantities of screen-cleaner.

6.4.7 *Colour graphics*

As indicated in a previous section, colour-graphic terminals are the most cost-efficient type of unit for the operator system in a central control room. The high-performance systems now available are known as full-graphic systems, as opposed to semi-graphic ones. The difference is in the way the coloured object is 'pictured' on the screen. In a semi-graphic or character based system, the object is built up with predefined blocks of pixels or picture elements, for example using a grid of 5×7 pixels to build one character. This has a major disadvantage in that the picture-builder is limited by the number of rows and columns of that character size on the monitor. The shapes he or she can draw or use are rather inflexible and the space available is restricted.

In a full-graphic system, the objects are 'drawn' by the software using every pixel on the screen. The only limitation is the number of pixels available on the

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screen. Full graphic today also reduces the time between picture change. The number of pixels is normally indicated as the number of dots used by the video gun, i.e. the resolution (of the dots used to generate a picture in a newspaper). A monitor with a colour resolution of about 640 × 480 pixels is sufficient for display of plant layouts as well as details. The screen should measure at least 19 inches diagonally, but note that as the screen size is increased the resolution must also increase to maintain a smooth, quality image. At 19 inches the screen will ideally have a resolution of 1024 × 768 or better.

Smaller screens detract from the effectiveness of graphic displays and should be used mainly as back-up facilities.

The rapid development of microcomputer technology enables operator stations in central control rooms to be based on powerful personal computers or workstations in which supervisory functions and operator graphics can be combined using add-on cards.

6.4.8 *Management-level operator systems*

The availability of personal computers and workstations has made it possible for management to use the same terminals as central operators. The sheer quantity of information needed by managers makes a powerful graphic system a prerequisite. The graphics in the operator system should be designed for use as a tool for building graphic displays for both the central process operator and the manager (see Figures 6.9 and 6.10). Managerial presentations also benefit to a great extent from windowing techniques, which enable the user to combine different types of information on the screen.

The manager's need for information is not limited to data for supervising

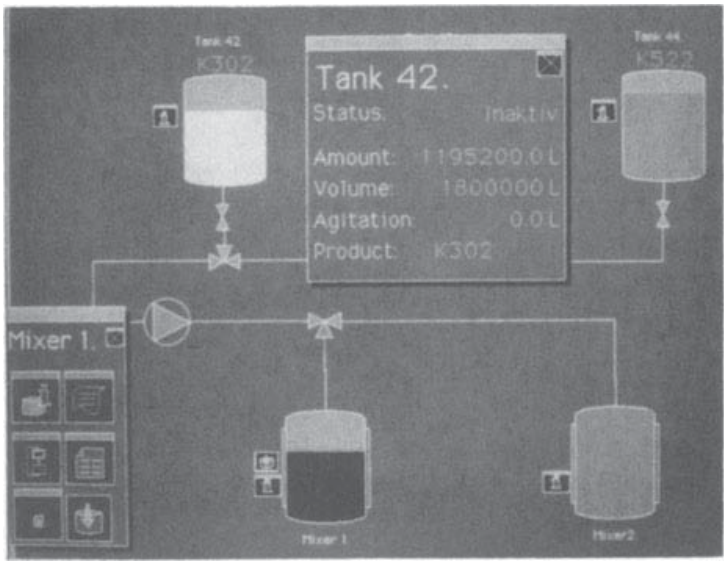


Figure 6.9 Windowed information for a process operator

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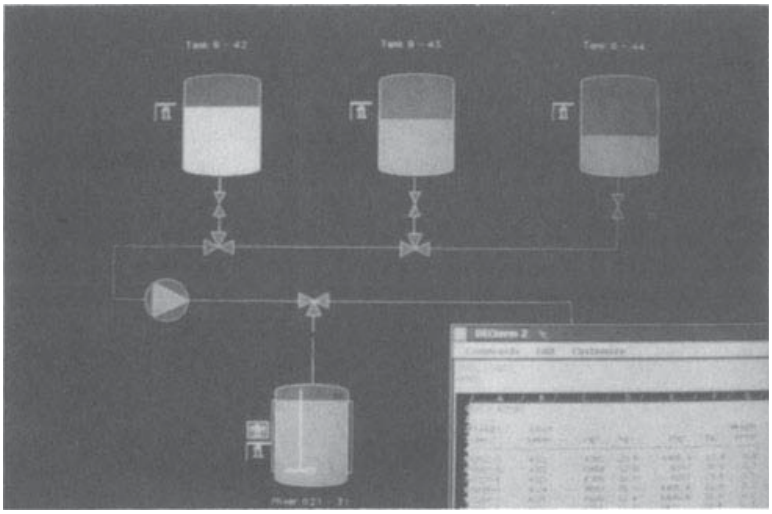


Figure 6.10 Windowed information for a plant manager

and controlling the process, as he needs to plan and analyse production. Information for these purposes is provided by systems that are external to the plant automation system.

The operator system must therefore include some means of enabling the manager to enter a network such as MiniMap or Ethernet in order to access, for example, the company's administrative system. Suppliers of operator systems now tend to emphasise what is known as open-system architecture, a very modish term which simply means that the supplier includes a heavily standardised interface that can be linked to a network without a great deal of expensive programming by communications consultants. The hardware interfaces are often known as 'buses', which can be visualised as a junction box to which various types of local hardware can be connected, and over which various types of signals can be sent. The software in an open-architecture system also includes what are known as structured query languages (SQLs), which are standardised languages for requesting information. Happily, for users, there is a very strong trend toward standardisation and away from proprietary software which would require the buyer to marry a supplier for life. Negotiations with a supplier should therefore always include a comprehensive and comprehensible discussion of standardisation. This applies first of all to the actual graphics, which should include a library of standardised symbols to accelerate tailoring the system to specific plant requirements.

The hardware, i.e. PCs and/or workstations, should also be standard, produced by well-known manufacturers. The operating system for managerial software above the process control level should also be standardised, as should the physical and software interfaces to other computer systems outside the automation system.

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6.5 Future operator interface systems

One of the main factors for the evolution of operator systems is the growing realisation that a balance must be achieved between automation and human participation. For the plant managers of the 1990s, the main goals are to optimise production and to maintain it round the clock as far as possible. But optimal production results are not necessarily achieved with 'idiot automation', that is with systems that reduce the operator to a passive observer who reacts only when a crisis occurs.

The trouble is that when a crisis does occur there is a need for fast analysis, decision-making and action. A profound knowledge of human nature is not necessary to understand that an operator who has been sitting for some hours doing nothing will not find it easy to suddenly start reacting appropriately in the new situation.

There are two basic approaches to this problem. One is obviously retrograde—cut down the level of automation and increase the number of operators, and give them a greater number of physical tasks to perform in the actual production system. No one seems to be very enthusiastic about this approach. The other is to involve the operator to a greater extent while increasing the degree of automation. This may sound like academic theorising, but it is already becoming a reality.

The idea is that automation systems are being developed which enable the computer to assume a growing share of routine supervision, so that the operator can concentrate on fine-tuning the plant and improving the performance of the production system. The computer supplies the operator with information at various levels of production which can be used to obtain the most out of the production system.

One of the main obstacles to this in the past has been the dependence of operator systems on programming expertise. Any change in the system, whether in response to changes in production or to the human requirements of the operator, required access to a specialist either in-house or from a supplier.

The introduction of object-oriented graphics has reduced this problem, as the operator himself can structure the presentation of information, using simple building blocks that contain all the data relating to an object. No knowledge of programming is required, as this is built into the system. There is thus a clear trend to greater integration of the operator system with the logic of automation.

6.5.1 *Presentation, simulation, evaluation*

An object-oriented operator system gives the operator freedom to structure information according to his needs. This is clearly illustrated by the capability for presenting alarms. Conventional systems normally do not have a capability for structuring presentations hierarchically so that important

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information can be separated from less relevant information. When one alarm is given, all the other alarms follow. The operator has to shift through a bewildering quantity of information in order to make the right decision.

With a full-graphic object-oriented system, the operator can suppress information to specific levels, so that if something goes wrong in or around a product tank, the screen shows only one or a very few alarms. Having inspected the information on the screen, the operator can then select another picture to see if other alarms have been given. He makes this selection on the basis of his knowledge of the process.

In the event that an operator with little knowledge of the process is on duty, the system itself can show the alarms automatically, level by level, changing pictures at a speed which is determined by the operator.

An operator with knowledge of the process can also use such a system to simulate the production process, as shown in Figure 6.11. He or she can extract pictures, change process values and obtain results in order to evaluate the effect of changes in production—without colliding with the current performance of the production system.

An operator who has knowledge of the process and access to a powerful object-oriented graphic system can thus make a valuable contribution to optimising the production process—and can also obtain greater job satisfaction.

Object-oriented systems can also be used to animate events on the screen. We can thus expect application of these systems to materials handling, which will in turn lead to greater integration of process control and inventory management.

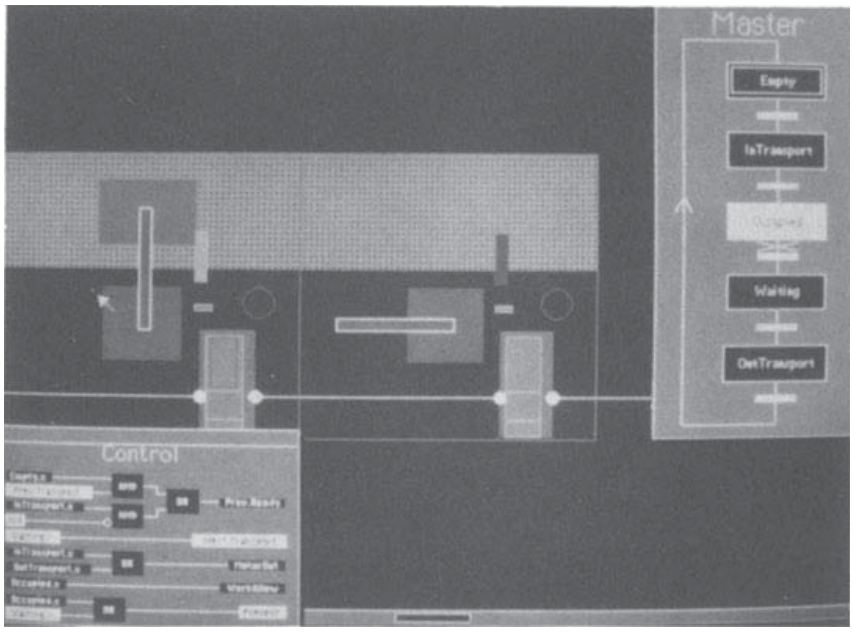


Figure 6.11 Simulation of a process sequence

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6.5.2 *Back to the mimic, down to the process level*

As previously mentioned, the trouble with conventional mimic panels is that they are expensive to produce and very expensive to change. While object-oriented graphics have the advantage of providing both an overview and access to details, the picture of the overview is still limited by the size of the VDU screen. This problem will probably be solved within the next few years.

Powerful computers will enable mimic diagrams to be displayed on the wall of a control room. In this type of system, the picture is projected directly on the wall, which serves as a giant screen. The picture will be constructed using the building blocks of an object-oriented graphic system, so that the mimic diagram can be modified quickly, easily and cheaply whenever needed. The operator will be able to use windows and zooms to obtain fast access to details, as is done today in a VDU-based object-oriented system. The continuous reduction in the price of hardware will also make portable hand-held units a reality in the near future. Operators will thus be able to walk about in the plant, which will solve a problem that is inherent in all automation systems, that the operator has to spend all his time in the control room and thus loses physical contact with the process. Losing physical contact with the process often involves losing touch with detailed knowledge that could be put to work to optimise the system.

6.5.3 *Integrated functions*

We have seen that an advanced object-oriented operator system gives the operator freedom to structure information and to simulate actual process performance. With access to back-projection and hand-held displays, such a system allows for integration of virtually all operator functions.

Handling of alarms can be tailored to human capabilities. Simulation techniques can be used to train operators in any part of the process. And simulation also enables operators to play a dynamic role in continuous optimisation of the production process.

For plant engineers and managers, the new object-oriented systems provide a total interface with the control system, in terms of supervision, maintenance and development. Among other things, the new systems include modules for analysis of system performance and for trouble-shooting, as the entire logic of the control system can be analysed on screen.

6.6 Summary

There is no doubt that the operator interfaces provided on any automated system can make or break its success. Designing a facility suitable for the operator himself is very difficult set against the demands of the control and

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management system, the engineering staff, the production team and the environment which all puts pressure on the designer to provide just what *they* want. Unfortunately it is difficult to satisfy all these at the same time, and some compromise has to be reached (or imposed!). Many otherwise successful projects have failed to meet their objectives because the operator interface was designed to be all things to all men.

This chapter has highlighted the need to select the right type of hardware, the right style of software and to apply the correct approach when designing the interface as a whole. It has also examined some of the 'object-oriented' systems which are now becoming available.

The final message to impart is that the operator interface is only part of the total system, but the visible part. It will not matter how effective the automation is in practice if it is not seen to provide the right information at the right time.

Further reading

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7 System accuracy and reliability

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7.1 Introduction

The dual requirements of accuracy and reliability have historically been considered as conflicting control system design parameters. Early mechanical control systems enjoyed a long working life together with a high availability by utilising simple, robust, well proven designs and materials. Attempts to improve the accuracy and performance of these systems frequently resulted in an increase in both component and system complexity, together with a decrease in reliability.

This very much remained the case throughout the areas of hydro-mechanical, electro-hydraulic, electro-mechanical, electrical, and even electronic control systems, until the introduction of software into control system technology. This integration of a 'software brain' with a 'hardware muscle' resulted in a 'complexity transfer'—the hardware portion of the system being released from complex computational and decision-making responsibilities, thus allowing greater emphasis to be placed on robust and modular designs.

The use of computers as an integral part of the control system has resulted in improved accuracies due to the use of digital processing in conjunction with complex mathematical algorithms. However, many early computer-controlled systems suffered from serious reliability problems. These were in part due to initial quality problems with the computers themselves, but many later horror stories were due to a complete lack of discipline during the software development life-cycle resulting from an underestimation of the importance of software quality as a factor of the overall system reliability.

So what of modern day control systems? The progress of technology has ensured that the building blocks within the system are both more accurate and more reliable than their counterparts of ten or even five years ago. The emphasis has clearly shifted from an individual dedicated component selection approach, to an integrated systems approach requiring the selection, configuration and application of flexible multi-purpose building blocks. The majority of automatic process systems within the food industry utilise off the shelf hardware, implying that standard component and reliability performance is

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adequate. It therefore follows that the design factor having the greatest impact on the overall accuracy and reliability is the system configuration. In particular, most devices incorporating electronics now provide some intelligence, and it is the wise distribution of this intelligence that is the key to a successful application.

An example of the application of technology increasing both accuracy and reliability is the motor car. Computer-controlled electronic engine management systems can precisely monitor parameters such as air flow and engine speed, whilst rapidly metering and controlling other variables such as fuel injection and engine timing in order to optimise engine performance. All this has been achieved during a period in which the application of new materials and lubricants has dramatically increased the standard service interval threefold.

One of the most difficult tasks facing an end-user is to specify precisely the accuracy and reliability required for the system. If this specification is too slack, then both product quality and throughput will suffer. If it is too stringent, then the capital cost of a complex solution may prove prohibitive and the whole project will never get off the ground.

The issue of cost as a limiting factor in either accuracy or reliability expectations should be considered in the context of both the initial capital expenditure, and also of the system maintenance during its life-time.

The issue of capital expenditure is the most obvious—a flight control system for a Boeing 747 Jumbo Jet requires state-of-the-art accuracy together with a reliability requirement based around the safety of several hundred passengers. Such a specification is justified for passenger airliners on safety grounds alone, but is clearly out of place in a typical food industry application, and would undoubtedly be rejected due to the unjustifiable capital expenditure required to implement the project.

However, the cheapest option, whilst readily receiving financial blessing at the initial procurement stage, may develop into an operational disaster out of all proportion. Systems which are being stretched to their limit at the testing/commissioning stages in order to meet the specified requirements are unlikely to maintain this standard of performance throughout their life. The cost of such inferior performance (accumulated over a typical ten-year period) together with the cost of maintaining an unreliable system and the effects of lost production, almost invariably make any financial saving due to initial cost cutting appear insignificant.

The purpose of this chapter is to identify factors which can influence accuracy and reliability, and to discuss the application, advantages and disadvantages of various techniques.

It is hoped that the potential end-user is given an insight into the practical strengths and limitations of automatic process systems, as well as giving the potential system developer an appreciation of the factors likely to be encountered when interfacing with the 'real world'.

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7.2 Accuracy

7.2.1 *General concepts*

The careful study and selection of a particular sensor, I/O interface and processor is critical in determining the accuracy characteristics of the system. However, the aim of this section is not to advise which manufacturer or component type is the 'best' or 'industry norm'—technological advances would indeed soon render such information obsolete. Instead, the intention is to approach the subject from a total system approach, and to discuss certain practical limitations which affect both measurement and control accuracies.

7.2.2 *Why is accuracy important?*

Why does the food industry invest heavily in accurate automated process systems? Consider the following example, a common scenario within a food plant where the process is not accurately controlled.

A process requires 100 litres of a product, but the operator recognises that the system has only produced 95 litres. The operator will then mix the remaining 5 litres in a bucket and empty it into the storage vessel.

The benefits of utilising an automated process system to improve the system accuracy are considerable:

(i) The consistency of batches will improve. Different operators will have their own methods for making adjustments for process inaccuracies and errors. Many costly manual process compensations will have occurred without management knowledge and without being recorded with, in many cases, the actual recipe as executed by the operators showing significant deviations from that intended by the process engineers.
(ii) Deviations from the norm (e.g. due to variations in raw materials) are easier to identify. This will assist in recognising unacceptable product at an early stage, and hence will increase confidence in the safety of the finished product.
(iii) The response to changes in the process are predictable. The success (or otherwise) of new processes and techniques can be readily assessed and quantified.
(iv) As confidence in the system increases, the frequency of quality control tests at intermediate stages may be reduced or even eliminated. This results in improved batch cycle times contributing significantly to the throughput of the process.
(v) The need for an operator could be eliminated and he could be released for other essential tasks.
(vi) Exact volumes of ingredients will be used in the process, thus minimising wastage of raw material.

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(vii) By eliminating manual additions, the opportunity for accidental (or even deliberate) contamination of the food can be reduced.

The overall benefits can therefore be summarised as a reduction in unit cost together with an increased confidence in food safety.

7.2.3 *Terminology*

In a control system context, the term *input accuracy* of measurement may be considered as referring to the degree to which the actual measurement result (as stored within the system processor) agrees with the true value of the variable being measured. The difference between the measured value and the true value is therefore the *inaccuracy* and may be either positive or negative. Similarly, the *output accuracy* of a system should be considered as referring to the degree to which the actual plant output (e.g. temperature) agrees with the desired value as interpreted by the system. (This desired value may be read from sensors, communicated by other systems, derived within the system application software or entered manually. An incorrect desired value does not affect the output accuracy—instead it indicates a conceptual design error.) The *overall system accuracy* is therefore dependent on the input accuracy, the output accuracy, and also the accuracy of the desired value itself, and can therefore be considered as the degree to which the actual plant output agrees with an ideal desired value. One issue that must be clarified when determining the 'accuracy' of the system is to know exactly what is required. It is common practice for suppliers to quote accuracies as a percentage of full scale, and for customers to want the accuracy as a percentage of reading.

The difference between the two can be highly significant. For example, a flowmeter giving 1% at a full scale flow of 100 litres per second ($l\,s^{-1}$) may seem acceptable, the possible error being $1\,l\,s^{-1}$ but when the flow drops to $20\,l\,s^{-1}$ the error will still be $1\,l\,s^{-1}$, or 5% of reading, which probably is not good enough. It is important that this is clear right from the start so that the appropriate measurement technique can be used, and any confusion arising from definitions is avoided. This chapter assumes accuracies are a percentage of full scale unless specified otherwise.

Measurement terminology already exists for sensors enabling devices to be selected against known specifications for linearity, resolution, temperature drift, sensitivity and other such characteristics. This terminology is not applied so rigidly in terms of complete control systems, with the result that the accuracy of a system is often seen quoted as a general figure in percentage terms. This figure is insufficient to define the exact characteristics of the system and gives very little guidance as to the actual performance.

The reality of the situation of course is whether or not the system produces the desired result! Many satisfied users consider their systems to be highly accurate when in fact they often have no idea of the variation between

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measured and true values at any particular stage in the process. This is because the parameter they are considering is the repeatability and not the accuracy.

For example, if an automatic control system meters x litres of water into a vessel it believes to contain y litres of product, then providing the result is always a solution with an identical consistency the system is likely to be referred to as accurate. In reality the water metering system and the level measurement may both be wildly in error, either due to inaccurate sensors or incorrect calibration of the system during commissioning. The user however is understandably more concerned and interested in the result of the process than in the exact amount of water added.

A further requirement may be that the system can reproduce the same result at various multiples of x and y (e.g. half batch manufacture). This requirement is now more than just repeatability because the difference between the measured value and the true value for each variable can vary over the complete operating range. This deviation may be expressed in terms of *linearity*, and is essentially a measure of how closely the measured value approximates to a theoretical straight line (see Figure 7.1). The ratio of the deviation at any point to the total theoretical output range is termed the *non-linearity*, and is often expressed as a percentage figure:

$$\%\text{non-linearity} = \frac{(\theta_t - \theta_m)}{\theta_{\text{total}}} \cdot 100$$

where θ_t = theoretical output, θ_m = measured output, θ_{total} = total theoretical output.

The linearity may therefore be expressed as:

$$\begin{aligned} \%\,\text{linearity} &= 100 - (\%\,\text{non-linearity}) \\ &= 100 - \frac{(\theta_t - \theta_m)}{\theta_{\text{total}}} \cdot 100 \end{aligned}$$

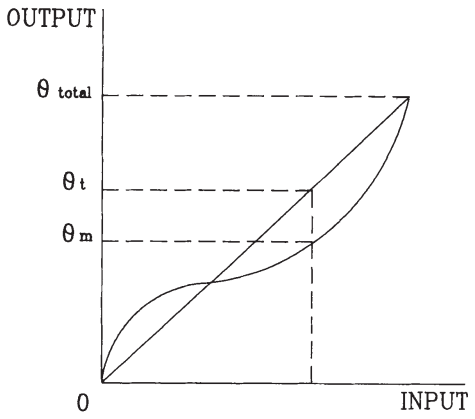


Figure 7.1 Linearity

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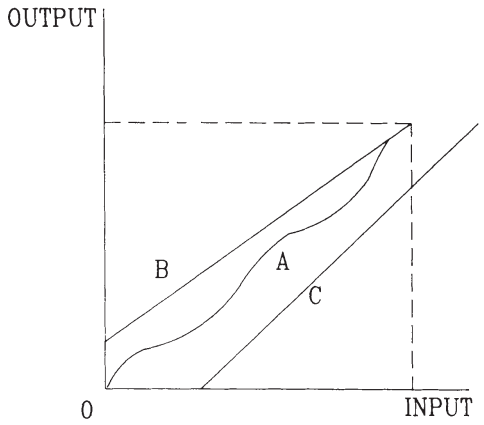


Figure 7.2 Sensor characteristics

Linearity is a major consideration in the selection of a sensor to be used for indicating purposes only, but is often overshadowed by other characteristics in a system context. Figure 7.2 shows the deviations from the theoretical for three sensors. Sensor B has a better linearity characteristic than sensor A. Many textbooks refer to the ability to reproduce measurements as *precision.* Sensor B could therefore be referred to as precise but exhibiting a large error, while sensor A could be referred to as imprecise but exhibiting no steady state error. Sensor C is of no practical use as it does not cover the full input range.

If the purpose of the sensor is merely to provide an analog signal from which a display may be driven showing the measured positions, then sensor A would normally be chosen purely on the basis of the specification data. However, the output signal from sensor B may be easily manipulated and an offset introduced, either by an electronic circuit built into the sensor itself or by software once the signal has been read into a processor via an analog input module. These conditioned data will then have an excellent linearity, and would therefore be more suitable for applications where process repeatability is required across a wide operating range.

This difference between precision and error is an important distinction to make whilst analysing the constituent parts of what can only be referred to as the generic term 'accuracy'. This concept is important both in defining the performance of the system and also in the selection of system components. Repeatability of measurement is often the most important characteristic in terms of the complete control system. Many systems within the food industry are precise but exhibit error. Any lack of accuracy in measurement is either compensated by conditioning the sensor output (either electronically or via software) or frequently by altering the requirements (e.g. adjusting a setpoint or changing a whole recipe). This results in the system being both precise and appearing to exhibit only small error.

The *reproducibility* of a device is the ability to repeat measurements. It is affected by characteristics such as *hysteresis* (the difference in input values

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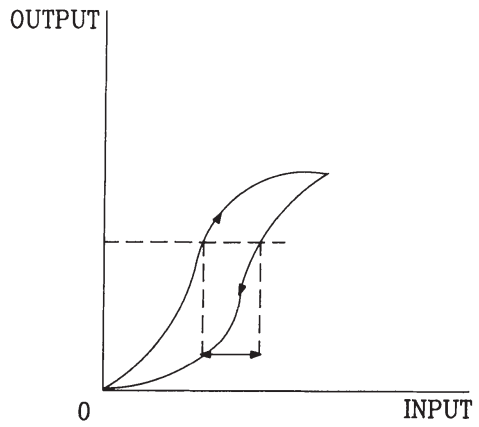


Figure 7.3 Hysteresis

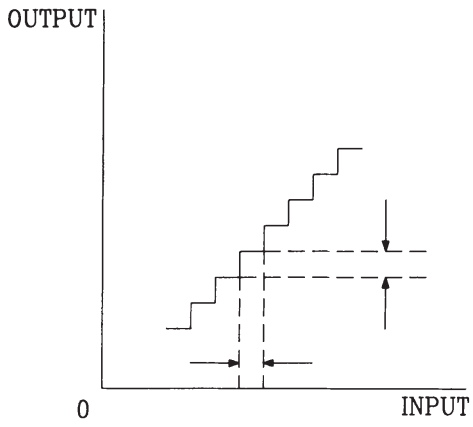


Figure 7.4 Resolution

required to produce the same output when the input is cycled—see Figure 7.3), or may vary over a long time period due to wear or ageing of the equipment. In system terms, the ability of the system to reproduce results over several months or even years gives the user greater confidence in the system performance. A repeatable process can result in less time being spent making manual compensations and quality control checks. Any changes in the process will also be easier to detect and pinpoint, thus reducing the time necessary for fault finding and diagnosis.

The *resolution* of an input device is the smallest unit of measure that the device can detect and respond to, whilst the resolution of an output device is the largest signal required in order to produce a change in the device output (see Figure 7.4). In practice, this could represent one count of an encoder output or one bit of a digital to analog interface.

7.2.4 *System configuration*

The system configuration is perhaps the major factor in determining the potential accuracy of a system. All aspects of control systems (sensors, actuators, I/O interfaces, processors) are available in different forms incorporating varying degrees of intelligence. The 'trick' is to distribute this intelligence wisely—a state of the art supervisory control computer installation will not compensate for a sensor with a noisy analog output.

In particular, special I/O requirements should be scrutinised during the system conceptual design stage, e.g. high frequency digital/analog input/output signals, intelligent I/O field devices with serial communications, analog I/O with non-standard current/voltage ranges, fast acting outputs reacting immediately to input signal change of state, and PID control loops requiring fast dynamic response. These are all cases which may necessitate a standard architecture to be modified to account for a specific requirement.

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The system processor should be considered as a general purpose machine. Improving a particular system characteristic such as accuracy should not normally be approached by substituting a more powerful processor, but should involve modifying the system configuration in order to shift intelligence nearer to the I/O device itself. The two typical solutions below illustrate how this can be done.

Example 1 A dedicated controller responsible for a certain subsystem, e.g. a dedicated weighing system responsible for metering ingredients in and out of a vessel. The architecture and processing power within this subsystem is concentrated to specifically achieve maximum accuracy and fast response. Communications with the host system are then by means of discrete I/O (digital I/O for stop, start, fault, etc., and analog I/O for demanded weight, actual weight, etc.) or via a serial link (see Figure 7.5). The use of an intelligent I/O device to convert the measured analog variable to a digital format preserves the integrity of the recorded value by eliminating any possible corruption of the analog electrical signal. However, serial communication between the device and the main processor can be slow in comparative terms, and this delay may itself result in a reduced response and hence larger dynamic errors elsewhere in the process.

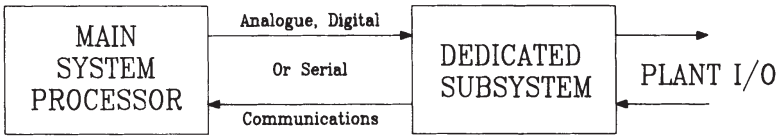


Figure 7.5 Dedicated subsystem

Example 2 An intelligent I/O module, e.g. a card capable of accepting a high frequency pulse train from an encoder, totalling the pulses, and then performing an action (such as de-energising a digital output) at the instant the accumulated count reaches a preset value. Application specific logic is written which normally resides within the intelligent I/O module, and communication of data (such as updated preset and accumulated values) is by means of the host system backplane (see Figure 7.6).

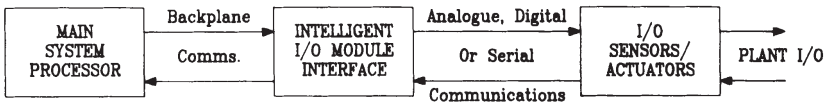


Figure 7.6 Intelligent I/O module

7.2.5 *Processor arithmetic capability*

A further design consideration is the arithmetic capability of the processor. The majority of processors currently used within the industry for real time

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control are 16-bit, but the relentless advance of technology will undoubtedly result in the increased utilisation of 32-bit and even larger processors within the next five years.

The internal design of a typical 16-bit processor results in numeric data being stored and manipulated in the following typical formats:

Integer. A 16-bit binary word may be represented as either 'signed integer' or 'unsigned integer'. The numeric range for signed integers is -32768 to $+32767$, while that for unsigned integers is 0 to 65535.
Double precision. Two 16-bit binary words may be represented as a 32-bit integer with a numeric range of -2147483648 to $+2147483647$.
Floating point. Two 16-bit binary words may be represented as a 32-bit real number with a typical numeric range of $\pm 3.4 \times 10^{-38}$ to $\pm 3.4 \times 10^{+38}$.

Whilst discussion of the above may appear just details of concern only to the 'boffins' in the control system detail design team, they are in fact limitations which need to be appreciated by all parties.

Many systems have suffered by failing to consider the long-term effect of an incrementing timer or counter. The system is typically tested and commissioned without timers or counters being allowed to reach their maximum value before being reset. Consequently, often several weeks or months into operation, the timer or counter integer accumulator reaches its maximum value ($+32767$ for a signed integer), is subjected to a further increment, and then assumes a non-sequential value such as -1! This is a simple problem which causes complete loss of accuracy in process calculations and can be avoided by careful attention to detail at the software design stage.

7.2.6 *Analog and digital signals*

An essential requirement for a process control system is the ability to convert between analog signals in the field and digital numbers within the processor whilst maintaining high accuracy.

In performing such conversions, inaccuracies inevitably exist. A common problem is that of internal processor calculation inaccuracy, even when performing simple arithmetic such as the scaling of an analog input. Many analog to digital interfaces are 12 bit, i.e. a variable input signal of 0–10 V d.c. (or 4–20 mA) would be converted by the processor to an internal integer in the range of 0 to 4095. Consequently, the resolution of the signal is 1 bit in 4096 (2^{12}), which is equivalent to 2.44 mV of a 0–10 V signal.

It is clearly important to utilise the complete analog range of a device. If a device has a range of 0–5 V, then only half of the available digital range is being used and the resolution is correspondingly 1 in 2048 instead of 1 in 4096.

Another difficulty experienced is that the analog I/O interface modules by nature employ circuitry which may drift with time and should be recalibrated on a regular basis to maintain the specified accuracy. Additionally, each of the

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analog I/O devices will exhibit certain inherent inaccuracies.

Furthermore, it is common for analog input signals originating from sensitive devices (e.g. strain gauges) to fluctuate with time. In order to compensate for random noise, filter circuitry is utilised on the analog I/O interface module, and digital techniques are employed within the processor software to obtain an average or weighted value. The value used within the software may therefore be precise, but in error at the moment it is used by the application software due to the deliberately introduced lags.

A further consideration is that data may be transmitted between the analog I/O interface module and the processor software at irregular intervals. Hence, the accuracy of any calculations relating to the rate of change of a variable (e.g. calculation of position by the digital integration of a velocity signal) depends on knowing the precise time at which the signal was sampled.

7.2.7 *Digital integration*

In the case of a flow meter which generates an analog signal, the application software within the processor is relied upon to integrate this signal with respect to time to obtain volume. However, the technique of integration with a digital control system is subject to the following accuracy limitations:

- The time intervals between sampling the analog flow signals may not be constant—the analog input module will introduce a delay which, together with the I/O update time from the module to the processor, and also the variable scan time of the processor itself, implies that the overall update time of the data as seen by the control system software may be far from constant.
- Variations of flow between sampling times will not be detected—this effect is most marked at the bottom end of the flow meter's range.

Both of the above factors may be minimised. Many systems now have facilities for achieving near constant update times, and mathematical techniques for improving the accuracy of digital integration are well proven.

7.2.8 *Example of weigh system accuracy*

An example of a system where the accuracy is dependent on an analog input is shown in Figure 7.7. The weight of the hopper and its contents is measured using strain gauge load cells and is subject to various measurement errors:

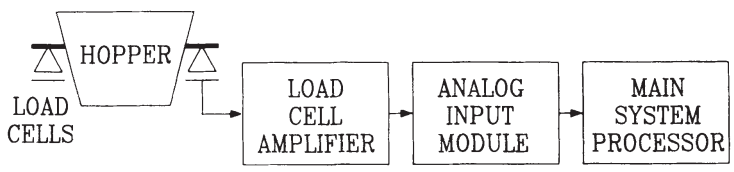


Figure 7.7 Typical weigh system

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Mechanical structure deformation. Any forces applied to the mechanical assembly (e.g. from associated pipework) will be reflected through the structure and will be measured by the load cell.

Vibration. Low range load cells are susceptible to vibration. These vibrations may be as a result of the process itself (e.g. a vibratory feeder discharging into the hopper) or due to unrelated external influences such as a nearby motor starting or even a fork-lift truck operating in the near vicinity. The effect of such disturbances is that the load cell signal will fluctuate. This signal can of course be filtered (either in the load cell amplifier or in the analog input interface module) and will also require digital filtering/averaging within the control system software.

Long-term drift. Long-term drift of the load cell signal at null may be attributable to drift of the device itself or its associated electronics; variations in the mechanical structure, for example the characteristics of flexible pipes and their connection arrangement to the hopper, may vary as the equipment ages; a build up (or even a reduction) in the amount of product deposited on the vessel internal walls. The control system can compensate for the effect of long-term drift by automatically taring the vessel weight at an instant when the vessel is known to be empty. The control system software then adds or subtracts an offset from the raw weight signal in order that the resultant weight value becomes zero. A false zero is thus obtained which overcomes any accuracy problems due to the 'vessel empty' weight drifting. This offset will remain in use until the next automatic tare.

It is also desirable that the full range of the load cell is used to measure only the contents of the hopper, and not the dead weight of the hopper itself. Although this hopper weight may be compensated elsewhere within the control system, it means that the system is only using part of its digital range for measuring the hopper contents, and the effective system resolution, linearity and other factors will be proportionally worse.

7.2.9 *Example of metering accuracy*

An example of a system where the accuracy depends on a digital input is the accurate metering of the various ingredients into a mixing tank. As previously discussed, accuracy may be enhanced by transferring intelligence closer to the variable being measured/controlled. In the arrangement shown in Figure 7.8, a sensor measures *volume* and generates a digital pulse for each unit volume metered which is then read by the host control system. An isolating valve effects a crude but widely used method of controlling the quantity of a fluid metered into the vessel.

Care then needs to be taken to ensure that the system can indeed detect and respond to every digital pulse that it receives. In practice, this means that the scan time of the system should be sufficiently fast to detect both the presence of

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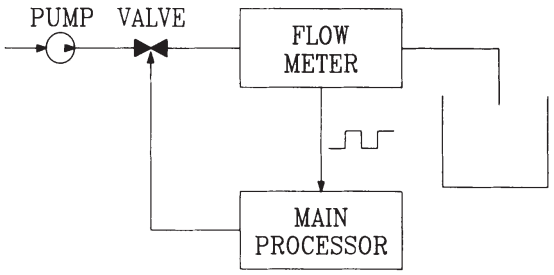


Figure 7.8 Typical metering system

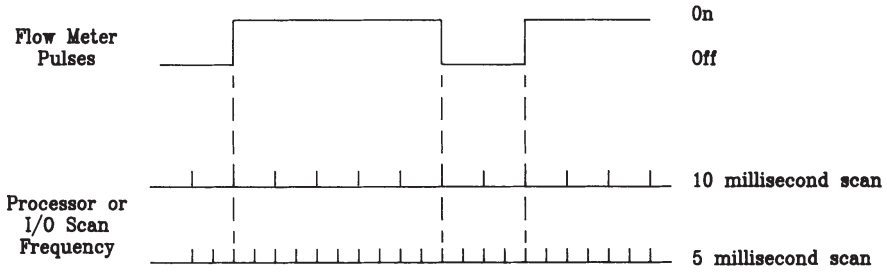


Figure 7.9 Pulse frequency and processor I/O scan frequency

any individual pulse and also the 'off' period between any two successive pulses, i.e. if the pulse duration is 50 ms and the off period between pulses is only 20 ms, then the system should examine the data more frequently than every 10 ms. In practice every 5 ms would allow a comfortable safety factor (see Figure 7.9).

Assuming that the system can in fact detect all pulses generated by the meter, inaccuracies may still exist due to:

Starting and stopping. The first and last pulse from the meter may be in doubt. At the point when the flow ceases, the meter may have measured 99% of the quantity required to generate the next pulse. However, this pulse will not be forthcoming, and the volume metered will be in error by almost one complete pulse. Similarly, at the point the flow recommences, the first pulse will now be generated after only 1% of a pulse unit quantity has been metered, again introducing a potential error of almost one pulse. These errors will naturally be minimised if the total pulse count is sufficiently large (i.e. the unit pulse quantity is sufficiently small). The drawback, however, is that the processor can only accept the digital pulses at a certain maximum frequency (e.g. 10 Hz) and the time taken to meter a specific quantity may become excessive.

Low flow. Many meters are notably less accurate at low flow rates. Errors (and also metering times) are minimised by maintaining the flow at a near maximum value for as long as possible. Precise metering requirements may nevertheless necessitate reducing the final flow to a much lower value and care should be taken to keep this time to a minimum.

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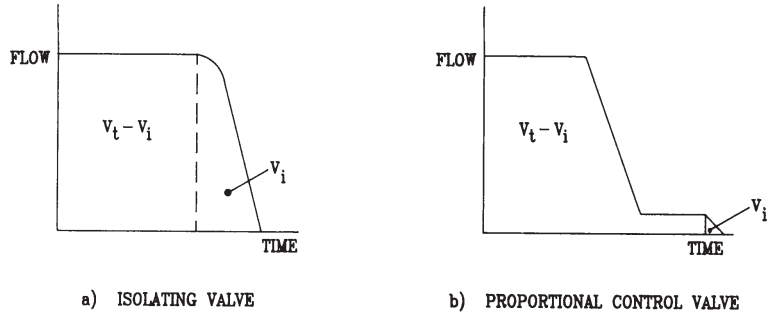


Figure 7.10 Allowing for inflight volumes. Key: V_t = target volume; V_i = inflight volume

By means of trial and error during the commissioning stage, the inflight volume (V_i) for the process may be determined. The application software within the processor is then adjusted so that the isolating valve is commanded to close at a volume of ($V_t - V_i$) in order that the final volume metered is in fact the original target volume of V_t (see Figure 7.10 a).

The introduction of a proportional control valve (in place of the isolating valve shown in Figure 7.8) allows a phased reduction of the flow, thus enabling the inflight volume to be reduced. Accuracy is now improved because the inflight volume, and hence the potential inflight error is reduced (see Figure 7.10 b).

Long-term repeatability may be preserved by comparing the final metered volume against the original target volume. Any deviation can then be reflected in an updated value for the inflight volume, thus compensating for variations in flow, product characteristics and valve response.

7.2.10 *Examples of level measurement accuracy*

Many sensors used with control systems do not directly measure the variable of interest, but instead measure a related variable. For example, a control system may need to know the volume of water stored in a vessel, but the hydrostatic pressure sensor actually measures the pressure exerted by the head

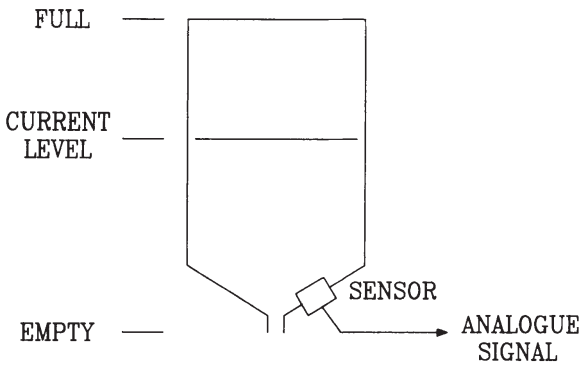


Figure 7.11 Vessel with hydrostatic level sensor

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of water above it. Depending on the accuracy required, the relationship between the sensor output, the level in the tank, and hence the volume of water in the tank, can either be calculated or calibrated on site.

Figure 7.11 shows a vessel with the hydrostatic sensor located near its base. The head of pressure measured by the sensor is independent of the tank diameter or shape. Furthermore, it is usually impractical to mount the sensor at the extreme bottom (true empty) of the vessel. The relationship between the sensor output and the tank volume is shown in Figure 7.12. This effect may be compensated by using a tank shape model within the control system software, always providing the data used in Figure 7.12 are available.

If the tank volume information is required merely in order to provide a graphical or numerical display on a supervisory system visual display, then accuracy is unlikely to be a major issue and the relationship between the sensor output and the tank volume may be approximated by calculations based on the sensor specification and the tank dimensions.

However, if the tank volume data are required either in order to meter product in or out of the vessel, or to determine whether or not sufficient product exists for a further batch, then accuracy is more critical and it is necessary to calibrate the system on site. This calibration is likely to necessitate adding known quantities of liquid into the tank and recording the sensor output to achieve a relationship as shown in Figure 7.12.

If the density of the product in the tank is subject to variation, then the sensor output will also be affected and further compensation will be required. The system will therefore need to be calibrated for each product with a different density, and the sensor output may then be scaled appropriately within the control system software. In this situation, other types of level sensor should also be considered.

The running of an agitator within the vessel will often result in the sensor detecting a fluctuation of the tank level. It is therefore common practice to average out the level signal within the control system software over a period of several seconds. The design of certain agitators causes a marked deviation in the derived level value even though averaging is present. This deviation is itself dependent on the actual tank level and product, and is consequently almost impossible to nullify within the control system.

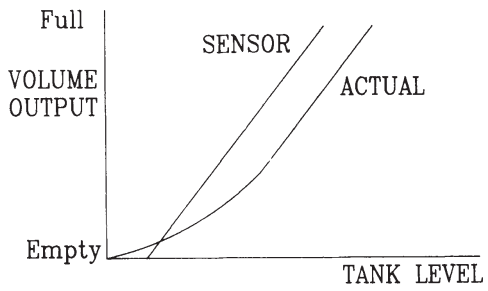


Figure 7.12 Relationship of sensor output and vessel volume

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7.2.11 *Estimation of overall system accuracy*

The accuracy of the overall system depends on the accuracy of all the individual system elements. The difficulty is that the net result is not necessarily the result of just adding up the individual components. Quantification of the system accuracy requires a basic understanding of the relationship between the individual elements which are presented below.

The following examples assume errors combine unfavourably, i.e. they are all additive. In practice all elements will be + or − although the worst cases will be when the polarities are all the same.

Addition Consider two values, X and Y, being added together; perhaps ingredients being measured into a vessel:

$$Z = X + Y,$$

where Z = end result and

$$dZ = \pm dX \pm dY,$$

where dZ = error in Z, dX = error in X, dY = error in Y

$$\% \text{ error} = \frac{dZ}{Z} \times 100 = \frac{\pm dX \pm dY}{X + Y} \times 100$$

The worst case occurs when the errors are of the same polarity, and as an example of this let

$X = 20$, accuracy 2%, so: $dX = 0.4$

$Y = 10$, accuracy 1%, so: $dY = 0.1$

$$\% \text{ error} = \frac{0.4 + 0.1}{20 + 10} \times 100$$

$$= 1.7\%$$

Subtraction Consider two values, X and Y where X is measured into a vessel before Y is removed.

$$Z = X - Y$$

$$\text{and } dZ = \pm dX - (\pm dY)$$

$$\% \text{ error} = \frac{dZ}{Z} \times 100 = \frac{\pm dX \pm dY}{X - Y} \times 100$$

Again the worst case error occurs with the same polarity.

As an example, using the values above:

$$\% \text{error} = \frac{0.4 + 0.1}{20 - 10} \times 100$$

$$= 5.0\%$$

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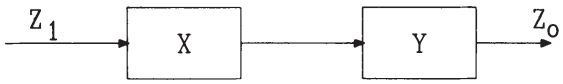


Figure 7.13 Individual elements in series

This shows that percentage errors can accumulate much faster than the individual accuracies quoted would suggest, unless this problem is 'designed out'.

Multiplication Consider two values, X and Y, which are in series, such as an instrument sensor and the input amplifier, as shown in Figure 7.13.

$$Z_0 = Z_1 \cdot (X \cdot Y) \quad Z_0 = \text{output result}$$
$$Z_1 = \text{input result}$$
$$\text{and } Z_0 + \mathrm{d}Z_0 = Z_1 \cdot (X + \mathrm{d}X) \cdot (Y + \mathrm{d}Y)$$

Simplifying this gives:

$$\frac{\mathrm{d}Z_0}{Z_0} = \frac{\pm X\mathrm{d}Y \pm Y\mathrm{d}X \pm \mathrm{d}X\mathrm{d}Y}{XY}$$

$\mathrm{d}X\mathrm{d}Y$ is small, so (approximately):

$$\%\text{error} = \frac{\mathrm{d}Z_0}{Z_0} \cdot 100 = \left(\pm \frac{\mathrm{d}X}{X} \pm \frac{\mathrm{d}Y}{Y} \right) \cdot 100$$

Using the example above:

$$\%\text{error} = \left(\frac{0.4}{20} + \frac{0.1}{10} \right) \cdot 100$$
$$= 3\%$$

These three examples show how simply adding the accuracies together will not produce a representative result. Far more care and attention must be given to *how* the errors will act together.

Common approximation The above examples pessimistically assume 'worst case' conditions, i.e. all errors are at maximum with the same polarity at the same time. In many cases, however, inaccuracies in the system elements are independent and occur randomly, and the worst case is rarely if ever achieved.

If the individual system elements exhibit a normal (Gaussian) distribution, then the overall system accuracy may be predicted from the standard deviation of the data available for each element. This approximation uses the 'root mean square' of the individual errors to arrive at a sensible, representative system error. Its validity rests in two facts:

- that 99.7% of results fall within three standard deviations from the mean;
- that the total variance for *independent* activities is the sum of the individual variances.

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It can be shown (the algebra is not shown, to keep this simple!) that:

$$\text{total error in system} = \sqrt{(dX)^2 + (dY)^2}$$

The difficulty with applying this method is in expressing the total error as a percentage. It is important that the total error is related to the same base as that used for the components. This means that if x and y are both full-scale values then the total error must also be compared with the full-scale output.

Using the example above, and assuming that the full-scale output is the sum of the ingredients:

$$\text{total error in system} = \sqrt{(0.4)^2 + (0.1)^2}$$

$$\%\text{error in system} = \frac{\sqrt{(0.4)^2 + (0.1)^2}}{20 + 10} \cdot 100$$

$$= 1.4\%$$

7.3 Statistical quality control

Statistical quality control (SQC) is a discipline that uses statistical methods for measuring and subsequently enhancing the control of quality in a process. Statistical methods are used to analyse the variations in a process, thus leading to corrective actions which may be employed in order to control that process. As with most quality control thinking, the emphasis is heavily on prevention rather than on detection.

SQC involves defining the process, measuring data relating to its capability and then defining corrective action resulting in an improvement in that process. Many good textbooks are available on this subject, but it is mentioned here because SQC is highly reliant on the accuracy of the information provided.

In the particular case of a food process where many different ingredients are being mixed together and then packaged into unit size containers, the measurements made by the automatic process system during the process can be of great importance in SQC. It therefore follows that the repeatability and stability of these measurements is also critical—another example of the importance of precision over accuracy in a system context.

7.3.1 *Automated data acquisition*

Techniques such as SQC rely upon the acquisition of the accurate, reliable data. The acquisition of these data may either be by manual means (e.g. measurements recorded on paper and then entered into the system) or ideally may be obtained automatically (e.g. from plant sensors recording process variables such as temperature, pressure, flow, etc.). The more difficult

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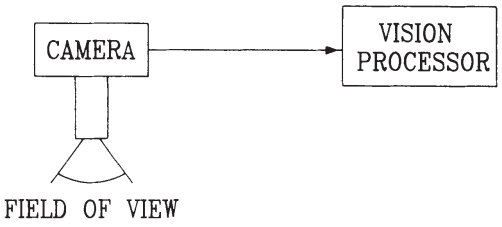


Figure 7.14 Automatic vision system

problems of accurately performing measurement tasks such as the dimensional checking of confectionery, detection of foreign matter within food, detection of damaged bottles, checking for the presence of labels and bottle tops, and the reading of bar codes and alpha-numeric codes can be solved using automatic vision systems.

These systems are capable of much more than simple go/no-go detection. A digital input to the system (e.g. from a limit switch or photo-switch) triggers a high-speed, two-dimensional image to be captured by the camera (see Figure 7.14). This picture is then digitised and the application software within the vision system can determine the area, diameter, circumference, colours (in terms of shades of grey) and other characteristics of the items within the frame.

The benefits of automated inspection alone are considerable. Inspection rates in excess of 1000 parts per minute are possible—speeds at which humans cannot perform accurately or consistently. The integration of the vision system with the control and supervisory systems enables statistical data to be obtained and analysed (both for production records and to anticipate future problems due to gradual process degradation) and also allows information to be fed back to earlier process stages, thus closing the loop around the whole process.

Certain factors do have to be considered when introducing vision technology into a factory environment. For example, a constant ambient light level is preferred, and this may necessitate placing the camera and lighting equipment within a light-proof enclosure. Maintenance of the camera lens and lighting surfaces is also important—the presence of grease, moisture or dust can produce erroneous results.

7.4 Reliability

7.4.1 *General concepts*

Reliability is concerned with random occurrences of undesirable events or failures during the life of a physical system. This physical system could be an electronic component, a human being or a control system incorporating subsystems performing specialist tasks. The following definition is often used for system reliability:

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'The reliability of a system is the probability that the system will perform its intended function adequately for a specified period of time when operating under stated environmental conditions.'

This definition identifies three important issues:

- The acceptance of the notion of probability which admits the possibility of failure.
- The concept of adequate performance for system parameters that deteriorate slowly with time.
- The judgement necessary to determine the proper statement of environmental conditions.

Reliability should be inherent in a design—it is not a 'bolt on' characteristic which can be added at a later stage by enhanced inspection and test effort. The achievement of reliability results from activities in three main disciplines, design, manufacture and field service.

Design

- A reduction in the complexity of the design resulting in easier manufacture, test, installation, commissioning, operation and maintenance.
- The use of proven equipment and methods.
- Duplication of modules to increase fault tolerance.
- De-rating: the practice of using components of a higher stress rating than the minimum requirements.
- Prototype testing (sometimes referred to as qualification testing).
- Subsequent feedback of all failure information into the design process.

Manufacture

- Control of materials, methods, and changes.
- Control of workmanship standards (e.g. the forming of electrical connections). The quantity of rework undertaken has a direct effect on the failure rate.
- Subsequent feedback of all failure information into the manufacture process.

Field service

- Provision of adequate operating and maintenance documentation and the undertaking of personnel training.
- The use of preventive maintenance techniques (including the elimination of dormant faults).
- Initiating feedback of accurate failure information to both design and manufacture.
- Replacement strategy—this may involve replacing items after a specific time as a result of a known wear-out characteristic.

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Reliability should be given full consideration in the original user requirements specification generated at the beginning of any automation project. A functional specification then results, followed by the design stage during which reliability predictions and design rules are used in an attempt to achieve compatibility with the original stated objectives. The equipment is then built and evaluated against the original requirements.

It follows that the inherent reliability of the system is initially derived from the hardware design, and is calculated from that of the chosen components, the configuration of the equipment and the various methods of interconnection. It is referred to as the design reliability, and is the value which characterises the system, even though it is rarely achieved in practice. The activities of manufacture, test, installation, commissioning, operation and service allow additional failure possibilities. The achieved reliability is almost invariably less than the theoretical design level.

The 'bathtub' curve used in hardware reliability analysis (Figure 7.15) is an example of the practice of treating more than one failure type by a single classification. It seeks to describe the variation of the failure rate of a product during its life. The curve is the sum of three separate overlapping failure distributions and is separated into three sections where the corresponding distribution prevails, as follows:

Infant mortality or early failures. These failures are due to small populations of substandard items exhibiting minute flaws, and are usually related to manufacturing deficiencies and inadequate quality assurance (e.g. loose electrical connections, inadequately soldered joints, impurities, cracked printed circuits, insulation or coating flaws, incorrect adjustment or positioning).

Random failures or useful life. These are usually assumed to be stress-related failures, that is, random fluctuations (transients) of stress exceeding the product strength. Inherent substandard items will also contribute to this distribution.

Wear-out failures. These may be due to corrosion, oxidation, breakdown of insulation, atomic migration, friction wear, shrinkage, fatigue, or any of a number of associated 'old age' failures.

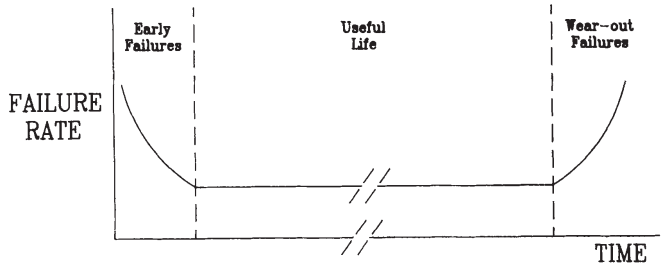


Figure 7.15 The 'bathtub' curve

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7.4.2 *System reliability analysis*

The general definition of reliability used earlier does not consider the age of the equipment—the equipment may be brand new, or may have been operating for a considerable time and was repaired when faulty. New equipment generally suffers from an accumulation of small defects which take time to locate and repair (infant mortality), so that the failure rate of the equipment falls significantly during the initial period of operation, and after that changes only slowly with time.

7.4.3 *Mean time between failure (MTBF)*

A useful measure of equipment performance which does not involve the period of observation is the mean time between failure (MTBF). The MTBF of a system may be measured by operating for a total time period (T), during which N faults occur. Each fault is repaired and the equipment is subsequently returned to operation, the repair time being excluded from the total test time (T). The observed MTBF may then be expressed as:

$$\text{Observed MTBF} = \frac{T}{N}$$

However, the observed value is not necessarily the true MTBF since the equipment is usually observed for only a fraction of its total life. The true MTBF can only be measured by life testing the system, which is usually impossible in the food, or indeed in most industries.

7.4.4 *Failure rate*

Another method of expressing equipment reliability is the failure rate, that is the number of faults per unit time. For many systems the failure rate is almost constant for much of the working life of the equipment. Where this is the case, the failure rate (λ) is the reciprocal of the MTBF:

$$\lambda = \frac{1}{\text{MTBF}}$$

7.4.5 *System availability*

The reliability of a system merely advises the probability that a job having a certain duration will be processed without equipment failure. A further measure of performance is therefore desirable. This must take into account the time lost due to repairing faults. The resulting information then enables the user to judge how much work the equipment can handle during a specified time interval.

This performance measure is the 'availability' of the system, and is measured

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from the running log of the system by dividing all of the 'switched-on' times of the system in a given period into two categories:

'Up-time' (U), during which the system is in working order.
'Down-time' (D), during which the system is faulty or being repaired.

$$\text{Availability} = \frac{U}{(U + D)}$$

In practice some adjustment to this expression is necessary. For example, any time devoted to routine or preventive maintenance is generally excluded from the calculation, since it is performed outside the hours of scheduled system operation. However, in the case of continuously operating systems, there is no spare time available for maintenance, and any time used for this purpose should be considered as down-time.

For many systems the failure rate is almost constant for most of the working life of the equipment, and the above expression can therefore be approximated to:

$$\text{Availability} = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})}$$

where MTTR = mean time to repair

In the particular case of safety critical systems, the reliability of the system is of utmost importance. However, most control system applications within the food industry are concerned with automating processes for financial gain, and the user therefore places availability ahead of reliability in his list of priorities.

System availability is often quoted as a percentage figure. A figure of 99% appears very attractive at first glance—in every-day terms, however, this would mean being without electricity for almost 15 minutes every day! MTBF figures of many thousands of hours together with MTTR figures of about 4 hours are frequently predicted for automatic process control systems. These predictions result in availability forecasts well in excess of 99.9%.

Another important factor to be aware of in assessing system availability percentages is how frequently the failure occurs. Taking the availability as 99% would relate to 1 second of down-time in every 100 seconds, just as it would be 1 day in 100 days. Clearly the first is hardly appropriate for a modern automated process—no product would be produced at all! However, the second may be quite satisfactory, if perhaps annoying every 3 months!

7.4.6 *System configuration*

Arguably the most influential factor in determining system reliability is the system configuration. Decisions such as whether to distribute or centralise the system intelligence, and how to organise power distribution throughout the plant will significantly affect reliability calculations.

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If availability is crucial, then particular consideration should be given to how the equipment may be isolated, repaired (or substituted), reinstalled and recalibrated without necessitating a complete system shut-down. Should manual overrides be provided to enable operator intervention?

The following sections discuss how a numerical value for reliability is derived, and the effects that various system configurations will have on this figure.

7.4.7 *Failure mode analysis*

In order to assess the reliability of a system it is divided into units, each small enough to enable its reliability to be assessed directly. In general, this requires sub-divisions down to component level so that reliability data gathered from many different systems incorporating the same components can be used (see Figure 7.16).

In addition to information about the number and characteristics of all the components in a system we require knowledge of the way in which they are connected together.

The following probability rules are helpful in understanding the system modelling involved in reliability.

Multiplication rule The probability of simultaneous events occurring is the product of the individual probabilities. The probability of events A and B occurring simultaneously is therefore:

Probability of A and B: $P_{AB} = P_A \cdot P_B$

Generally, for N events: $P_{AB\cdots N} = P_A \cdot P_B \cdots P_N$

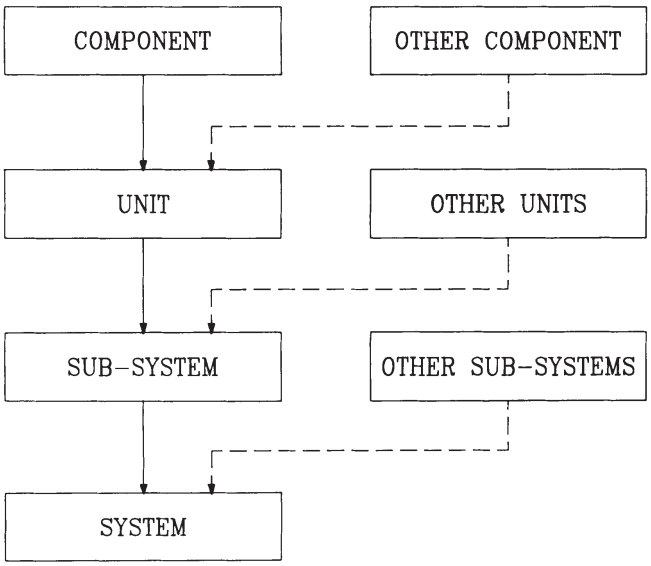


Figure 7.16 System reliability decomposition

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Addition rule The probability of either event A, or event B, or both occurring is:

$$P_{(\text{A or B})} = P_{\text{A}} + P_{\text{B}} - P_{\text{A}}P_{\text{B}}$$

which becomes:

$$P_{(\text{A or B})} = 1 - (1 - P_{\text{A}})\cdot(1 - P_{\text{B}})$$

Generally, the probability of one or more of N events occurring is:

$$1 - (1 - P_{\text{A}})\cdot(1 - P_{\text{B}})\cdots(1 - P_{\text{N}})$$

7.4.8 *Series system*

The simplest component arrangement (often referred to as a 'series system') is one in which each component is necessary for correct operation of the system. Consequently, a failure of any one component must cause a system failure. Consider the series system comprising two valves shown in Figure 7.17. System failure occurs if either valve fails. The reliability (probability of success) of the system is the probability that valve A does not fail and valve B does not fail. Using the probability multiplication rule:

$$P_{\text{AB}} = P_{\text{A}}\cdot P_{\text{B}}$$

If the failure rates for the valves are λ_{A} and λ_{B} respectively, the expected number of failures (N) in a time interval (T) for the system is given by:

$$N = (\lambda_{\text{A}} + \lambda_{\text{B}})T$$

and the corresponding MTBF for the system is:

$$\text{MTBF}_{\text{system}} = \frac{T}{N} = \frac{1}{(\lambda_{\text{A}} + \lambda_{\text{B}})}$$

If A and B are identical and $\lambda_{\text{A}} = \lambda_{\text{B}} = \lambda$, then:

$$\text{MTBF}_{\text{system}} = \frac{1}{2\lambda}$$

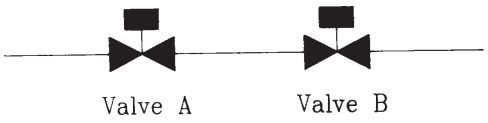


Figure 7.17 Series system

7.4.9 *Redundant system*

The general principle involved in a 'redundant system' is to provide more than one way of meeting the functional requirements of the system, such that if one

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component fails, thus disabling one subsystem, other subsystems can continue to operate satisfactorily. The designer's objective is to achieve a substantial improvement in reliability/availability at an acceptable cost—this decision is likely to be based on a comparison of extra initial capital outlay versus the benefits of increased production resulting from an improvement in system availability.

The application of redundancy may be considered for the complete system (processors, I/O system, power supplies, cabling, sensors, actuators, etc.) or may be applied selectively to critical components or sub-systems.

Redundant systems can take various forms:

Full active redundancy. Duplicated units which are all powered up and operating. Any one surviving unit ensures system non-failure.

Partial active redundancy. A specified number of units may fail without resulting in system failure, e.g. two out of four engines of an aircraft.

Conditional active redundancy. A form of redundancy which occurs according to the failure mode (e.g. three supposedly identical signals are fed to an input module. If two out of three identical signals are received by the module, the signal is reproduced at the output).

Standby redundancy. Additional units are activated only when the operating unit fails.

A candidate for redundancy that is always worth investigation is the control system main processor. Failure of this unit involves not only loss of control over the I/O system, but also loss of any dynamic data stored within its memory (e.g. accumulated values of timers and counters, shift registers, latest inflight volumes, etc.). The time lost in resetting the system to a status where the process can safely restart will greatly exceed the time taken to replace the hardware, and whole batches may be jeopardised in the process.

Figure 7.18 shows two processors connected to the same I/O system. Processor A is initially the primary processor which has active control over the I/O system, and processor B is the back-up processor which performs a listen only function (i.e. monitors inputs without controlling outputs). A transfer of data continuously occurs between the primary and back-up processors such

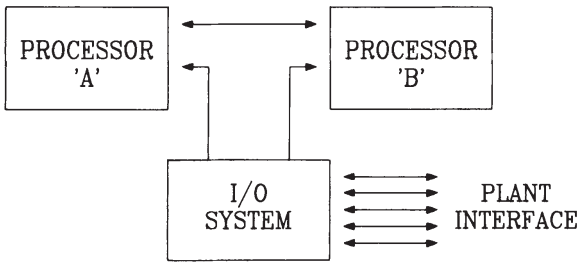


Figure 7.18 Main system processor with full active redundancy

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that the back-up unit is always aware of dynamic data such as timer and counter accumulated values. In the event of a failure of processor A, processor B automatically assumes control of the I/O, effecting a near 'bump-less' transfer. Processor A may then be repaired/replaced and will resume operation as the back-up unit.

The reliability of the system may be estimated using the probability addition rule:

$$P_{\text{system}} = 1 - (1 - P_{\text{A}}) \cdot (1 - P_{\text{B}})$$

If the failure rates for the processors are λ_{A} and λ_{B} respectively, then the corresponding MTBF for the system is:

$$\text{MTBF}_{\text{system}} = \frac{1}{\lambda_{\text{A}}} + \frac{1}{\lambda_{\text{B}}} - \frac{1}{(\lambda_{\text{A}} + \lambda_{\text{B}})}.$$

If A and B are identical and $\lambda_{\text{A}} = \lambda_{\text{B}} = \lambda$ then:

$$\text{MTBF}_{\text{system}} = \frac{2}{\lambda} - \frac{1}{2\lambda}$$

$$= \frac{3}{2\lambda}$$

The implementation of full active redundancy will therefore increase the MTBF of the system processor by 50%.

7.5 Software quality assurance

The incorporation of application-specific software within an automatic process control system affords the designer much greater freedom of hardware configuration and architecture. A consistent and common approach to hardware design may be employed resulting in fewer devices per system, and, perhaps more important, fewer types of different device per system, thus making the system easier to maintain. The consequence will be a quantifiable increase in both hardware reliability and availability.

7.5.1 *Software failure*

Less tangible is the effect of the software on the overall system reliability and availability. Failure mode analysis of the hardware design is practical because of a direct link between component failure and system failure, e.g. a broken wire results in the loss of a signal.

There is no physical change associated with a software failure. A software expression (such as an 'IF' statement) does not have a stated MTBF in the

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same way that a power supply may have. Furthermore, the quantity of software failures is not directly linked to the quantity of software code. Software faults (bugs) may appear in many different guises. Many bugs appear as a result of particular sections of code being used for the first (and perhaps only) time under a particular set of circumstances.

Comprehensive simulation testing of every possible software and I/O state permutation in real time is generally impossible. Indeed, software testing involving an accurate plant simulation can at best only show the presence of bugs. It cannot prove their absence.

Therefore it must be assumed that the potential to cause a software failure always exists. Great emphasis must therefore be placed on the 'robustness' of the software. Invalid operator keyboard entries, input data received from defective plant sensors and garbled communications messages should not cause the system to fail. These conditions should instead be detected by the software, and their occurrence should be brought to the operator's attention. In the event that the software is required to handle an excessive amount of data (e.g. multiple alarms and communications during a major plant fault), it is essential that the performance of the system degrades gracefully then recovers, rather than fails in an uncontrolled manner.

7.5.2 *Software error rate*

Unlike the hardware 'bathtub' curve, there is no wear-out characteristic for software, but only a continuously decreasing infant mortality. Each time a bug is identified it is corrected. Even in a mature product, subsequent software modifications are always potential sources of new bugs, and the error rate is likely to rise (see Figure 7.19).

7.5.3 *Assuring software quality*

The difficulty in predicting software failure has resulted in the emphasis being firmly placed on assuring the quality of the software, rather than calculating its reliability.

Three factors are crucial in achieving software quality:

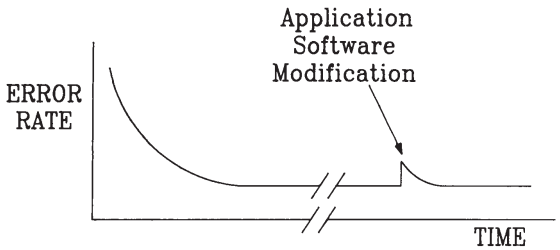


Figure 7.19 Software error rate

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- The definition and implementation of a software quality assurance policy.
- The identification and application of a software analysis and design methodology.
- The adoption of proven software programming standards.

7.5.4 *Software quality assurance policy*

Figure 7.20 shows the typical software development life cycle for a real time process automation application.

In order to ensure control of the software development life cycle and to maintain consistency of the software development process, a statement of policy is needed to define:

- criteria against which the life-cycle documentation may be evaluated;
- the review process including the responsibilities of both the developer and the user regarding acceptance procedures.

Software quality assurance is thus provided with a framework around which interested parties may critically review the 'deliverables' (technical documents such as specifications, flow-charts, documented source code, test reports, etc.) evolving from each stage of the life cycle.

7.5.5 *Analysis and design methodology*

The life-cycle products can only be constructively reviewed if the format and nature of the technical documentation is both rigidly defined and easily understood. A considerable advantage of utilising an accepted methodology is

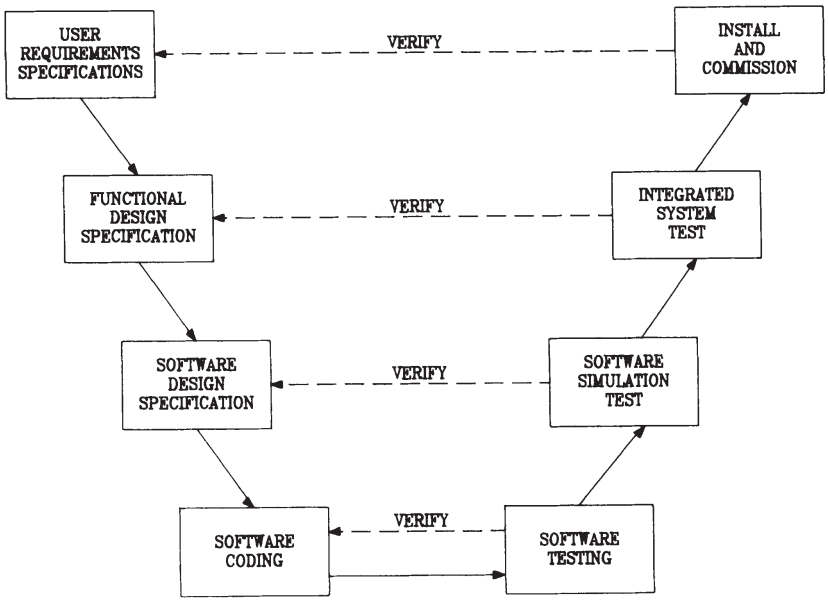


Figure 7.20 Software development life cycle

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that the documentation may be evaluated against specific rules to determine whether it is correct and complete. Furthermore, the reviewers are given visibility of the software analysis and design activities, allowing comment on the software developer's interpretation and proposed implementation of the requirements at an early stage before software coding commences. The mystique of software development is thus suppressed, and all interested parties can have confidence that the original design requirements are being considered and satisfied.

7.5.6 *Programming standards*

The adoption and inclusion of existing, proven standard software modules from a fully documented asset library will significantly diminish the quantity of virgin software to be coded and tested, thus enhancing the reliability of the system as well as reducing the development time scale.

7.6 Summary

This chapter has aimed to identify the main influences on the accuracy and reliability of automated systems. In summary the following points should be kept in mind when developing or applying such systems:

(i) Careful consideration of the required accuracy and reliability of the system must be given at the initial requirements definition stage. If these requirements are too stringent, then the project costs will be excessive; if they are too lax, the result will be an inadequate system requiring constant maintenance.
(ii) The accuracy and reliability of standard components are acceptable for the majority of automated process systems within the food industry. However, the accuracy and reliability of the overall control system is greatly influenced by the system configuration.
(iii) The advantages of an accurate control system include a reduction in unit cost together with increased confidence in the safety of the finished product.
(iv) Reliability is not a feature which can be added by means of enhanced inspection and test effort. It needs to be inherent in the system design.
(v) The difficulty in predicting software failure requires effort to be directed toward assuring the quality of the software, rather than attempting to calculate its reliability.

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8 Achieving integration

IAN BAKER

8.1 Introduction

This chapter, as the title suggests, discusses the 'What is it?', 'Why do I want it?' and, having decided that it is necessary, the 'How do I get it?' of integrating these stages.

We will detail the various levels of control and data transfer within a typical food production plant and the practical considerations of achieving integration at each level. The chapter is interspersed with examples of integrating these stages and in some cases situations that the writer recommends should be avoided. The subjects of feeding forward and feeding back of data is explored, as are the subjects of material audits, quality assurance and the integration of remote sites into schemes.

8.2 Integration

8.2.1 *Background*

As a prelude to discussing the topic of *integrating stages together* we will first, at the risk of repeating text in other chapters, establish what is meant by *integration* and then why there is a need to integrate the various stages in the manufacture of food products.

A definition of integration is to form into a whole or to complete, and this is applied to the bringing together of individual elements to form a whole system in a food production plant. This can be the linking together of the corporate mainframe computer to the lowest level of the shop floor or process plant controller to form a coordinated manufacturing operation.

8.2.2 *Why integrate?*

We must also ask why the chief executive of a large food manufacturer would want to integrate the plants and production facilities together. In the past and, to a large extent in present times, food manufacturing plants and manufacturing and process plants in general have been islands, albeit islands of

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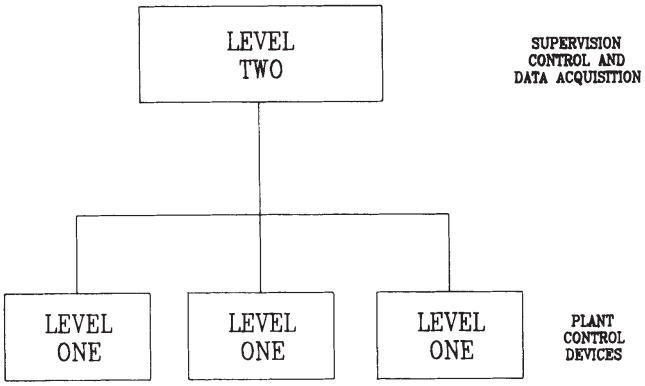


Figure 8.1 Plant level control

automation. Although there has been a degree of automation they have nevertheless been islands with very little in the way of communication in an automatic form with management, let alone with management computers. Control of plant items is in the main by electro-mechanical devices, programmable logic controllers, single loop controllers and distributed control systems. In the larger and the more modern plants there is usually a level of supervision, control and sometimes data gathering above this lower tier of control (see Figure 8.1).

The need for integrating these two levels of control and monitoring will be known to the majority of readers. Level one controllers with a few exceptions undertake the sequencing of valves, pumps, agitators etc. to provide process control of the plant. In some of the more sophisticated level one controllers information is displayed to operators by the use of colour graphic systems to provide plant status information, alarm indication and very basic reports. Where the need exists for bringing together a number of individual controllers to coordinate their actions, or where several different areas of plant can be controlled or supervised from a central location then a system at a higher level is employed. This system, conventionally referred to as a level two system, provides supervisory control of the plant by means of colour graphic screens in a similar manner to a single operator station at level one but are usually more

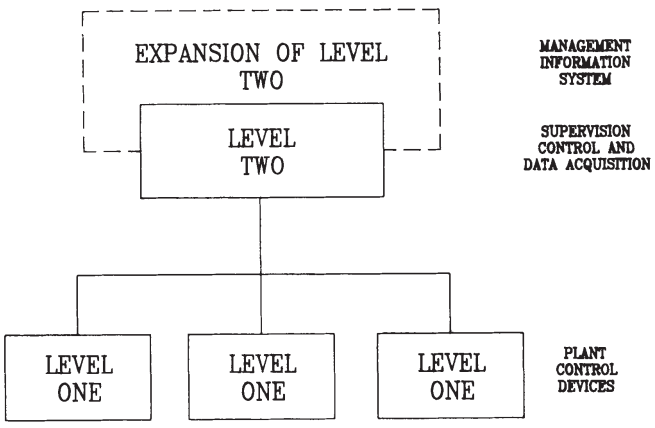


Figure 8.2 Plant level control with MIS incorporated

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powerful in their performance and have much greater scope for data storage, trending of displays, etc. Very often the system employed at this level is similar to the level one controller. There is now an increasing movement however towards the employment of personal computers with proprietary software packages at level two.

Expanding level two into providing not only data acquisition (DAS) and supervisory control and data acquisition (SCADA) but also management information systems (MIS) is becoming more common in today's plant and gives production supervisors and managers such information as batch efficiencies, machine downtime and estimated times to run on batches (see Figure 8.2).

At the top of any corporate structure is the mainframe computer and it is at this level (by convention referred to as level 3) that market projections, order processing, MRP, MRPII, quality assurance records, distribution control, etc. are implemented and archived. A major area of omission in the current architecture in most plants is the ability to successfully link level 2 computers to level 3 machines, and to be able to pass information and data in both directions in real time. This integration is essential to the optimising of any plant by reducing information transfer time, and eliminating errors caused by the manual keying in of data.

8.2.3 *Information transfer requirements*

When designing a plant or facility involving automation and where there is a requirement to integrate the various stages of the process together it is essential that the designer considers firstly the broad aims of the information transfer requirements. This is followed by the detail of who needs (as opposed to who wants) information and in what format that information should be presented.

The designer in conjunction with plant managers and operators should determine the information that is needed at each stage of the process and assess the optimum source of these data. Having established the validity of the requirements and the best and alternative sources of information the designer can then set about determining the most cost effective and expedient method of designing the routes of communication of the plant.

8.2.4 *System coordination*

It is of prime importance that the aims of the individual component parts of the design meet the criteria of the whole of the production requirements to present a unified, cohesive and fluid system. Before we discuss how production systems in general and food manufacturing systems in particular can be integrated together we will identify the common elements that exist within most types of processing organisations regardless of the specific product being manufactured.

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Each manufacturing or processing plant will have the following elements that will need to be co-ordinated:

- There will be a forecast (usually by a sales or marketing department) of the demand for the finished goods.
- This forecast will be used to produce a production schedule and this can, and in modern plants should, be done using a manufacturing resource planning (MRPII) or just-in-time (JIT) program.
- From the MRPII/JIT package data are passed to an order processing system for the procurement of raw materials.
- Raw materials will then be received and placed into suitable bins, hoppers or warehousing prior to use. This storage may need to have environmental control.
- At the appropriate time in the manufacturing cycle, as determined by the production schedule, the raw materials are worked to produce the finished article. This may be achieved in several stages, as depicted by Figure 8.3.
- Having processed the raw materials and manufactured a finished product this then has to be packaged in a form that facilitates ease of handling and

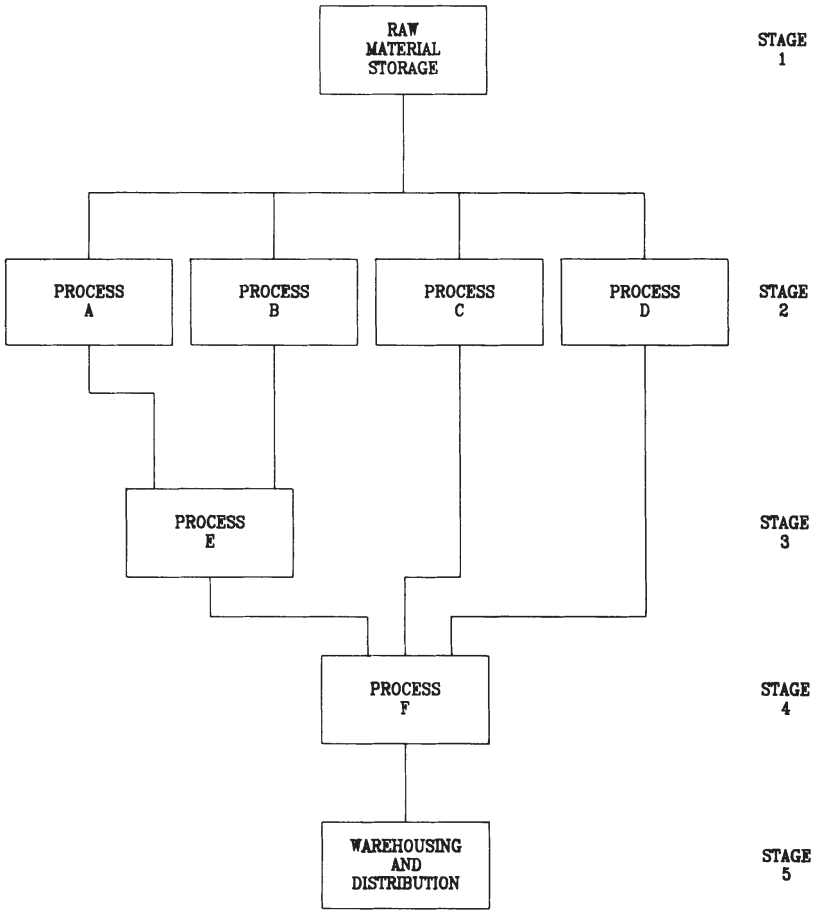


Figure 8.3 A typical manufacturing process

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distribution. It should be realised that there will be many stages of handling before the product reaches the consumer, e.g. factory, warehouse, road/rail transportation, wholesale and/or retail outlet, and finally the houseperson or catering staff.

- From packaging the product will in most cases be subject to some sort of storage prior to distribution. As with raw material storage this could be subject to special environmental considerations which could be entirely different to those previously required.
- The goods are then made available for distribution on demand.

8.2.5 *Connecting elements together*

The above list of individual component parts of a system will of course be familiar to all plant managers and engineers as separate elements of a production facility but consideration must be focused on how the elements are to be bound together to form a cohesive system. In the 1990s it is most unlikely that even with the development of such agreements and standards as MAP and TOP that any product supplied by one manufacturer will be directly compatible in either hardware or software terms with a complementary item marketed by another manufacturer. It is essential therefore that consideration be given to the subject of the physical connection of elements together. Having achieved a physical link the designer then has to ensure that there is software compatibility between the devices such that 'intelligent' data out of one level are received, understood and usable at the next level.

On the subject of physical connections, there exist various standards such as RS232, RS422, RS485, IEEE 802.3, IEEE 802.4, etc. and it is a relatively easy task to connect a cable between say a programmable controller at level one and a computer at level two. There are various buzz words in the industry such as wide area networks, local area networks, broadband, wideband, master/slave relationships, floating master, batten and token passing, etc. and it is easy for an engineer who is not dealing with the topic on a daily basis to become confused or even misled by the amount of information available to potential integrators of systems.

Aside from the transfer of simple information, e.g. in the form of ASCII files, the exchange of data will invariably involve the use of software packages in the form of protocol convertors. Such convertors, for instance, enable a PLC manufacturer's proprietary programming language whether it be Ladder, SCF, STL, Boolean or Graphset to pass information to and receive information from a program written in C, FORTRAN, PASCAL or any one of the myriad of programming languages used in level two computers. The writing of protocol convertors is an extensive subject and can and invariably does take a number of man months of a proficient software engineer's time and effort to achieve and thus will have a considerable cost implication on any project manager's budget.

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8.2.6 *Defining integration*

We have looked at the physical constraints and the software programming hurdles that need to be overcome. Now we should make the point about what can be realistically achieved and what it is necessary to achieve. To illustrate this point, examples of what should not be achieved are given.

Some years ago a specification for a sewage treatment works control and monitoring system was prepared on behalf of a water authority by a firm of consulting engineers and preparation of outline designs for a control system to meet the criteria of the specification requested. Whilst the document on the whole presented a reasonable picture of the user requirement there was one particular sub-section that is given here as an example of what is unreasonable to expect of a system. The sub-section in question stated that all analogue sensing devices and signals into the system should be sampled at intervals of 500 ms, trending them for operator information and archiving these values for future use.

There is obviously nothing unusual about a requirement to sample present trends to the operator and archive data for future analysis except that the specification related to rapid gravity sand filter beds in a large sewage works. In such plants the majority of analogue signals come from sensing devices detecting the levels in the filter beds, flows in pipes to and from the beds, positions of penstocks, the differential pressures across the beds, etc. Whilst it is just conceivable that such a timescale could be required in some of the associated control aspects, to require that these data be sampled for trending purposes at these intervals is patently not necessary and those who have even the most basic knowledge of the operations of plants of this nature will know that turbulence caused by water flowing into a bed causes relatively large variations in signal levels. Equally the differential pressure across the bed changes so slowly that it could take hours for a bed to become clogged to such an extent that it needs to be taken off line for backwashing. Clearly the consulting engineers responsible for this document had failed to appreciate the reality of the operation of the plant to which the specification pertained otherwise they would have selected more reasonable timescales.

Similarly, we recently came across an example of a computer program written by a 'data processing' software engineer for a SCADA system. The program was written in such a manner that in one area the response time to an operator pressing a pushbutton on the panel was reflected in the output device being switched some 17 seconds later. This was because the programmer did not have an appreciation of 'real time' control and the user requirement and software specifications were not sufficiently explicit in their content to detail maximum response time permissible in the sequence of operation.

Again the culprit did not have an appreciation of the real world of automation and control. Experience of many plant operators across the country in numerous industries has shown that any delays in excess of 1.5 to 2

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seconds from initiating an action to seeing a response make an operator concerned.

Both the above examples highlight the need for considerable forethought of what is required together with the knowledge of what is achievable—within normal commercial constraints—when defining integration.

Information to be transferred must be readily available to the recipient and be packaged in such a form that it can be deciphered easily by the receiving machine. Again there is no need to transfer every piece of data on each scan of a system, but rather the system should be programmed so that only information that has changed since the previous exchange need be transmitted. A vital part of specifying an integrated production plant is to consider carefully the passage of information between items of equipment on the same level and then between levels of the plant management and control systems.

Having established that integration is required and can be achieved, let us now consider the type of information transfer that can be achieved and the benefits to plant designers, manufacturing management, production directors and directors with financial responsibilities in a food manufacturing plant. Firstly there must be feed forward and feed back of information to provide the most effective and efficient system.

8.3 Feed forward

Feed forward of information is the passing of data from one stage of a manufacturing process to the subsequent or following stages of the production facility. These data are passed for a number of reasons including, but not limited to, warning the following stages that a batch of biscuits is passing from the previous stage or that the next brew to pass from the mash mixer to the lauter tun is gyle number 1492 and, therefore, the next stage of the beer-making process should be using recipe number 1492 stored in its data base for that purpose. Feed forward of information when incorporated in level one and level two systems is usually automatic. Due mainly to constraints of an extraneous nature, feed forward of information from level three systems to level two systems and, in the installations where level two does not exist, to level one systems is usually by manual entry of paper trails. Here manufacturing managers or supervisors interpret the information received at level two or through an operator interface at level one keying information to program the production facility.

As an example, if a batch change is required that necessitates a certain machine being warmed to a specific temperature such a change would obviously take a period of time to achieve. The feed forward mechanism would signal the appropriate plant level controller to make the change initiated by the supervisory system or MRPII package such that when the batch change actually takes place the machine is already at the appropriate temperature.

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A further example of this need for feed forward could be a bottling line which produces not only bottles of red wine and white wine but produces both of those colours in different size bottles, e.g. 70 cl, 120 cl, etc. A further variation could be that some bottles need a cork and others are fitted with screw tops. Then of course any change in bottle size or the colour of the contents necessitates a change in labels and, as there can be up to five labels on a bottle of wine, there is another dimension to be considered. An MRP or MRPII system running on the mainframe will have passed to the management level supervisory system information relating to an impending batch change. At this intermediate level the instruction to make the necessary changes to each element of the line is made such that from the time the change in bottle size is registered at the bottle depalletiser each machine in the line is ready for the new bottle size as the first bottle arrives. In the case of a change in product type, i.e. red wine to white wine or sweet wine to dry wine, then an intermediate step to change the raw material source and a CIP routine to clean the filler will be initiated (see Figure 8.4).

The above are examples of the need to feed forward information to minimise any delays in a batch production type environment. There is also a necessity to feed back information which can be beneficial to planning and therefore the overall efficiency and thus profitability of a plant.

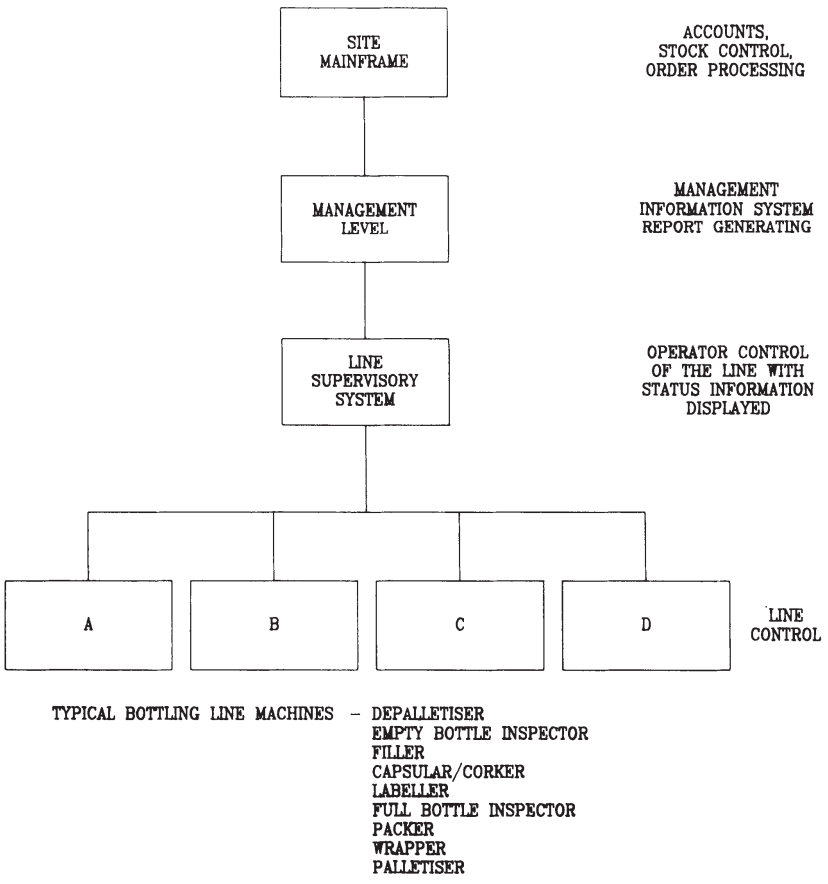


Figure 8.4 Bottling line system block diagram

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8.4 Feedback

Feedback can be defined as an analysis of information derived at one point of a process with instructions or data being transmitted to a previous stage or stages as a result of that analysis. Prior stages could be an earlier machine in the production line, an earlier process of stock preparation for that line or even the production scheduling system that schedules the production on that line.

Using the example of the bottling line again, the line comprises a capsular for putting screw caps onto bottles and a corker for inserting corks into the necks of bottles; either one or the other of these operations could fail. This failure could be due to a mechanical failure, an electrical failure or simply that caps are not available—feed forward system failure! In any of these cases the fact that the machine is not available can be fed back into the system and production re-scheduled so that only batches that have to be corked are processed by that particular line and batches requiring caps are routed down another line until the faulty capsular is available. This involves all three levels of an integrated system, as follows.

- The capsular machine control at level one reports the failure to the line supervisory computer at level two.
- The supervisory computer communicates the breakdown to a computer running a maintenance software package in the works engineering department.
- The MIS system at level two logs the data for future analysis and reports the loss of production to the MRPII package at level three.
- The MRPII system reschedules production for that line in the manner that will least affect the overall *factory* production requirements and down-loads the appropriate instructions to the level two MIS and SCADA systems.

With further forethought and planning of the system integration the efficiency of each machine on a line can be analysed and conclusions drawn as to the suitability of a particular element on a line or the overall performance of a line. It could be for instance that line 1 operates in a more efficient manner when putting dry white wine into 70 cl bottles than line 5 with the same product. A management information system would quickly note the relative efficiencies of the two lines when bottling these two products and feed the fact back into the scheduling system so that the most effective means of production may be used. Instead of re-scheduling production to suit the lines the information can be reported to an expert system running on a computer in the maintenance engineering department and further detailed investigations undertaken to establish the root cause of the apparent inefficiencies of line 5 and the problem rectified so that both lines perform in the same manner and to the same standard.

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8.5 Production management information

8.5.1 *Resource optimisation*

An effective management information system integrated into the production plant will make it possible to correlate various pieces of data obtained from control and monitoring systems within the factory or production process plant. This correlation of information may be used by supervisors or managers to determine for instance the optimum use of manpower in a production environment. Taking as an example the manning levels of a typical production line and having stripped out any special circumstances such as machine breakdown, an MIS installation could by analysis determine the following:

10 operators produce 8 000 items in 8 hours.
12 operators produce 10 000 items in 8 hours.
13 operators produce 10 500 items in 8 hours.

It can be seen that whilst there appears to be a significant benefit in the utilisation of an extra two operators to achieve a 20% increase in the volume of goods produced the addition of 30% labour over the original workforce appears only to produce a 25% increase in productivity and the expediency of this further increase needs to be justified. Management must evaluate the cost of employment of the extra personnel and balance this against the additional profit directly attributable to the selling of 2000 or 2500 items made by the two or three operators brought in to augment the original production staff. The information to enable management to make this evaluation can only be made readily available by the integration of data on the cost of employment and the profitability of the items being manufactured; this would normally be held on the level three mainframe computer with information relating to production such as efficiency figures which would be obtained from shop floor data collection systems.

A further decision made by management as a result of having real time information at their fingertips could relate to the percentage of rejected items in any batch. For instance, ten operators could produce 8000 items per hour of which 0.5% are below the minimum standard and thus rejected. By making available additional resources of say two operators the efficiency of the line could benefit and that percentage of rejects could be decreased to 0.2%. The increased effective productivity of the line could outweigh the cost of the additional labour allocated to the line and thus the profitability of the plant increased. It is obviously the goal of all production managers to have zero defects in their plants but without a clearly defined policy of quality and without investment in the tools for control and monitoring there can be little chance of identifying the areas where money is being wasted, for wasted it is. The integration of the various plant areas together provides the data necessary to identify the problems. It does not in all cases however supply the answers as

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to how defects may be eliminated, that is where management comes in. All decisions relating to resource optimisation depend on the following criteria:

- labour availability;
- raw material supply;
- production capacity;
- the market for the product.

An integrated system allows the management team of a production facility with multiple production lines to study production effectiveness. Having accurate information in real time affords production the luxury of exercising 'what if' scenarios in order to plan for eventualities.

8.5.2 *Manufacturing information*

With information derived from level one controllers combined with data from level three systems it is possible for a management information system at level two to produce reports and analysis. Typical of the information that might be processed is that shown in Table 8.1.

With the aid of historical information relating to a plant or production facility it becomes possible to forecast accurately the requirements in terms of time and resources to manufacture the various items needed. This has the benefit of ensuring the maximum usage of resources and inefficiencies in the system are eliminated.

8.5.3 *Material audit*

With increasing competition it is the plant manager's responsibility to ensure that the plant operates at maximum efficiency and effectiveness so that the product marketed is of the utmost quality within the specification and at the

Table 8.1 Information required and its likely source

Detail	Source
Total items produced	Level 1
Total items planned	Level 3
Total items possible	Level 2/3
Percentage efficiency	Calculated
Production hours available	Level 2/3
Production hours lost	Level 1
Production hours employed	Level 1
Percentage efficiency	Calculated
Staffing levels	Level 1
Man hours worked	Level 1
Man hours lost	Level 1
Overtime hours worked	Level 1
Plant efficiency	Calculated
Labour utilisation	Calculated

Key: Level 1: Plant controllers, Level 2: Plant supervisory system, Level 3: Production planning system.

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most economic cost. The need to know exactly how much of each raw material item or ingredient is used, how much is wasted and with regard to quality control, when and how it is used is ever present. We will touch only briefly on the quality aspect as this is covered in more detail later in this chapter. All raw material, whether it be cocoa beans, sugar or syrup, flour, biscuit or any other ingredient used in food production, has a life span before deterioration sets in and needs to be used within that span or discarded. An audit trail of raw materials, part processed products and 'final assembly' items provides management with the tools necessary to know that for instance the flour in hopper A should be used before that in hopper B.

Consideration should also be given as to how a material audit system can affect profitability by ensuring an accurate stock control procedure so that stock holding is regulated, its usage known and, using JIT principles, replenishment controlled. In very broad terms if there is stock on the shelf, that equals money out of the bank until the stock is turned into product and that product sold. There is, however, a balance as illustrated in the following real life example. A buyer for a car components company negotiated a very good deal whereby he obtained a massive discount on a substantial order which in practice would keep production supplied for many months ahead. There were however two major practical difficulties with the deal:

- There was insufficient space in the warehouse of the receiving company and insufficient manpower to deal with the impending delivery.
- The supplying company would have struggled to meet the specified delivery dates.

By implementing a material audit procedure the company were able to employ an order call off approach where the manufacturing system logged the item used. This was tied to production planning and the quantity of components required in the next delivery calculated. The supplier was then informed in time for him to schedule his production to comfortably meet the customer's requirements.

To cite a further example: in the wine bottling plant a material audit will know that x thousand litres of grape concentrate will produce under normal production planning y thousand boxes of wine. If at the end of a shift the management information system shows that either 50 more or 50 less than the production plan indicates has been produced the system can be used to show the region in which the error has occurred. The reasons could be an accumulation of a number of seemingly insignificant errors on each filling head, missed counts on a pack counter or inaccuracies in the concentrate dilution system. We realise of course that a fully integrated system would be utilising the information in real time to highlight the problem well before the end of the shift.

By the judicial use of the data collected by the MIS the root cause of the under or over usage of the concentrate can be established and corrective action taken. The quality of the product can be stabilised and the excess costs

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incurred can be eliminated. This closed loop control can only be achieved by the *total* integration of the plant.

In the same way a material audit knows that an alcohol-free brew of lager or beer has a much shorter shelf life than a keg of the brew before the alcohol has been removed. Keeping a record of when a batch is kegged, how long that keg is in the warehouse prior to delivery to the trade is obviously of prime importance to a quality manager. The number of times each keg is used is also important and a material audit trial can assist in determining the life of the keg.

8.5.4 *Quality assurance*

It is becoming or indeed has become a requirement for all design and manufacturing organisations, including food manufacturers, to implement quality assurance systems. This must not be confused with quality control, which checks that the product itself is manufactured to specification. To enable manufacturers to offer assurances that their product has been manufactured with quality in mind there has to be a continuous rigid quality monitoring procedure implemented throughout the whole of the organisation. This monitoring must be the norm in all areas and departments from administration, through production and dispatch. Records have to be maintained throughout the process and the key to any QA procedure is traceability. The ability to review all aspects of, say, the manufacture of a chocolate biscuit is essential to quality assurance.

This means that the source of the raw materials—cocoa beans, sugar or glucose, milk power, etc.—has to be known, the date of delivery, the batch number, the conditions under which the ingredients are stored are all of relevance to quality. The route that each ingredient takes from raw material infeed to final packaging is known and the processes that each ingredient goes through will be logged. If there is a need to look at the history of a particular chocolate bar those concerned have the resources to review the QA and product tracking together to identify any potential problems.

This method is not only useful in tracing problems or substandard procedures but if, for instance, a brewery produces a particularly good brew in a period then by looking at historical records of the production cycle during that period the analysis could be used to reproduce the same effect to repeat the quality previously obtained.

Typical information collated during the logging phase might be as follows.

Raw materials All data relating to the materials origin, its date of receipt, its storage conditions (extremes of temperature, humidity, etc., the duration of storage), the batches to which the material was directed and in what quantities. From these data the MIS can determine optimum usage, storage periods, and feed forward and feed back.

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Process parameters At each stage of the process all parameters affect the quality of the product. For instance, the length of time a chocolate mix is present in a conche machine, or the temperature curve in each zone of the oven baking the biscuit. Other parameters might include the humidity in the storage area of the biscuit, the speed of agitation of a mix of dough, the speed of a conveying line with specific regard to the pressure in the filling heads on a bottling line, etc.

Packaging and storage From the manufacturing lines the product, whether it be chocolate biscuits, soft drinks, beers or lagers, etc., has to be wrapped, bottled, kegged or bagged in some manner and then moved to an intermediate storage area prior to dispatch to distribution depots, wholesalers or hostelry. An integral part of the preservation of the quality of the finished goods is the conditions under which the products are stored, the length of time of storage and the ability to record parameters for future analysis is an essential element of quality control.

8.5.5 *Telemetry systems*

Often the constituent parts of a system are geographically separate. In the U.K. production scheduling may be in London, the process plant in Luton, canning in Manchester and distribution depots at seven or eight different locations throughout Europe. In the USA these functions may be in Washington DC, Pittsburgh and Atlanta, with distribution centres throughout North America and Canada. The physical distance between these locations requires that effective communication channels are established, and the correct information to be transferred is identified. It is vital that the correct level of information is identified; for example, if a production machine in Luton fails for a ten-minute period there would be no need to notify the packaging line management in Manchester. If, however, there is a total loss of output then production scheduling in London will need to be informed so that a complete schedule reevaluation can be undertaken and an alternative schedule can be prepared to minimise the loss. This evaluation might result in the complete rescheduling of production, possibly culminating in the manufacture of a different product which does not require the use of the out-of-service machine. The implications of these discussions would also result in probable modifications to both the packaging and the distribution arms of the organisation.

8.6 Summary

We can summarise this chapter by stating that achieving successful integration is possible, practicable and is not, for most plants, prohibitively expensive. The

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most important aspect to consider when deciding on integration is to answer the question as to who needs what information and in what form the data are most effectively presented. Integration is the bringing together of the various elements of a manufacturing plant to form a complete system that satisfies the needs of production staff, engineering skills and administration personnel at levels from the order clerk to the financial and managing directors.

As can be seen from the above list of elements that exist to be coordinated, the range of disciplines covered is extensive and diverse. Broadly speaking, the disciplines can be segregated into four main areas and all personnel affected by the implementation of integration should be given the opportunity to express their views as the design progresses. The four disciplines are:

- Product administration.
- Product preparation.
- Production.
- Storage and distribution.

Consideration must be given to the practical aspects of linking different areas of the plant together. This means selecting hardware that facilitates easy connection of other equipment to it. Consideration has to be given when ordering a new wrapping machine from Germany that it will be compatible with a bottling machine from Italy and the conveyor system from England.

Production scheduling forms a major part of management decision-making within food production. The industry tends to be more complex than many other manufacturing industries due to the unique 'shelf life' factor of both raw materials and finished goods. It is becoming usual for these manufacturing organisations to employ specific tools such as MRPII systems to assist with their effective production planning.

Specifically with regard to manufacturing each batch of product will require full production life-cycle tracking. This tracking allows quality audits to be carried out with ease.

In situations where production has been planned in an effective manner the plan must not become static and must be capable of reacting dynamically to events as and when they occur.

Material audits can show loss or gain in material volumes during production and again these highlight inefficiencies or possible quality control problems in manufacture. If the systems have been integrated properly the source of these problems can be easily identified.

With the aid of historical information regarding the ability of the plant to manufacture various products it becomes possible to forecast accurately the time and resources needed to manufacture the various items required. It may be possible to correlate various items of historical data and thus modify the future plant operation, e.g. if production efficiency is compared graphically against labour totals it may be found that there is an optimum cost effective manning level. Effective information provides management with the ability to experiment with 'what if' situations like this.

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9 Computer enhancements

DEREK SPENCER

9.1 Introduction

The purpose of this chapter is to explain more fully which hardware and software enhancements are likely to be of practical use in the control of food processing rather than detailed theoretical developments which may just be a practical proposition in five or ten years' time. The rate at which process control is developing also makes it highly likely that the ten most useful items in ten years' time probably have yet to be invented. However, what probably have been invented are the component parts which will make up that new invention. This has largely happened through market pressures, which if not started off then certainly have been given an impetus from the personal computer revolution. It is upon this general principle that the chapter will be based.

9.2 Background

Before looking at the likely enhancements over the coming years it is important to consider what is required and what to look out for on the road to achieving this.

9.2.1 *Why do you want a computer anyway?*

If you have not already answered that question it should be obvious that in terms of today's technology if the process cannot be expressed in words and pictures it probably cannot be fully automated. Bear in mind whatever the features of the process control computer used, whether it was difficult or easy to program and commission, it is left to two uncompromising interfaces for the rest of its life:

- the human interface (operator),
- the plant interface.

If they do not like it, no matter what technology is employed, it will not last.

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9.2.2 *Technology is well in advance of what you can buy*

If one is kept up-to-date with technical developments one may well be tempted to go out and look for a 'bomb-proof fifth generation computer', using parallel transputers based on galium arsenide chips with RISC software. If not even a word of these terms is understood, read on, because they are explained later. However, even if they represent some of the latest advances it is highly unlikely that they could be bought in one processor (even at a cost) because they have been mainly developed by separate companies who do not necessarily want to share their technology.

9.2.3 *Who is going to specify and program the automation?*

This is another question which has already been touched on in previous chapters. (Who specifies the process control? Obviously one who understands it.) Software and hardware developments are now reaching a stage where it is possible to incorporate the knowledge of the process control engineer with that of the computer programmer, neither of whom generally understands or sympathises with each other's jobs.

Take for example the PLC (programmable logic controller) programmed in relay ladder diagram. This replaced sequence relays in the automotive industry. That is fine when the process contains lots of sequences as in conveyors and packing lines, but how many relays are there in the chocolate temperer, steriliser, evaporator, etc?

The power and size of the computer is becoming such that it now has sufficient memory and speed to be able to talk to the process engineer in his or her own language without vast cost implications or sacrificing of necessary functions. Systems which allow direct 'programming' are now coming onto the market to work alongside the existing technologies and put the process engineer back in control.

9.2.4 *Who is going to maintain the system?*

Once again the advances in technology make a system available which will probably have sufficient self diagnostics to be able to identify an electrical/electronic malfunction, thus allowing an electrician with the basic knowledge of handling electronic components to change the faulty module. Reliability of modern electronics is generally such that failures are comparatively rare and self diagnostics are therefore vital.

Despite the often quoted phrase 'The computer has failed', after initial commissioning the electronics will not usually fail unless they are used incorrectly. It is far more likely that an electro-mechanical failure will be the source (e.g. a wire breaks, solenoid gets stuck, etc). Even if the particular system being installed does not yet have diagnostic capabilities beyond identifying

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which of its electronic modules are at fault there are PC-based packages coming onto the market which interface to existing installations which show diagnostics, fault recording and plant downtime monitoring without the maintenance engineer having to leave the office.

9.2.5 *The push behind current developments*

To the process control user it may appear that the major suppliers of automation for the food industry are already being pushed, but that is only part of the scenario. The suppliers of the equipment used in turn depend on hardware and software developments from major corporations and countries who may not have process control in the food industry very high on their list of priorities.

As an example the government-backed Alvey Programme has its origin in the announcement of the Japanese Fifth-Generation Programme for Artificial Intelligence in the autumn of 1981. The Alvey Programme started in 1983 along with other Fifth-Generation Programmes, notably in Europe and the USA, in order that a competitive situation could be maintained. This principle follows all the way through from government, major component suppliers, system and software suppliers to system integrators, all leapfrogging each other to maintain the best possible commercial position.

By the time all this technology gets to the user it may not be the very latest, but it should at least be tried, tested, fairly stable, and above all useful.

9.2.6 *State of the art: what does it mean?*

State of the art should mean using all of the commercially available recent developments, but it can mean merely that the particular supplier of the equipment is using the phrase to make his product sound good.

9.3 Hardware enhancements

At the rate hardware has been developing, if projected far enough into the future, it would eventually be given away free with the software. This of course is not a good situation for the hardware suppliers and so the most likely trend for the next five to ten years is that hardware will not decrease much more in price but it will significantly increase with regard to facilities and performance.

There are equally strong signs of standardisation to the degree that hardware of different suppliers will work together without major problems and that all hardware will progress to a more open style of architecture so that modules can just be added. The areas of communication standardisation have already been mentioned in previous chapters, but there are signs that organisations are gathering together to maintain standardisation and there-

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fore interchangeability with each other's product. For example, AIM (automotive identification manufacturers), which is working towards international standards for scanners, printers and detectors, not only in bar code or optical recognition form but any alternative technologies achieving the same purpose of identification. Unfortunately, experience to date has shown collaborations of this type to be less than successful, if well intentioned.

9.3.1 *Miniaturisation at operator and plant level*

Hardware development has gone and will continue to go in the general direction of more memory and faster speeds right up to current physical limits, after which new materials and methods will inevitably bring another step change. The most significant utilisation of the evolution of greater, faster memory for the same price means more space for user-friendly software which talks your language (as opposed to computer language) and which still has the speed to cope with your process.

Although miniaturisation has distinct advantages at the processor level it can only go so far at the point of interface with the plant and the human interface; indeed there are some who would say that miniaturisation at the operator level has already gone too far. These people will still insist on using the wall plant mimic even though it is actually more costly and far less versatile in construction than video mimics. Taking the plant mimic as an example, the amount of data viewable on a screen, has, up until now, been limited by the number of pixels (dots) on the television screen and no matter how big its physical construction the definition limit has been in the order of 1000×1000 pixels.

Recent developments especially in LCD (liquid crystal display) technology are breaking these barriers so that adequate definition can be achieved and a full-size, programmable wall mimic display will soon be available.

At the plant level, the size of the input/output (I/O) termination areas has changed little in the last fifteen years. This is due to two basic facts:

- The actual connection to the sensor or more particularly the actuator uses a finite size of cable.
- The segregation (electrical isolation) required between individual circuits on the same card needs the physical distance unless it is to be made of significantly more expensive materials.

Since there has been little market pressure to miniaturise in this area it is unlikely to change in anything but highly specialised applications for many years to come. Whatever happens, both the plant and the operator are going to require a system which is environmentally bomb proof, does not have to be treated like a new-born baby, and can be cabled up and maintained by people with standard sized hands!

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9.3.2 *The rate of development for speed and size of processors*

The key term is VLSI (very large-scale integration) which has meant the inclusion of enormous amounts of otherwise discrete components (e.g. transistors, resistors, etc.) into one single chip. Within today's technology this has its finite limits, as opposed to software development, for example in artificial intelligence, where development is not bounded by physical properties.

It is much easier to make predictions for hardware development, as the technology of VLSI depends on the certainties of physics, rather than on the uncertainties of man's intellect to understand and imagine, as does artificial intelligence.

In order to improve performance, both in the active element capacity and more fundamentally in the speed of VLSI, higher packing densities have to be achieved. Moore's Law—that heuristic law that predicts a doubling of the memory elements on a chip every year—has held now for some twenty years of integrated-circuit growth in complexity. At the start of the Alvey programme in 1983 line widths on the chip of about 3 micron were current and the 256 bit DRAM (dynamic random access memory) was just coming into use. The programme targets were to achieve 1 micron resolution in five years by 1988, and like virtually all LSI targets, that was achieved. Now the market standard memory is 4 Mbit on a chip, with 16 Mbit in the development laboratories.

The European Jessi project calls for a 64 Mbit chip to be achieved in the laboratories by 1996. For that, progress will have to be even better than the predictions of Moore's Law, but no one seriously doubts that 64 Mbit will be achieved, even if the target of 1996 may be optimistic. One can argue that the world competition, especially from Japan, is so strong that without an ambitious target there is no point in Europe embarking on the Jessi programme.

There is no question that there is a physical limit to growth for integrated circuit performance since the lines are becoming so narrow that the normal laws of conduction will break down as the number of atoms across the line becomes too few to sustain low resistance. This lies at about 10^{11} components per chip at, say, 0.05 micron line width. The technological limit is probably at about 0.1 micron so the maximum packing density is, in practice, at about 10^{10} components per chip. About 128 Mbit per chip therefore seems to be the limit. Figure 9.1 shows the progress over the years towards smaller and smaller elements.

There could be several possibilities for transcending these limits:

- To use a material with a faster inherent switching speed, typically gallium arsenide. This will give faster elements, not more elements on a chip.
- To use wafer-scale integration to enlarge the chip, by introducing

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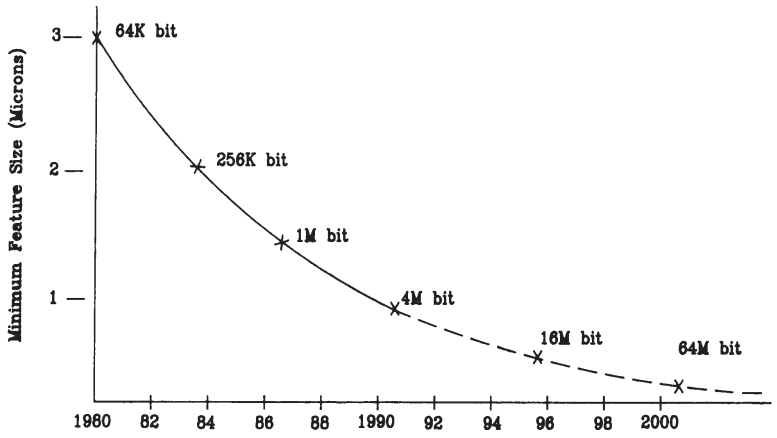


Figure 9.1 Progress in number of memory elements on semiconductor chips

redundancy to overcome the faults inevitable for an acceptable yield rate on the chip surface that will arise as the surface area is allowed to grow.

- To use a so-called warm superconducting flash over the lines to minimise the resistance.
- To use opto-electronics which surpass both the speed and interference problems posed by electronics.

However, it is clear that there is still another ten or 15 years of continuing growth in conventional semiconductors. That means that the standard PC will grow in power by a factor of at least 100, perhaps 1000, by the turn of the century, with memory capacity that could be up to 100 times the current provision—all, of course, at no extra cost. What we will do with all this capacity is another question—possibly much of it will go on improving the human interface.

9.3.3 *Transputers*

If they have not been included in this chapter someone would have complained; however, they are still a component and only useful if properly integrated into a processor so that the process can be better controlled. The transputer was developed in the early 1980s by a team at Inmos. The transputer is, essentially, a powerful microprocessor on a chip—but equipped with four broadband communication paths, making it the ideal element in an array of parallel processors. Figure 9.2 shows how these are typically arranged.

Various firms in the UK, Europe and the USA have now put parallel machines on the market using transputers. One machine of considerable interest is the Supernode, which was primarily developed by Southampton University and RSRE, in the first place assisted by a study grant from the Alvey programme, and then under the Esprit programme. It is now on the market from Parsys (essentially Thorn-EMI) in the UK, and Telemat in

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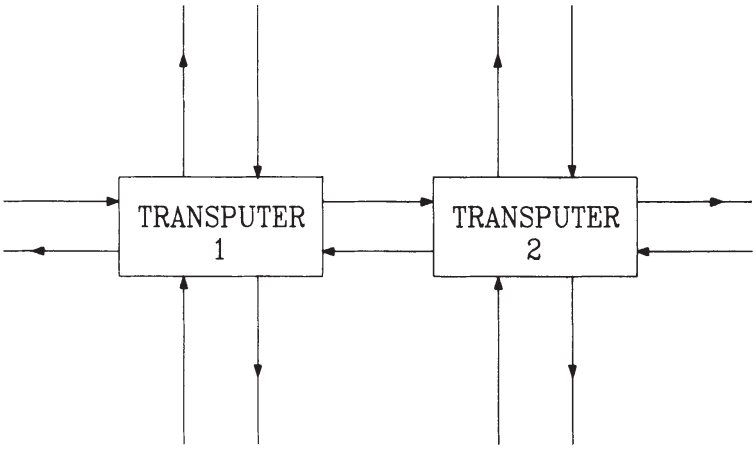


Figure 9.2 Transputer network using bidirectional communication path

France. It has been suggested the Supernode is the first machine to come to the market from any of the Fifth-Generation programmes.

9.3.4 *Parallel processors*

Parallel processing has been with us for some time now and should not be confused with multi processing. Parallel processing means splitting a task into many parallel activities, whereas multi processing means executing several tasks at the same time, usually in separate processors. The market for parallel machines certainly exists, and image and speech processing will not become widely used until such powerful parallel machines are available at an acceptable price.

For calibration purposes, it is sobering to look at the development of what are normally thought of as the most powerful computers, the Cray series, though versions with more than one processing stream have been available for many years. The Cray's architecture essentially depends on using the most powerful components that are around, using a highly efficient pipeline processor so that floating-point vector operations can be carried out extremely efficiently, and all other operations, at least as fast as the fastest of conventional processors.

The multi processor facility has been used for handling several jobs at the same time, rather than breaking one job into its parallel streams. But with the number of processing streams predicted to grow to 64 for the Cray 4, due in the mid 1990s, one must assume that some degree of true parallel processing will be deployed. Incidentally, the Cray 3 will be the first machine to use gallium-arsenide components rather than silicon in the quest for speed without too much power consumption.

It is as well to remember that a massively parallel processor was built in the UK in the 1970s and has now accumulated more applications software than any other parallel machine. The digital array processor (DAP) was first put on

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the market by ICL, and is now selling well in the USA, as well as Europe, through AMT, Associate Memory Technology Ltd. The latest version contains 4096 elementary processors, and the machine is ideal for 'SIMDY' working (single-instruction multiple data) of the image-processing type for example.

9.3.5 *Multi processors*

As stated above, multi processors can execute several tasks at the same time, and may well include processors which themselves have parallel processors. These in turn may use transputers as the actual chip or at the very least employ the latest VLSI technology to give maximum capacity and speed to process control. Multi processors have been most evident for the food industry at the PLC (programmable logic controller) level where, since about 1979, GEC first brought onto the market their GEM 80 which had the individual tasks of video, ladder diagram and communications being handled by separate processors all with access to a central highway for process information and database.

9.3.6 *Dual systems*

Dual systems have been with us for some time, in the sense of one processor in a standby mode waiting to take over in the event of a failure of the other. This has extended to the logical situation of triple systems where high integrity and safety are of utmost importance, as in the nuclear power industry. Before going on to describe some of the enhancements now available it is best to consider why a dual or triple system is required in the first place:

- loss of data is unacceptable;
- loss of production is unacceptable;
- safety implications;
- a combination of all the above.

9.3.7 *Dual standby systems*

These can be computers, PCs, PLCs or any combination but basically consist of one device waiting to take over the task of the other if it should fail. This is normally decided by the state of the watchdog circuits which trip the machine in the event of a catastrophic failure. The second processor will have been keeping itself entirely up to date and is therefore ready to take over without stopping the process. This technology has been around for some time now but is made easier by the availability of faster and more secure switching circuits. The principle is generally suitable for saving data and reducing downtime, and is shown in Figure 9.3.

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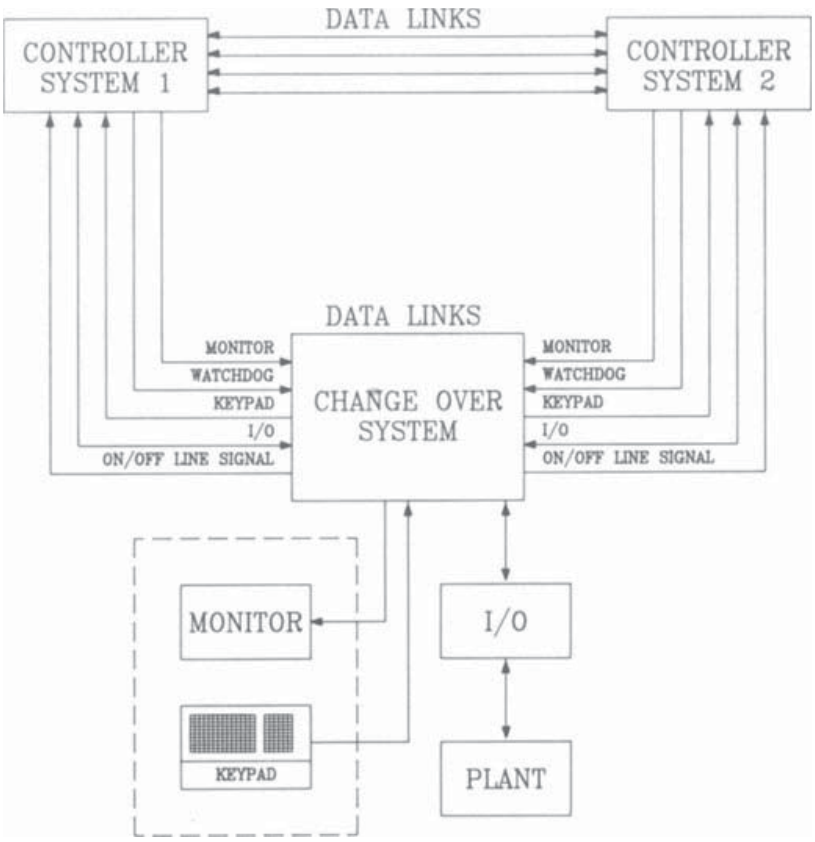


Figure 9.3 Changeover system

9.3.8 *Dual and triple redundant systems*

These systems can be described as having two or three (or more) of everything and are specially configured to keep running even though the failure may have occurred in one of the duplicated (or triplicated) circuits as shown in Figure 9.4.

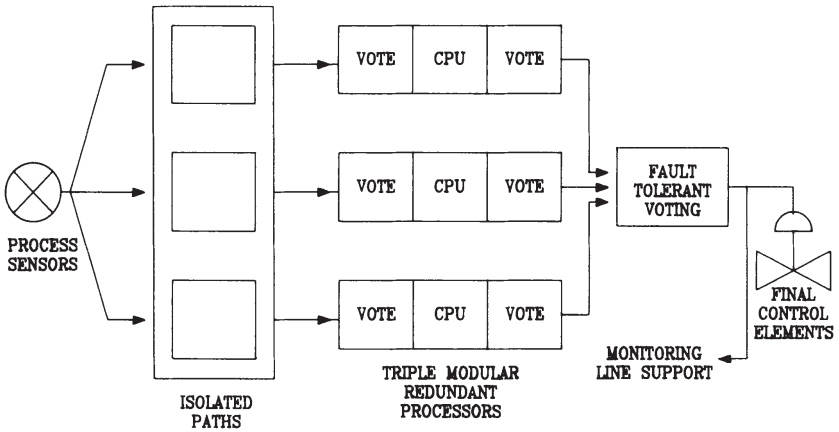


Figure 9.4 Triple modular redundancy

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Apart from specialist safety-biased industries such as nuclear or petrochemical, banking seems to have been the market impetus behind the first purpose built and commercially available dual redundant mainframe computers (Tandem and Stratos are two well known systems available in the UK).

Because of the advances in micro-chip technology, PLCs were not far behind in being able to provide the facility of triple redundant systems at not very much more cost than single systems (e.g. not three times the price). The UK manufacturer August Systems has a fully triplicated PLC which can be programmed in both ladder diagram and other popular control languages and can be triplicated on a two-out-of-three voting system transparent to the user except in times of failure. Earlier systems had to effectively be programmed three times and relationships between programs worked out by the user.

9.3.9 *Inventions still waiting for technology to catch up*

Despite the fact that the trend is towards large capacity, faster, cheaper processors there are quite a few devices on the market which were invented just ahead of their time and only with the next impetus of speed and capacity in VLSI technology will they become commonly used. The following elements represent an indication of some of these:

Vision processor Vision processors have been on the market for several years, using parallel processors, but still are not fast enough or cheap enough for common use for in-line food processing. The reason is because of the sheer amount of data which need processing to take a yes/no decision on a production line which is likely to be moving at more than 600 items per minute.

If items are running at 600 per minute there are just 100 milliseconds to identify the fault and remove the item. If 100 milliseconds sounds a long time in computer terms think of the picture, only defined down to a 256×256 dot matrix and each dot to only 64 levels of grey (not colour), scanned by 256 parallel processors—taking the picture from the camera into the memory alone would have absorbed about 20 milliseconds, with each mathematic function performed on the stored image about another 20 milliseconds. You do not need to have a very complicated decision before 100 milliseconds is used up. These figures are based on actual equipment available about three years ago. Therefore between now and five years' time the speed, memory and camera development rate will be sufficient to bring an intelligent vision computer peripheral onto the market cheap and fast enough to be used on line.

Speech recognition Although also around for several years they are still waiting for memories large enough and fast enough to interpret all the variations in a human voice. It is still faster and more accurate to push buttons

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at the moment, although there are some impressive examples of its use around, and whilst these have a limited vocabulary at present they do indicate the benefits which will accrue.

Voice synthesis The inverse of speech recognition, voice synthesis is well developed already, but then the receiving device, being human, is a lot more intelligent!

Biological sensors A lot of important and useful work has been carried out by research associations (notably the Leatherhead Food Research Association) and a few commercially available sensors are now on the market which use the action of the biological process to produce an electrically measurable signal which can relate directly to the chemical composition of the product (amount of sugar in a solution, for example). Since the sensors are biological they are also biologically degradable and tend to wear out in about three months. Future developments should cure this problem.

Acoustic measurement This measurement is simply taken by measuring the noise levels at certain frequencies to determine whether a process is proceeding correctly, finished, etc. Practical application of this method has been carried out at Rolls Royce and this has been further researched at LFRA to relate the technique to food applications. An example of this was a CIP (cleaning in place) process which was probably kept going for much longer than necessary—just to be safe. However, it is noticed that when the cleaning had been completed the noise pattern changed, although the process continued for some time as a safety margin. If this change had been electrically measured by a strategically placed microphone sensor, the cycle could have been terminated earlier, thus saving costs without any health risk.

9.3.10 *Production methods*

VLSI enables fewer components to be included on a printed circuit board but the actual method of production is enabling more automation to be used and hence lower cost. The most significant aspect of modern production is surface mount technology which basically means that all (or the majority of) components in a PCB are placed on the surface of the board automatically by robotic devices and soldered in automatically. This makes the production of the PCB almost automatic, connections are made to a guaranteed standard, and the overall reliability of components is steadily improving.

The production of PCB for the automation controlling of the process is probably using some of the same technology employed in most process control for the food industry, certainly personal computers, robots and now vision systems. In all this gives a PCB which has guaranteed quality with few external connections liable to fail and is an overall reliable product.

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9.3.11 *Adaptive control*

Adaptive control is usually referred to in terms of process automation which can adjust to any new requirements in order that plant control is kept at an optimum level.

Although adaptive control is becoming well known, the reason for including it in this section is based on the fact that apart from perhaps the self-tuning controller these techniques need more and faster memory than is currently available to make them sufficiently user friendly so that the process engineer (as opposed to the programmer or the mathematician) can use them with confidence.

The usual reasons for requiring adaptive control in the first place are for example:

- Ageing or gradual malfunctioning of plant.
- Variable disturbances, e.g. ambient conditions or quantity of material being processed.
- Changes in transport delays due to physical movement or substances.
- Plant modifications, for example a new part.
- Non-linear characteristics such as plant characteristics vary as operating conditions change.

Adaptive control itself is also divided in three distinctive areas, gain scheduling, model reference control and self tuning control.

Gain scheduling Gain scheduling makes use of a look-up table of controller terms so that the controller is set to the best value for each range of measured values. For this to operate effectively the full range of gain settings over the entire plant operating range must be in memory and a gain value must be provided to cover every circumstance.

Model reference control Although gain scheduling is simple to operate it is extremely difficult to obtain the high-performance results often required by the overall control system. Where a number of performance objectives are specified, which is normally the case, the criteria for controller selection can be considered in an exact mathematical form so that a complete control system design can be carried out; that is, that there exists an ideal model which performs in the desired fashion. The plant under control can then be compared with this ideal model and a control system design carried out in order to force the plant to perform like the ideal model. This is in fact the basis for model reference control.

Self-tuning control This term should be self explanatory in that the loop being controlled, usually by a three term controller, continuously adjusts itself to maintain optimum values. This is an example where peripheral devices such

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as single loop three term controllers can have sufficient processing power within themselves to have a reasonable mathematical model in place.

9.3.12 *Opto electronics*

Fibre optics for communications was probably the first visible sign, although opto-isolation or optical diodes have been used for many years to provide isolation between electrical circuits which otherwise would have meant greater physical distance or more costly isolation material between circuits. The basic principle of opto electronics is that signals are processed into a light form which is faster and more noise immune than electrical or electronic equivalents. There are a number of areas where the use of light will enhance the overall performance of systems:

Data storage The famous CD (compact disc) is a form of optical storage since the signals are read off by light and cannot be interfered with as in magnetic storage. IBM brought out an optical disc for data storage about six years ago with the advantages of large capacity (about 340 Mb) but with the disadvantage that it cannot be re used and overwritten as with magnetic discs, since it altered the surface of the disc irreversibly. This is referred to as a 'WORM' disc —write once, read many. This is fine for long-term storage of data, and since the discs are removable one ends up with process data saved on the equivalent of CDs. Other manufacturers have improved on this and now 800 M bytes of storage on one disc is available.

However, the technology is changing once again and read/write discs are becoming available. One must suppose that they will eventually replace the Winchester Discs in common usage since they need no physical contact and have greater capacity. However, the Winchester technology has been very reliable, compact and will take some displacing.

Communications As remarked at the start of this section, optical fibre communications have been here for some time; however, the main problem was always how to make an optically perfect joint (soldering is fine for electronics). This problem is now more or less overcome and opto-electronic communications will bring faster, broader band, noise-free technology to all process control soon.

General processing enhancements GEC Hirst Research, to name but one UK organisation, have already developed opto electronics on a 'chip' to the level that it will bring faster, more powerful processors to the market already surpassing the electrical boundaries imposed by electronic technology. It is not expected to be in factory use for the next five years, but at least the method now exists in research establishments.

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9.3.13 *Intelligent peripherals and input/output*

This paragraph could have been a chapter or even a book in itself, but will be restricted here to an outline of what is obtainable now and is becoming available. The main reason for wanting intelligence available away from the central processor is continuous need for cheaper, faster, smaller micro processing electronics which enables intelligence to be economically located in any device large enough to have its own power supply and standard communication link back to the centre.

The trend started with obvious peripherals such as printers and operator terminals, but now has extended to sensors and I/O, which all save in both central processing load and cabling costs. Take for example remote I/O which enables racks of I/O cards to be located close to the plant into which they interface, thus saving a massive amount of parallel cable runs which now need only run a few metres to the I/O racks, which in turn are then serially linked back to the central processor on only four conductors (or fibre optics). This has now been extended to 'smart' I/O blocks which are in themselves termination racks and can be configured for basic decision taking before communicating with their controlling processor, thus saving on cabling, processing time and possibly cubicalisation since the modern format is for robust modules which can be located directly onto the plant devices in question. Two examples of currently available PLC compatible ranges are GEC GEMSMART and GE GENIUS.

It is no longer a large financial implication beyond the initial development for the manufacturers to make peripherals intelligent and this trend will continue where advantages in operating speed, costs and safety can be gained.

9.4 Software enhancements

Software is generally looked on by the process control engineer as a necessary evil which has to be tolerated if automation is going to be achieved with any degree of flexibility close to the requirements of his plant. That was generally true until recently when the hardware gained sufficient capacity and power at the same cost to make the software more user friendly. As it becomes more user friendly so personnel other than computer programmers will use it—for example, word processor and spreadsheets on personal computers are now commonplace and used throughout industry. This in turn has meant more standardisation so that software can be interchanged. Software generally refers to a program which has been written at some time by a computer programmer and is loaded into the computer (processor) so it has instructions on how to control a particular process. Table 9.1 gives comparison between the various 'levels' of software which are available, together with an indication of what experience is required to use them. The software may take several forms varying from pre-written software which give the basic facilities to

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Table 9.1 Software comparisons

High level	Medium	Specialist	Assembler	Machine code
←——— Not machine dependent ———→			←——— Machine dependent ———→	
Statements powerful but not flexible	Simpler statements but able to use library of facilities	Very simple statements relating closely to actual end process	Very flexible but not statement powerful. Efficient in space and speed	Very efficient, fast and flexible
Generally needs programmer experience	Generally needs programmer experience	Application engineers can program without special computer knowledge	Needs very special programming skills	Totally unintelligible by anyone other than expert in a particular machine
Examples —PASCAL —FORTRAN —Forth	Examples —'C' —BASIC	Examples —Ladder —Grafcet —Icon	Examples —Relate directly to actual computers, e.g. ICL assembler codes	Examples —Relate directly to actual computers, e.g. Intel 8086

All software is eventually compiled (converted) into machine code to actually run

make the computer usable at all—to self-contained packages which allow a non-programmer to use the computer—as in the use of a word processor or spreadsheet for example.

Most software is loaded into the machine via some storage media such as floppy discs or cartridge tape, but there also exists another variety called firmware which is pre-programmed software residing in non-erasable memory on integrated circuits or programmable read only memory (PROM).

9.4.1 *Standardisation*

Greater use of software has promoted standardisation. As an example the operating system for all IBM compatible PCs until recently was MS-DOS (microsoft-disc operating system) and therefore everything had to work with that operating system. Unfortunately MS-DOS is not multi-tasking (it has to do one job at a time) and is limited in its use of memory. This causes problems as far as any serious process control is concerned. There was also the UNIX operating system which was multi-tasking and can use more memory but hardware had not developed sufficiently for its use on anything but larger mainframe or mini computers such as the DEC VAX range.

Now there are sufficient advances to enable us to run UNIX software on PCs (386 processors for example) and this appears to be establishing itself as an international standard for the immediate future at least.

Other standards seem to be formulating, such as X-WINDOWS for display software, and OSI for communications software. The general idea is that soon

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all packages should be interchangeable by use of common operating systems, displays and communications. Bodies such as the OSF (Open System Forum) are tending to establish this pattern in the USA, and now in the UK, to give the user more choice and to be far less likely to have invested in a machine (processor) and software which cannot be upgraded after a very short life.

9.4.2 *Software developments*

The main developments have not necessarily been in the direction of new languages but more in the development of packages using perhaps several high level languages to make up one user friendly piece of software which can run on readily available hardware. These packages have varied from the database, spreadsheet, word processor type which are generally used for MIS (management information systems) to graphic data acquisition systems which give an easy-to-read, easy-to-configure supervisory picture of the plant control to computer-aided process engineering which enables the process control engineer to program the plant controller or PLC in a language closely resembling the actual physical process to be controlled. The latter type of package is the most significant enhancement in real time control in recent years and will become more commonplace.

9.4.3 *Management information systems*

There are many commercially available packages which most people will be aware of such as spreadsheets, word processors and database programs which allow a non-specialist to manipulate, store and retrieve data in the manner most useful and understandable to him or to herself. Most of these packages are designed to run on IBM PC compatible under MS-DOS but there is a general trend towards making these packages available on the more powerful PCs, VAXs and workstations running under other operating systems such as OS/2 and Unix.

The most significant development has meant the availability of more purpose-written management information system type packages which relate more directly to the process control industry and gather the data direct from the actual process as opposed to manual entry; this leads on to the data acquisition or SCADA (supervisory control and data acquisition) packages which tend to do that gathering.

9.4.4 *Data acquisition and SCADA packages*

These packages have existed for many years as part of the distributed control system (DCS) available from all of the well known and traditional manufacturers of process control (e.g. Foxboro, Honeywell, Taylor, etc.) but over the

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last three or four years PC and VAX packages have become freely available in the form of user-friendly, configurable SCADA systems linked in to PLCs or micro controllers at the plant level. This has made the supervisory level more supplier independent but has meant that the purchaser has to know more about the interfaces unless the services of a systems integrator are employed.

9.4.5 *Computer-aided process engineering*

This latest form of package has only just become commercially available at the more economic end of the market which integrates the writing of the software at the plant level, through the supervisory level up to management information systems all into one.

The principle of these packages is pictorial, similar to CAD (computer-aided design) techniques, but takes it further into the production of executable process control of the plant level without using any obviously 'computer'

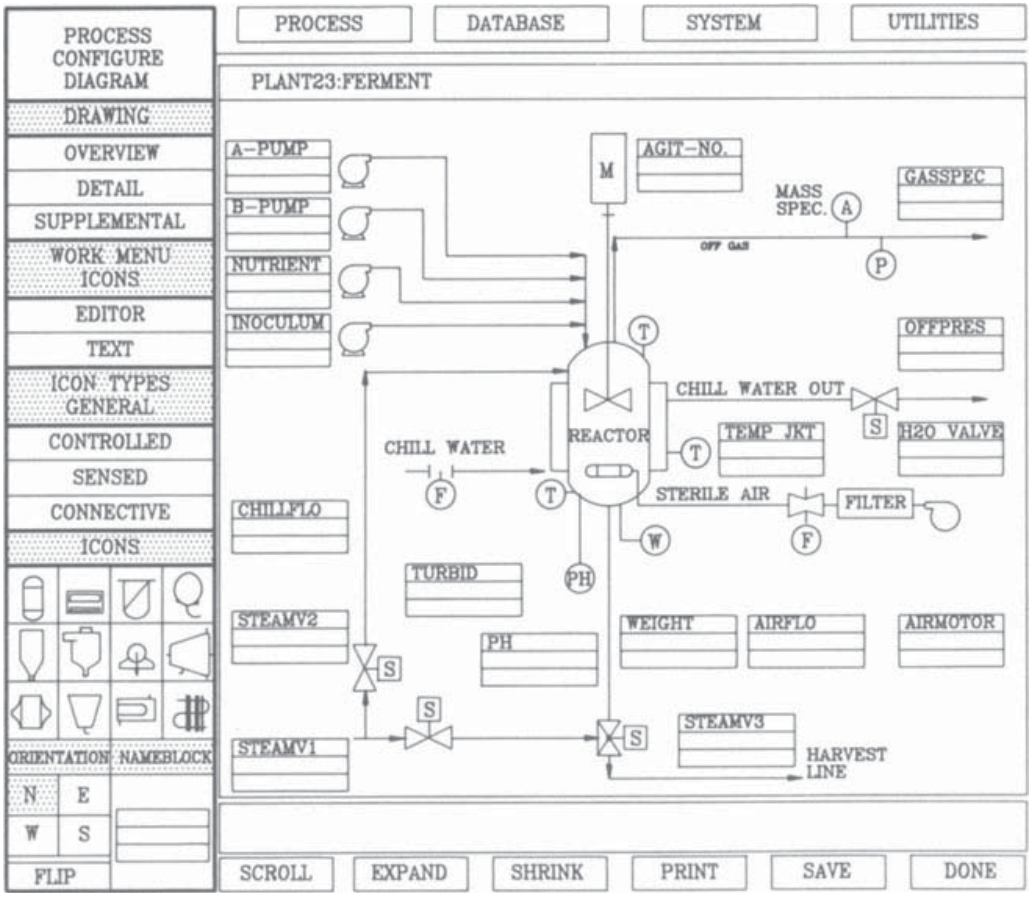


Figure 9.5 Computer-aided process engineering—drafting the flow diagram. The process flow diagram is drafted on-screen by pointing and checking over standard ISA process symbols

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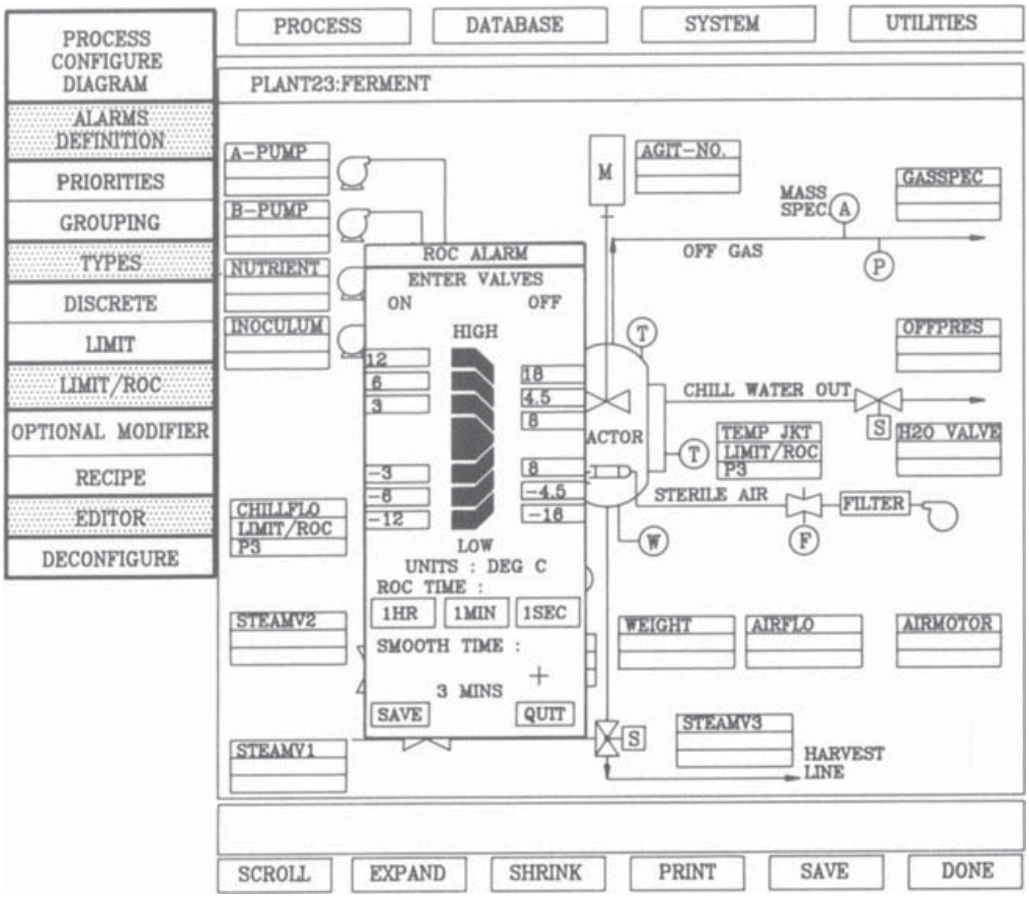


Figure 9.6 Computer-aided process engineering—select and specify settings. The engineer selects points to be alarmed and specifies alarm type, high and low levels and priority

languages, ladder diagrams or the like. Examples of this format are shown in Figures 9.5, 9.6 and 9.7.

This new class of software product uses the graphical interface to configure the process control strategy. The methods are applied to design and evaluation of a sequential, batch, continuous or mixed process scheme. The engineer simply draws on-screen a standard process flow diagram and then overlays the usage of the plant equipment with a state-machine sequence and diagrams of closed loops.

Graphical interfacing dramatically lessens the engineering time and effort normally required to implement and support such a system. Only control and process engineering experience is required with the system.

All aspects of plant control are available from this type of package, from the design and configuration of the operator's graphic formats, through PID closed loop control, report and alarm generation, I/O point allocation and identification to automatic system documentation. This cuts out the need for the process engineer to interpret his thoughts into graphic, ladder diagram or any computer languages.

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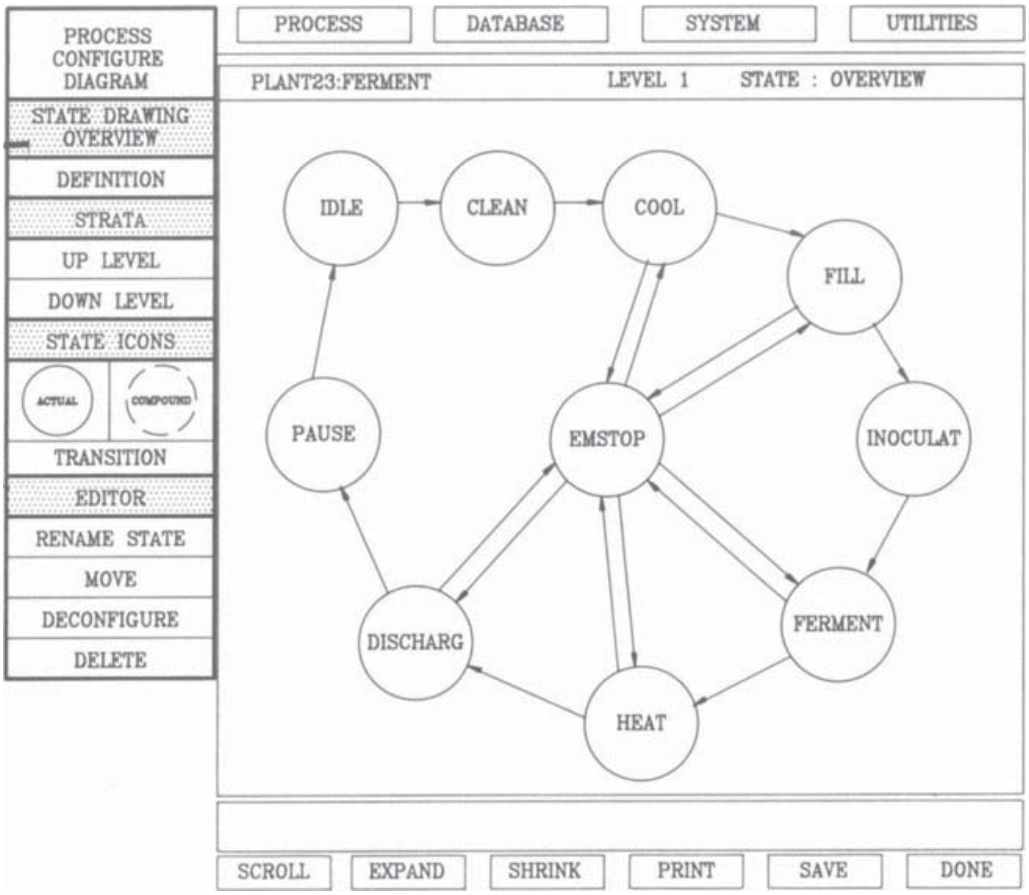


Figure 9.7 Computer-aided process engineering—link the modules together. The states diagram shows the sequential steps in the process: circles are states and arrows are transactions

9.5 Hardware and software together

As mentioned earlier in this chapter, hardware is on course to be provided 'free' with the software in about ten years' time if the present trend continues. On the other hand, software written by specialist programmers is becoming more expensive as wages rise. Nevertheless, if suppliers of process automation want food process engineers to buy their equipment it needs to be sufficiently economical (cost effective) in the first place, and therefore easy to use so that process control skills do not have to be continuously translated into computer language to make it work.

9.5.1 *Reduced instruction set computers*

Reduced instruction set computers (RISC) are an attempt by combining hardware and software solutions to speed up computers without the major changes otherwise required to existing technology. They achieve this by

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reducing the number of software commands available to, or used by, the computer to the minimum. This is possible in practice since all developers of software languages design their systems to be all-encompassing, and will include instructions or routines which the majority of applications will rarely if ever use.

A RISC machine removes these instructions from the 'main' system with a consequent increase in speed as it takes shorter time to access any required command. The other, infrequent instructions are stored in an 'auxiliary' system where they can be accessed but more slowly than before. However, since they are used infrequently this slow response is not significant to the computer's performance.

9.5.2 *Computer integrated manufacture*

The manufacturers of automation equipment sometimes give the customer the impression that the barriers to implementing this new technology are merely technical. In fact, the very idea of computer integrated manufacture demands that the firm develop a coherent strategy for its manufacturing operations.

A manufacturing strategy demands in turn that the firm's overall strategy will be developed and executed. Top management has to evaluate, in a commercial sense, the role of manufacturing in the long-term plan. This evaluation can be quite subtle. For example, consider the question of manufacturing flexibility. There may be a requirement to achieve the lowest cost production. Alternatively, there may be a need to balance low cost with a high degree of responsiveness to rapidly changing market demands, or to systematically improve quality levels. One set of solutions will not accomplish all these objectives. Table 9.2 indicates the various applications which may be adopted within a CIM scheme, together with the likely objectives or outcome for each.

The investment steps taken towards each of these objectives are likely to be quite different. There has to be a practical limit to how flexible a manufacturing system can be because the cost of very extensive flexibility is very high.

9.5.3 *Factory of the future*

The 'factory of the future' is a collection of technologies which are popularly grouped together by writers in the field of factory automation. The most significant of these is computer integrated manufacturing. CIM is central to realising advanced manufacturing techniques; it describes a cohesive computer data base and communications system which integrates all the functions in manufacturing: process control, manufacturing product design and production planning.

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Table 9.2 CIM objectives and applications

Applications	Shorter development cycles	Improved quality	Reduced inventories	Flexibility	Automation of small batches	Lower overhead expenses
Group technology database	YES					
Forecasting			YES			
Simulation languages				YES		
Query languages				YES		
Computer aided process planning	YES				YES	
AI/expert systems	YES					
Mathematical programming			YES			
Statistical analysis		YES				
Structured analysis	YES					
Solids modelling	YES					
Graphic parts database	YES					
Design drafting	YES					
Interactive graphic simulation				YES		
Links to NC, robotics, test equipment		YES			YES	
Drawings data base	YES					
Document production and retrieval						YES
Technical publications automation						YES
Production database			YES			
Materials requirements planning MRP1			YES			
Manufacturing resources planning MRP2			YES			
Distribution requirements planning DRP			YES			
Shop floor control				YES		
Despatching handling control					YES	
Statistical process control					YES	YES
Adaptive control		YES			YES	YES
Energy management						YES
Maintenance management						YES

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CIM aims to capture information and share it throughout all areas of the factory, and down through all levels of process control, from the automatic control of a single switch to high level decision-making about production volumes. CIM is radical in its vision, but has to be implemented in an evolutionary way. The most effective approach identifies individual localised projects with a high interim payback.

Descriptions of these new technologies are often accompanied by photographs of shiny new robots, which did not exist twenty years ago. Photographs can be misleading because they focus on objects. In fact, it is the integration of information and coordination of efforts which are central to advanced manufacturing methods. CIM is an information technology. So while robots, multi-colour computer screens and automatic guided vehicles are manifestations of a new generation of factory equipment, they are not central to the concept. If we pause to think about it, the Japanese were developing systems of plant communication like just-in-time inventory management (JIT) in the late 1960s and early 1970s. They did this armed only with pencil and paper, and without the benefits of the new process equipment technology we have today.

9.6 Summary

The revolution of economic, user friendly process control systems has already begun and will continue for some years to come. These offer great prospects for improved systems performance and consequently greater returns for those who invest in them.

It is obviously important that we do not automate for automation sake, but also that we do not wait too long. We can always wait for the next generation, model or version of process control equipment and in the meantime the process may be costing more than necessary to control. We must make sure that however innovative the new hardware or software enhancement is, it does come within the boundaries of the developing international standards, or at least we should check that there are no disadvantages in not following one of these standards.

As a final word of caution, if the enhancement is so new and innovative make sure that the supplier is likely to be around in a few years to come!

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10 Expert or knowledge-based systems

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10.1 Introduction

Knowledge-based systems are increasingly used in production engineering. Unfortunately, for those who do not have a background in artificial intelligence, the territory occupied by such systems is new and peculiar. Many a manager has started out on the path to expert systems, perhaps because of a successful application in a related area, or just because a lot is written about this new technology and it seems worth investigating, but the uninitiated soon find that the inhabitants speak a different language and, worse, cannot agree among themselves about the appropriate way. And so many a project has been abandoned that might have been successful.

However, commercial guides were available but they went to the other extreme, suggesting that anyone who could write English could write an expert system, dismissing the need for serious engineering standards to be applied to expert system projects and generally persuading the gullible with the assurance that they would very soon be successful, given just a little effort.

Those who have successfully completed an expert system project will tell you that it was indeed difficult, but that the rewards repay the effort, provided a few precautions are taken. Seek sound advice: the cheapest system may not necessarily be the most effective; and, above all, know what you want and why. There is nothing at all surprising about these commonplaces, and anybody approaching a major engineering project in another area would hardly need to be advised that it is a good idea to plan the whole understanding from the start, work out what it will cost and what will be gained and so forth. Yet it seems constantly necessary to warn those approaching expert systems that the normal rules of project planning must be adhered to, and that the same sort of costs and benefits will be encountered as for any difficult but productive technology.

The main purpose of this chapter is to set out the points that should be considered by anyone investigating the feasibility of an expert system. We start out, as you should, by asking what an expert system does, in what respects it is better or worse than an expert, and how it may be fitted into a larger process. Only once these points are settled do we look at the technology available. In fact most applications that are feasible at the moment can be done with very

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simple expert system technology; very few applications require the use of the most advanced techniques, and most of them would be ruined by attempting the use of such processes. The range of techniques available in theory far outreaches those that can be reliably used in practical systems. However, if you decide an expert system is needed you will soon be surrounded by people trying to sell graphically-based, access-oriented, middle-out, demand-driven multiple-world frame servers, so a brief survey of such matters is presented here and a glossary of technical terms is given at the end of the book.

10.2 Experts

The importance of expertise in production engineering will be apparent to anybody looking at the simplest production process. These processes are those carried out by experts, but more typically in modern manufacture a production process will be established and maintained by experts but staffed by non-experts or machines. Nevertheless, the importance of the expert is made clear every time the process has to be altered or something goes wrong.

Expertise is not homogeneous. There are experts who understand the theoretical basis of the production process and who can design a new process from scratch, and at the other extreme, in practice often just as valuable, there are experts who, through experience over a number of years, have acquired the ability to correct and maintain the production process. The distinction is sometimes made between 'knowing what' and 'knowing how'; on the one hand, knowledge of some physical or chemical law; on the other, knowledge of how to achieve a result. Perhaps in an ideal world the latter would always be based on the former, but in a world where production processes already exist and require understanding, the useful expert will always blend the two sorts of knowledge in some proportion.

An expert system, correctly engineered, can partially replace the expert in the production process. Later we shall qualify this statement and show what the preconditions for a successful expert system are and what can realistically be achieved. The field of expert systems, in common with other areas of artificial intelligence, has suffered from general pronouncements without due qualification; like many technical innovations they have been first derived, then discovered and projected as a panacea for all industry's ills, then disillusionment has set in because there are quite a lot of problems that cannot be immediately solved by the expert system; however, major benefits have been gained by those who concentrated on qualifying the problems and attempted the feasible ones rather than those who were satisfied with arguments at a high level of abstraction. There are now many expert systems in use in production, and the new decade will see many more; they have not totally transformed the world but have been integrated with existing technology and processes.

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In the light of these remarks, the reader is asked to take the very simple statements that follow as a first approximation to what some systems can do in the right environment, and not to judge the claims of expert system technology without first assessing all the qualifications set out in the rest of this chapter.

An expert is a complicated and perhaps unfathomable human system, but as far as his or her intervention in the production process is concerned, may be seen as a decision-making system; in other words, problems are submitted and responses are dictated. The expert's knowledge can never (in practice at any rate) be reduced to a series of problems and solutions, because he or she can solve new problems, grossly or subtly different from problems seen before, provided they fall within the range of that person's expertise: in short, he or she is more than a data base of examples. Anybody with a knowledge of elementary arithmetic is an expert of sorts; and because they have mastered the procedure for multiplying two numbers they can calculate the product of two numbers they have never before seen by applying the correct rules. In just the same way, the critical knowledge possessed by the expert is based on a set of rules.

An expert system, then, will aim to reproduce the rules used by the expert. The rules will not necessarily be simple (if A and B then C) but may involve various high-level constructions, such as probability, default knowledge and other technicalities that we shall look at briefly later on. That is not too much of a problem: the generation of suitable computer formalisms for such constructions, knowledge representation formalisms, is well advanced. The problem lies in obtaining the rules from the expert and transferring them into the computer. Experts may operate using rules, but they rarely formulate the rules explicitly; a number of techniques for extracting rules for knowledge acquisition have been developed.

This complex of techniques is the basis for expert systems.

Expert systems technology is at least 25 years old. Among the earliest systems were MYCIN (which was used for medical diagnosis), PROSPECTOR (used to assess potential sites for mining), and XCON (used to configure shipments of computer equipment). XCON is still in production use at DEC, making considerable savings. Fault diagnosis has remained a popular area for expert systems, and many ideas appeared for the first time in medical systems.

10.3 Non-experts

The most important aspect of engineering of an expert system is non-expert personnel. They, after all, will still be around when the system operates and will (probably) notice a difference. An expert system is not a technological marvel to be shown off on a supercomputer at conferences and exhibitions; it is a part of the production process whose role needs to be carefully considered.

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An expert system project in production engineering should start out from a clear model of the production process. This need not be very complicated, and typically may have five to ten components, but the interfaces between those components must be clearly worked out. For example, suppose a production line is producing units that go through a testing process. If test A fails the unit is thrown away; if test B fails it is put back into the process earlier on; if test C fails it must be rectified. At this point an expert is called in to analyse the fault and prescribe a solution. The offending unit is then handed to a rectification section with instructions about what should be done. Here is a simple portion of a model within the production line, with a number of entry and exit points, a tester, an expert and a rectification department. The expert's input will be the failed unit and his output will be a set of instructions to the rectification unit.

Now remove the expert and put in an expert system. It is of critical importance to check that this new model works, even though the expert system is just a black box at the moment, because if the model does not work then no amount of sophisticated expert system technology will make it work; the specification will be incorrect. The questions to be asked are: are those really all the expert inputs? In practice does the expert not receive feedback from the rectification department? For example, do they sometimes ask 'why?' when told to perform a particular rectification. Or 'how do we do that'? If so, an expert system that just tells them what to do but cannot explain its reasoning will not suffice. Does the expert really just examine the object? Even if that is so, you can be sure that the computer will not, but will require either an extra operator or some sensing equipment to answer questions about what is wrong.

Perhaps the expert is constrained in some ways. If his or her rectification solution involves component X and there are none of those in stock, are there alternatives? Are there company policies that restrain the solutions adopted? Does the expert in practice sometimes realise that something is amiss in production, skip the rectification and go over and tune the production process? We are accumulating a complicated model of production with many expert interactions, but it is better that we should do that now, before the system implementation begins, than build something that is wonderful but does not do the job we find we want it to do.

10.4 Building expert systems

Having decided the job to be done the next question is: is it feasible? This does not just mean, is it technically possible, but is it economically justifiable? What will be the benefits and costs of the system?

First assess feasibility. Write down precisely the input and outputs for the potential system; the inputs should not be too broad. For example, if the state of the world economy in three months' time is a consideration, you should

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probably abandon the project. Is there an expert who currently performs the tasks demanded? This is the critical question, for the elicitation of the knowledge of this expert is probably going to be the most difficult part of the project. Sometimes the rules to be followed are already neatly written down in procedure books, but it is very rare that recourse can be made to these without any expert assistance.

Next, look at the technology available and decide whether it can cope with the problem, and if so, with what success rate. No expert system ever achieves 100% success; disregard those that claim they do. Your technological survey should reveal that some percentage of problems will be too complicated or vague for the computer and will still have to be referred to the expert; if the computer can cope with 90% of cases without reference to an expert then you have freed 90% of the expert's valuable time, which is no mean achievement.

Then assess the cost of the system. Will you develop it yourself or call in a specialist developer? In either case you will probably have to maintain it yourself, so allow for having someone around who understands how it works. Remember, that while the system is being developed the expert will spend much time giving his knowledge; if this will not be possible, or will cost too much, don't bother starting.

Now one can assess the benefits of the development, and, if it seems advantageous, proceed to a requirements specification. If the analysis in this section seems rather negative, that is because it pays to be very realistic in the early stages of a project in order to avoid disappointment at the end. Expert systems projects have the unhappy property that aiming for a realistic target may score a bull's eye while aiming for a slightly unrealistic one will miss altogether.

10.5 Technology

We have deliberately deferred the technological problems to the end because, in our view, they are of the smallest importance. Too many expert system projects are technology driven, that is, the project is undertaken not because there is a need to be met but because there is a tool to be used. Ultimately technology is an important constraining factor; in this section we review some developments that make expert systems more powerful.

The easiest way to represent rules is in the form if A and B and C then D, for example. This was the only form of knowledge representation used in early expert systems; it has the advantage of flexibility, so that on the one hand, if I know A and B and C then I can infer D (forward chaining) or on the other if I want to prove D then I must go away and prove A and B and C (backward chaining). In fact, rules are still the core of expert systems, though the term rule-based system has a slightly derisive connotation, implying absence of modern improvements.

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Perhaps the most serious weakness of rules in their simplest form is their failure to capture defaults. An expert may phrase a rule in the form 'if it's an A do X; if a B then Y; but if I don't know anything special about it then I do Z'. Of course, this can be rephrased 'if it's neither an A nor a B then I do Z', but there are objections to this; practically, if there are a lot of special cases then this may be a very long rule, and, more important, it doesn't really capture the feeling of the rule, for if another class C of special cases turned up then it would cease to be equivalent.

So a useful notion is a default rule, the one to be used when none of the others applies. In fact, this simple two-level structure for general and special cases is often too simple. More powerful is the notion of inheritance. In a system there may be some rules that apply to all products; some that are specific to each product (A, B, C and D, say) and some that are specific to variations of products (A1–A4, etc.). For example, there are standard rules for packaging except that A3 has to go in special boxes; now instead of stating all the rules for products again for A3 products, I simply specify that A3 inherits all the properties of A products, which in turn inherit all the properties of products. I may then specify a general rule for packing products (not just one for A1, A2, A4, B, C and D) and give A3 its own rule, which, being more specialised, will override the general rule. This has the very practical advantage that the general packing rule is only stored in one place, and if it changes need only be changed once; it also means that when new products are introduced they will automatically be given the general packing rule unless a special rule is specified for them.

Collections like the A product group are called classes. Individual factors in classes are called objects, and recent developments in object-oriented programming have enriched the language of inheritance, for those willing to master the complexities. In the jargon of object-oriented programming, each object has a pack method taken from a class. Methods are more general than the system we have seen; for example, if a subclass has a method it may react with an inherited method in different ways; it may override it or may be added to it. For example, if B2 products require extra testing, an added method would enable them to be subjected both to the general and to the specific testing procedure.

A not-so-recent development has been the use of uncertain reasoning. Sometimes an expert will not answer 'yes' or 'no' to a question but 'probably' or 'possibly'. As these terms are themselves rather vague, expert systems that use uncertain reasoning usually expect the expert to supply a numerical value between 0 and 1 (a probability) to indicate how sure he is of something. There are a number of problems with this approach. It is difficult to place much reliance on the expert's number, other than to classify it as 0, 1, between 0 and 0.5 and between 0.5 and 1. Unfortunately systems then apply completely arbitrary rules for calculating, say, the probability of A and B given the

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probability of A and the probability of B, and the answer may depend critically on whether an input was, say, 0.31 or 0.32 when the expert is simply unable to assign probabilities with this accuracy. The simplest solution is to try to avoid uncertain reasoning. If it is inevitable, because the expert simply will not answer yes or no, then it should be used in as limited a part of the system as possible, and results obtained should not be used for critical tasks without being checked first. Recently, a new discipline, called fuzzy logic has been developed, and its development may make it possible to model more accurately the expert's assessment of probability in qualitative terms.

Turning from techniques for knowledge representation to techniques for knowledge elicitation, it has been generally recognised that this is the major obstacle in many projects, and efforts have been made to produce techniques to make the process more efficient. Some of these are rooted in psychology, the unfortunate expert undergoing what amounts to psychoanalysis in a bid to extract what he knows; others are gentler, and leave more to the expert, simply giving him formalisms to make it easier to express his knowledge.

One possibility has been canvassed extensively; that is the suggestion that knowledge could be extracted automatically by the computer learning from the expert. We have said that the expert's knowledge is more than just examples, but that does not mean that examples cannot be used to convey the knowledge. The expert's judgements are simply stored in a computer and fed to a program that can do rule induction. Rule induction deduces from the fact that the expert has thrown all 500 green units into the bin in the last week of the rule that green units should always be thrown in the bin. Of course, this may be wrong; the expert may only do that in odd weeks, for example. However, given sufficient data a rule will be produced.

Again there are disadvantages: principally, that the rule produced is typically very complex and not suitable for inspection by the expert to see whether it seems right, so the production process is entrusted to a computer program that uses a rule that nobody understands. This can cause concern in some quarters.

Very recently a more general form of machine learning based on what are called neural networks has become popular. A neural network does not build a rule at all; it recognises a pattern in the expert's decisions, and then reproduces that pattern in its own decisions. Of course these are even harder to verify, but it cannot be denied that they have extraordinary capability, especially with low-level tasks such as voice recognition.

The ability of a computer to form expert judgements is a new and powerful technique, whose power has only just begun to be exploited. Machine learning, a still more advanced application of AI, promises great things for the future, but at the moment should be regarded as a research topic rather than applicable technology.

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10.6 A practical guide

To the potential user, the description of the limits of the technology is probably less useful than an indication of how the current technology may be acquired. We conclude, therefore, with a brief survey of systems that may be used for development. However, remember first that whatever manufacturers say, none of these systems is suitable for immediate use by non-specialists. Some learning will be involved. The more powerful the product, the harder it will be to use. Remember, secondly, that there is no point in buying the product with the longest list of features if you either do not need or do not understand most of the features. Small PC-based shells are very suitable for most projects. Remember, thirdly, that whatever claims are made the system is most unlikely to integrate with any of your existing software; you will have to do a lot of work making them talk. Interfacing with hardware is even less likely, and even communicating with the system over a communications line may be a problem. In particular, do not believe any claim that a system has real-time capability. Finally, help yourself to free advice. Any vendor should be willing to discuss your problem with you and demonstrate other systems developed on his product; and there are several consultancies that specialise in expert system applications. Exhibitions such as the one organised by the British Computer Society Expert Systems Specialist Group are a useful way of contacting suppliers and consultants.

In practice, there are three ways to move forward if you intend to apply such systems:

10.6.1 *The very hard way: write it yourself*

A cheap solution is to write everything yourself in a programming language; but this is quite hard, and although there are books that tell you how to do the interesting bits, you will probably find that you spend 90% of the time on the user interface, which nobody tells you how to do. C is popular for speed, and very portable provided you don't do any input/output, but leaves all the work to you. C+ is more powerful but not particularly suited to simple rule-based systems. Prolog is the European favourite for this sort of work, just as LISP is favoured in the US; both are hard to start and then very powerful once you get the idea. Ask suppliers about adherence to standards.

Prolog implementations: Quintus Prolog (SUN, VAX), BIM Prolog (SUN), Prolog-2 (PC, SUN, VAX), Quintek (SUN, VAX), Poplog (with LISP too—SUN, VAX), LPA Prolog (Mac, PC).

LISP implementations: Golden Hill (PC), Poplog (with Prolog-SUN, VAX). There are also special purpose LISP machines (Symbolics, Xerox, TI) but these are very expensive.

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10.6.2 *The quite hard and very very expensive way: use an AI toolkit*

An artificial intelligence (AI) toolkit gives you an AI language (usually LISP) and a mass of code, typically the entire output of a university department for about five years, that may be used, and also a very sophisticated user interface. First, can you afford it? Not only is the software expensive, but it requires masses of memory and disc space. Even if you can afford the development system, what will it run on in production use? And you probably have to recruit a very expensive programmer to program it. Nevertheless, once you do the calculations it may be worthwhile buying all this for the savings that can be made. However, if you aren't ready to make that sort of spending commitment there are plenty of cheap systems that you can use to assess the technology.

LISP based toolkits: KEE (most commonly used: SUN); ART (SUN); KnowledgeCraft (SUN); Goldworks (PC).
Prolog-based toolkits: Prometheus (PC), Flex (Mac, PC). These are generally cheaper than their LISP counterparts.

10.6.3 *The cheapish but still fun way*

We are now looking at systems running on PCs. These are shells, in that a certain amount of the expert system is prewritten for you, and you simply slot in the knowledge. The more sophisticated shells give access not just to rules but also to classes, objects and uncertain reasoning, and may also have pretty graphics. The extra facilities are useful if you want to find out what they can do, and even if you decide that you only need a simple rule system, you have not paid much extra for them.

Most complicated: Nexpert, Egeria.
Middle rank: Leonardo, XI+.
Simple: Crystal, Advisor-2.

The final word of advice in this practical guide is to choose the *simplest* system that will do the job.

10.7 Summary

We saw that the main question to be answered when constructing an expert system was how that system would fit in with the rest of the production process. If that problem can be solved, then the question of how the expert system should be constructed should be looked at from the technical point of view, preferably with the help of somebody who has worked with the technology before.

In computing, inventions seem to go through at least four phases. First of all

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everybody says that it cannot be done. Then somebody manages to do it, provisionally and with plenty of problems, and everybody immediately shouts that it can be done, it has been done, it's available on your home computer now, and so forth. Enough people are taken in by this for a boom in the technology to take place, as a result of which, firstly, a lot of problems are discovered and, secondly, systems are refined and made more robust and practical. In the third phase it is discovered by the makers of fashion that the new technology has not accomplished everything (as they recently said it would) from which they deduce that it has achieved nothing, and so a slump in the technology takes place. In the fourth phase it is discovered that the technology is pretty useful, in its place, and people quietly start using it for real applications and making money out of it. Meanwhile some unfortunate new discovery is being hailed as the solution to every problem imaginable.

Expert systems have now passed through the painful third phase and are starting to play a significant role in increasing productivity. It is still necessary to avoid hype, jargon and technology-for-the-sake-of-technology, but the same is, after all, true of hi fi equipment; underneath all that there is a useful and reliable technology. Its application should be considered urgently by managers of most large-scale production systems in the next few years.

Further reading

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Glossary

a.c. Alternating current.

Access-oriented Access-oriented programming is a type of object oriented programming in which methods are invoked whenever the value is examined.

Accuracy The difference between the measured value and the true or required value.

Actuator A device to convert electrical (or other) energy into mechanical movement.

AGV Automated guided vehicle. A truck which can move along a pre-defined route according to a set of programmed instructions.

Algorithm A set of rules or formulae which will always produce a solution to a particular type of problem or indicate that no solution exists.

Alpha numeric Character based information capable of including both text (alphas) and numbers (numeric).

Analogue A continuously variable signal as distinct from one which varies in discrete steps. Spelt 'analog' in many text books.

AQAP-1 A national standard concerned with quality control.

Architecture The way in which the various physical or logical components of a computer are arranged.

Artificial intelligence Trying to get computers to behave as though they were thinking.

AS400 A series of mini-computers by IBM. Normally suffixed by a reference which defines the model, for example AS400/B45.

ASCII American Standard Code for Information Interchange. It is a seven-bit code comprising control characters and printing characters used for the representation of alphanumeric characters.

AS/RS Automatic storage/retrieval system. A system such as a warehouse or carousel where goods can be stored and recovered automatically.

Auto synchronise A method of ensuring that the data and programmes of two machines match exactly.

Auto tuning A method by which a control loop can change its own PID values in an attempt to provide the best possible control at any particular operating point of the system.

Availability The proportion of any given time interval that a device will be in service.

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Backward chaining Starting from the desired conclusion and trying to prove the conditions that imply it.

BASIC A common programming language available on many smaller personal computers.

Bit A binary digit taking a value of either one or zero.

Bottom up Starting with the lowest or base units and working towards higher ones.

BS5750 A British Standard which sets out how companies should establish quality assurance procedures for their operations. See also ISO9000.

Byte A set or word of eight bits.

CCF Common cause failure. An event which causes all systems to fail in the same way.

Cell controller A supervisory machine responsible for a number of other machines in an area of a factory.

Central operator interface Devoted to a complete production unit, or to sub-units such as cleaning in place, processes or tank farms.

Channel One path of a multi-path control system.

CIM Computer integrated manufacture. The linking together of otherwise independent manufacturing equipment by computer system.

Circuit breaker A device for interrupting the supply of electrical energy.

Class A collection of objects, normally having some common property.

Cold standby An arrangement by which a second computer can take over the functions of a first if it fails, but where the changeover is effected manually. This may include manually transferring data on removable storage. See also hot standby.

Computer A machine, controlled by a stored programme of instructions, which accepts input data, processes the data and then takes some action.

Configuration The arrangement of the various parts of a system necessary to perform the tasks required of the system.

Controller A device which provides control. Often used to refer to a PLC.

Data processing A general description for the work done by a computer. It is particularly associated with commercial computing.

DEC Abbreviation for the Digital Equipment Corporation.

d.c. Direct current.

DCS Distributed control system. A type of computer used for process control.

Default A value to be assumed if no other is supplied.

Demand-driven Not doing something until required to. Same as lazy.

Digital A device which operates with discrete voltage levels, or bits.

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Dynamic response The way that the output of a system changes in real time.

Eager Act as soon as you have all the necessary information. Opposite of lazy.

EMI Electro-magnetic interference. Any disturbance in a system due to the effect of electrical or magnetic waves.

Ergonomics Design of equipment and environment to suit the natural needs and capabilities of human beings.

Ethernet Method of connecting a number of computers to provide serial communication.

Expert system A system that performs a task and computes a response using a knowledge base.

Faceplate display A graphical representation of a single loop controller.

Fibre optic Transmission of data by light along a fibre optic cable.

Firmware Computer program stored in read only memory which forms the basis of how the computer will operate.

Floppy disc A low cost flexible medium for data recording.

Forward chaining Starting with the available information and reasoning towards a conclusion.

Future-proof Capable of cost-effective modification to meet future improvements in technology and/or user needs.

Fuzzy logic A method within expert systems of expressing the chance that an answer is correct or not. See also uncertain reasoning.

Gain One of the control terms of a three-term controller. See also proportional.

Graphic display A video display unit designed to display pictures and diagrams on a screen, usually in colour.

Hard disc A magnetic data recording disc made from rigid or hard magnetic material. These discs are often non-removable, hermetically sealed, dust-free units.

Hardware The physical components that make up a computer system.

Hierarchical system A method of interconnecting computers so that each level in the system only receives and sends data with the machine directly above it and those directly below it in the control pyramid.

Hot standby An arrangement by which a second computer can take over the functions of a first if it fails, with the changeover being fully automatic. See also cold standby.

Hysteresis The effect where the output for a given input differs between a rising and a falling, or forward and backward condition. Sometimes referred to as 'backlash'.

Induction Deducing rules from facts. For example, because the sun has risen every morning until now we assume it will rise tomorrow.

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Inheritance Objects in a class inherit all the things appropriate to that class. If an object can be in several different classes then this is 'multiple inheritance'.

Input Any information coming into the computer and requiring processing.

Intelligent sensor A field-mounted device capable of accepting a physical input, converting it to an electrical signal, processing the signal and providing a coded output of some type.

Interface The point of meeting between a computer and an external entity, whether an operator, a peripheral device or a communications medium. An interface may be physical involving connections, or logical involving software.

I/O Abbreviation for input/output. An abbreviation widely used to refer to inputs and outputs to programmable controllers.

ISO9000 A European Standard which sets out how companies should establish quality assurance procedures for their operations. See also BS5750.

Isolation The separation of the sensitive electronic parts of a computer from electrical interference from plant items.

JIT Just-in-time. The technique of scheduling production to supply the finished products just at the time required. This reduces the need to hold stocks.

Kilobyte One thousand bytes.

Knowledge acquisition Extracting knowledge, usually from experts. Sometimes called knowledge elicitation.

Knowledge base Like a data base but full of knowledge, often expressed as rules, instead of data.

Knowledge-based system Same as expert system.

Knowledge representation A way of making knowledge accessible to a computer program.

Ladder diagram A programming language used to represent electrical devices in a computer. Most commonly found in programmable controllers.

LAN Local area network. A computer network linked by a cable or fibre optic cable, usually in a single building or room.

Lazy Not acting until your output is needed. Opposite of eager.

LCD Liquid crystal display. A type of display for providing information, often alpha numeric.

LED Light emitting diode. A method of providing alpha numeric information, and giving a greater light output than LCD.

Light pen A device which is pointed at an area of computer screen and a button on it pressed to select an operation. Unlike the mouse or trackball the pen itself replaces the pointing symbol.

Linearity A measure of how closely the measured value follows a theoretical straight line.

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LISP A programming language based on lists, much used in artificial intelligence.

Local operator interface Used at the process level for control of individual sub-processes, machines and sensors.

Management information system (MIS) An information system designed to supply managers with the necessary information to plan, staff, direct, and control the operations of the organisation.

MAP Manufacturing automation protocol. Protocol developed mainly by General Motors Corporation to enable communication between programmable controllers, supervisory computers, machine tools, robots, etc. of different manufacturers.

M byte Mega byte. One million bytes.

Measured value The parameter to be controlled in a control loop.

Microprocessor A single integrated circuit containing all the elements of a central processing unit, which forms the heart of a computer.

Middle-out Reasoning from some middle point both backward and forward to reach conclusions.

Mimic diagram Schematic representation of a plant, often etched on a metal or plastic panel and using coloured lights to indicate plant status.

Mnemonic A type of programming language, based on Boolean algebra, often found in advanced programmable controllers.

Mouse A device used for moving a pointer symbol across a computer screen. This is achieved by sliding the device across a table or special mat, and when the pointer is at the right place pressing one of the buttons on the device allows an operation to be selected. See also trackball.

MRP Material requirements planning. A system which uses bills of material, inventory data and master production schedule information to calculate requirements for materials.

MRPII Manufacturing resource planning. Similar to MRP but for scheduling manufacturing facility resources.

MTBF Mean time between failures. The average time between successive failures of a device.

MTTR Mean time to repair. The average time required to repair a device which has failed.

Multiple world A system where several different possibilities can be investigated in parallel.

Mycin An expert system developed for the medical profession to test whether to take a drug which ends with the letters -mycin.

Network A method of connecting various computers together, by a cable, fibre optic or possibly by radio link.

Neural network A method of organising computers to create something like a brain but much simpler. It attempts to emulate the lowest level of nervous activity.

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Non-linearity The ratio of the deviation of the measured value from the linear to the total theoretical output range.

Object-oriented A programming style in which the program is organised around the objects to be manipulated rather than the manipulations to be performed.

Object-oriented graphic system A software display system, usually in colour, in which information is tied to graphic symbols that can be manipulated by the operator.

One out of two (1002) A method of using two computers to control one process for reliability purposes.

Operator interface The equipment used to present information to the plant operator and issue commands to the computer system.

Output A signal going from a computer to the plant and/or operator.

Overshoot The amount by which the measured value of a control loop exceeds the desired value during transient changes.

Parameter An element or variable of relevance to the process and measured (or calculated) within the computer.

PASCAL A high level programming language used in many computer systems.

PC Normally personal computer, but sometimes used for programmable controller.

PDP A family of mini-computers by DEC. Usually suffixed by a number which defines the model, for example PDP11/44. See also uPDP.

Peripheral Any input, output or storage device connected to the central processing unit.

Personal computer A computer intended for use by one person at a time. Also known as PC.

PLC Programmable logic controller.

PID control A method of closed loop control which incorporates proportional, integral, and derivative action.

Probability A number between 0 and 1, or 0 and 100% indicating how likely an event is.

Process control Set of activities pertaining to systems whose purpose is to provide automation for continuous operations.

Program (or programme) A group of instructions held within the computer which when acted upon by it will produce the pre-defined result. The shorter form is the commonly adopted standard.

Programmable controller Programmable electronic control equipment performing tasks formerly undertaken by conventional relays, but including communications and processing capabilities as well. Also known as PLC.

PROLOG A programming language based on logic, much used in artificial intelligence systems.

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Proportional band An alternative way of expressing gain in a PID controller.

Prospector An expert system developed to advise where to go and dig for gold or whatever.

Protocol Set of rules or conventions governing the exchange of information between computer systems.

QA Quality assurance. The procedures through which quality can be achieved.

QC Quality control. The method of measuring how close to the desired value the resulting materials or values are and taking action to correct deficiencies.

Random failure A failure of hardware which cannot be predicted, often caused by ageing.

Real time system A computer system which receives input data, processes it and outputs signals without delay to control the source of the input. In computing terms the opposite is 'batch processing' where it doesn't matter when the processing is done, or how long it takes.

Reboot A method of starting up a machine so it runs with the correct information available.

Recover/Restart Restoration of normal processing after hardware or software malfunction through detailed procedures for file backup, file restoration, and transaction logging. This may be linked into a standby system.

Reference The desired value input to a control loop. See also set point.

Repeatability The ability to repeat measurements with accuracy. Note that results may be repeatable, but exhibit 'hysteresis'.

Resolution The smallest unit of measure that the device can detect and respond to.

Rule-based system A system whose knowledge base consists of rules of the form 'if A then B'.

Sample interval The time between successive readings of a value in a real time computer.

SCADA Sequence control and data acquisition. A computer designed to store large quantities of data, and provide small amounts of sequence control.

Scan time The time between successive cycles of a program in a real time computer or PLC.

Sequencing The step-by-step operation of a process.

Serial link A data path which carries signals one after another (serially) along a pair of wires rather than simultaneously along many wires in parallel.

Serial port The connection on a computer to which the serial link is connected.

Set point The input to a control loop. See also reference.

Scheduling Deciding when and where each operation necessary to the manufacture of a product is to be performed.

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Shell A simple expert system with all the knowledge taken out. Add a knowledge base to get a complete expert system.

Simulation The design and operation of a model of a system.

Software Computer programs and their associated documentation.

SQC Statistical quality control. The use of statistical methods for measuring the overall accuracy of a total batch by sampling only a number of items.

Stability The likelihood that a change of input to a control loop will give a smooth change of output, rather than a highly fluctuating output.

Standby system An arrangement where another computer is available to take over control if the first fails. See hot standby and cold standby.

System accuracy The degree to which the overall system output agrees with the ideal desired result.

System reliability The probability that the system will perform its intended function adequately for a specified period of time, under defined operating conditions.

Systematic failure A failure caused by design fault or external influence which causes all equipment of the same design to fail in the same way.

Tag number A unique identification given to a plant device, usually used in process industries.

Tape streamer A magnetic storage device which uses cassette tapes as the storage medium.

Thermocouple A device for providing an electrical signal corresponding to the temperature at the thermocouple tip.

Three term controller A device which provides proportional, integral and derivative control. These are the three terms referred to. See also PID control.

Toolkit Lots of parts within an expert system that can be put together in different ways to form a complete system.

Top down Starting with the highest level units and moving towards the lower ones.

Trackball A pointing device similar to a mouse except that the device itself is not moved. The movement is achieved by turning a ball set into the top of the device. See also mouse.

Trend A display which shows how a particular parameter changes with time.

Two-out-of-two (2002) A method of using two computers to control one process for reliability purposes.

Uncertain reasoning Reasoning that makes allowance for not knowing for sure whether something is true or false. See also fuzzy logic.

uPDP A family of mini-computers by DEC pronounced 'micro PDP'. A development of the PDP model in a smaller box. Usually suffixed by a number which defines the model, for example uPDP11/73. See also PDP.

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uVAX A family of mini-computers by DEC, pronounced 'microVAX'. A development of the VAX model in a smaller box. See also VAX.

VAX A family of mini- and mainframe computers by DEC.

VDU Visual display unit. A computer terminal which uses a monochrome or colour screen for output of alpha numeric information or graphics. Usually accompanied by some form of input device such as a keyboard (standard or special), trackball, mouse or light pen.

Window Capability of dividing a computer display into sections by splitting the screen, each area containing different information.

Word A group of bits assembled to form one block of information. Usually refers to one byte, but sometimes two.

Workstation A VDU containing a computer which allows the unit to perform more than one task at a time. An intelligent VDU.

XCON An expert system developed for showing how DEC VAX computers can be connected together.

Zone An area of the process which can be considered as an entity.

Zoom Close-up or enlargement of graphic information presented on a VDU.

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