ASPECTS OF DECISION MAKING

FOR METAL POWDER PRODUCTION

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S U M M A R Y

Production in the metal powder making industry is to a great extent a 'matching' procedure.

Many base powders can be produced via the processes, but they will not match customer requirements unless subjected to extensive 'manipulation'.

As a result several 'control' stages are available. At production, at separation stage and at blending stage. It appears initially that complete control is possible.

However, lack of reliable information on process capabilities and poor definition of products together with a complex blending problem make decisions extremely difficult.

The work described in this thesis presents, it is believed for the first time, a coherent approach to management decision making in this industry.

A multi-decision stage optimisation is suggested and case studies are presented.

A variety of advanced and standard methematical modelling approaches are utilised, including Dynamic Programming, Linear Programming, Simulation and Industrial Dynamics.

The research concludes with an outline of further work required to productionise the recommended course of action.

KEY WORDS: METAL-POWDER MISMATCH BLENDING

MATHEMATICAL MODELLING OPTIMISATION

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The work described in this thesis has been carried out independently and submitted for no other degree

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CHAPTER ONE

INTRODUCTION

1.1 General

Many industries are by now making regular use of 'scientific' method of decision making in directing and controlling their production operations. Among these are the mass production industries and the batch producers of many engineering items, as well as food and allied industries. There do, however, exist various industries which have so far made almost no progress in using modern decision making methods.

The reasons for this are found in either the difficulty of 'quantifying' production or even in 'qualifying' what will be produced.

Among the industries so affected are metal powder manufacturers (the subject of this research) and foundries of various types.

In both cases the very act of finding out what has been produced is difficult to achieve.

In the case of metal powder making, the problem is complicated by the lack of certainty in what will be produced.

In these circumstances, the managers in metal powder making industry have often been forced to resort on their pure managerial experiences to make the various planning and controlling decisions. Since the problems of operational planning and control in metal powder making industry are too complex to be solved by the intuitive models of the managers, these decisions did not often result in effective utilization of the resources at their disposal.

Indeed, the following symptoms which can be observed in even the most reputable metal powder making companies are the evidence of the existence of such a proble,.

a) Despite posessing a productive capacity of higher level, in terms of tonnages, than the requirements of their relative market demand, metal powder making companies have often been operating under the capacity of their respective markets - expressed differently, they can often not satisfy their relative market demand.

b) Metal powder making companies have often been holding in inventory a high level of stocks of unsaleable products and a low level of stocks of more marketable products, which has resulted in a high level of their cash being absorbed by, and misused in their stock and implies a lack of control over inventory.

1.2 Survey of Previous Works

A literature survey on metal powder (technology and production) revealed that almost all researchers looked at the problems of powder manufacturing from a process control/engineering point of view - engineers, scientists and statisticians who worked in this field being most attracted by the technological complexity of the process and the product of this industry, have put in tremendous efforts, and have published many patents and reports dealing with, either the construction of the apparatus used for powder making or concerned with process control problems - finding correlations between the powder quality parameters and the process parameters. (references 1,4 through 12)

This approach, which is a traditional approach of control engineers, has resulted in extensive progress in the technical control of powder manufacturing:- Mechanisms of control have been fully investigated and process parameters have been established for the manufacture of various metal powders (1) This in turn has enabled powder manufacturers to establish their own set of plant settings for the achievement of various possible qualities of the powder.

These possible qualities, however, are not precise qualities to give exactly what the customer requests. For instance, the 'particle size distribution' of the produced powders, (the parameter of most concern in this study) that can be achieved through the process, cannot match the customer-requested powder exactly, except on very infrequent occasions

However, in contrast to this emphasis on technical problems, little has been reported on the managerial problems of production in this industry, and surprisingly, there is almost no published evidence of any research on such problems.

Review of the technology of various process industries revealed that petroleum refineries are involved in operations somewhat similar to those of the powder manufacturing industry. For example, the distillation process is similar to the atomization process (the manufacturing process studied in this project) and involves simultaneous manufactur of a range of products whose proportions are fixed for a particular plant setting(2),(3),(13),(15).

Moreover, both industries meet the problem that there may be a mismatch between the customers'-requested products and those products that can be achieved (initially) from the processes. To sell their products, however, both have to apply additional processes, on their products to match them to the customer-requested products. In the oil industry they apply cracking processes and blending operations, and in metal powder making the manufacturers blend the various powders.

The problems of operational control in a refinery have been approached(3) in detail, but the approach used in this industry is not directly applicable to the metal powder making operational problems. The major reason is that the powder properties are not quantifiable as easily as the fractions of crude oil or as final products are quantified in the petroleum industry. They (the approaches) require much modification if they are to be used in organising powder manufacturing.

The literature on production and inventory control has also been surveyed. The problem of planning and scheduling the production and control of the inventory in multi-product industries have been approached by many management scientists. For example, Eilon (14), (16) discusses the problem of plant loading in a multi-product chemical plant. Dzielinski and Manne (17) used the computer simulation to study the behaviour of a hypothetical multi-item production and inventory system under various inventory control policies applied. There are many examples of these type of approaches in the literature and some of the work being done are highly advanced mathematical treatment of the cases involved. However, all these works concern with the products which are defined easily and assume that the production rate response of the process or machine for producing the individual products are measurable with certainty. In the case of metal powder making the products are defined only in statistical terms and this often goes under various alterations too. For example, a product is defined by the probability of it containing a particle of specific size and this probability is allowed to vary from say % 85 to 1. Within this wide range the product has some given class or grade category. In addition to this the stock materials are often subject to manipulation i.e. they undergo 're-sieving' to fill the customer orders. This is often necessary because the manufacture of that particular order may be more expensive than running out of stock for other customer orders.

The work presented by Henry and Jones (18) however provides a similar case to the situation met in metal powder making industry. Electrical devices of various qualities can substitute for each other and the manufactures seeks a method of allocating the production to customer orders which a) minimizes the production quantity required to fill the requirements and b) to minimize the build-up of stock of low qualities products which could can not be substituted for higher quality products. This problem however is less complex than the blending problem of metal powder making in which the range of substitution of particles of a particular mesh category is only limited to a few products.

Finally the idea of SKULL (31) which develops what he calls it the Process Control/Operational Research Interface is a point of departure for approaching the problems met in metal powder making industry - now that the process can not be further engineered or inparelled to the progress of process engineers the resource allocation idea of operational research would be used to get maximum out of the existing system.

1.3 Research Programme

The aim of this study is to provide managers of those metal powder making companies who use the atomization method of manufacture, with tools and procedures which facilitate more effective control over the production functions of their respective companies.

Managerial control of production involves, basically, the design of operating procedures and controls, which guide the production decision making tasks of lower management. In powder manufacturing, where 'production' is to a great extent a 'matching' procedure, and, there is an uncertainty about the specification of the 'should-be products', the design of operating procedure and controls would not guarantee the maximization, at every instant, of the expected value of the utility that can be obtained from the use of resources. This is due to the fact that the state of the plant resources are not predictable.

The design of mechanisms aimed at better matching of requirement and achievement, and which facilitate better decision making, seems a more logical approach and constitutes the main objective of this study.

1.4 A Brief Outline to the Chapters of the Thesis

The work proceeds through a general study of metal powder and its manufacture in order to introduce the context and the environment of the problem addressed and approached in this project, Chapter 2 is most concerned with this task. It gives a brief outline of the nature of a "metal powder" and introduces its characteristics as demanded by customers and to the extent required in this study. It also identifies the major operations involved in the manufacture and production of metal powders and outlines the atomization process and its output characteristics in particular.
Finally, it illustrates briefly the limitations encountered in technical control of metal powder manufacturing processes.

Chapter 3 identifies those managerial problems production control and decision making, which are addressed in this project and which are, to a great extent, consequential on this technical problem.

Chapter 4 introduces the management science/operational research techniques which suggest themselves as tools for assisting managers in powder companies in tackling the production problems highlighted in Chapter 3.

The analysis of the applicability, merits and requirements of these techniques have also been carried out in this chapter and the method which was sought in this project as the most appropriate one, has been identified.

Chapter 5 formulates the mathematical modelling of the major operations of the powder production process and tries to specify the role of these models in the managerial problem-solving (or decision making) tasks of managers of powder making companies.

Chapter 6 contains discussions about the work and presents the conclusions.

Chapter 7 gives suggestions concerning future work and recommends the construction of a dynamic model which can help the managers of metal powder making companies to design improved policies for their companies.

CHAPTER TWO

METAL POWDER MANUFACTURING INDUSTRY - AN OVERVIEW

2.1 The Need for Metals in Powder Form

Metal powder manufacture is a highly specialised industry sector, covering powders in iron, copper, aluminium, tungsten, molybdenum and most commercially used alloys of these metals. The reasons for requiring metals in powder form are manifold and include:-

Production of explosives,

Production of sintered metal components (Powder compact substitutes for wrought metals),

Paint constituents,

Grinding and shotblasting media,

Electric filament production,

and the manufacture of specialised alloys which are impossible to make via the conventional (melting) route.

Table 2.1 shows some of the uses to which metal powders are put.

2.2 Characterisation/Quantification of a 'Metal Powder' as product

'Metal Powder' is the final product of the powder manufacturing industry. Unlike the products of other industries, this product is not capable of being easily defined or quantified.

TABLE(2.1) Typical Applications of the Powders (5)

Production method	Typical powders	Typical applications
Atomization	Stainless steel	Filters, mechanical parts, atomic reactor fuel elements
	Brass	Mechanical parts, flaking stock, infiltration of iron
	Fe	Mechanical parts (medium to high density), welding rods, cutting and scarfing, general
	Al	Flaking stock for pigment, solid fuels, mechanical parts
Gaseous reduction of oxides	Fe	Mechanical parts, welding rods, friction materials, general
	Cu	Bearings, motor brushes, contacts, iron-copper parts, friction materials, brazing, catalysts
Gaseous reduction of solutions (Hydrometallurgy)	Ni	Iron-nickel sinterings, fuel cells, catalysts, Ni strip for coinage
	Cu	Friction materials bearings, iron-copper parts, catalysts
Reduction with carbon	Fe	Mechanical parts, welding rods, cutting and scarfing, chemical, general
Electrolytic	Fe	Mechanical parts (high density), food enrichment, electronic core powders
	Cu	Bearings, motor brushes, iron-copper parts, friction materials, contacts, flaking stock
Carbonyl decomposition	Fe	Electronic core powders, additive to other metal powders for sintering
	Ni	Storage batteries, additive to other metal powders for sintering
Grinding	Mg	Welding rod coatings, pyrotechnics
	Ni	Filters, welding rods, sintered nickel parts
	Fe	Waterproofing concrete, iron from electrolytic cathodes (see Electrolytic above)

A schematic representation of a metal powder is shown in Fig. 2.2.1.

It is simply identifiable as a mass of particles of various shapes and sizes. A complete characterisation of it however requires that all characteristics of a 'single' powder particle (shown in Table 2-2a) and those characteristics which elate to a 'mass' of particles (shown in Table 2-2b) are determined (6). A description of all these characteristics is not the aim of this work but a brief introduction to some of the characteristics of the powder such as particle 'size', 'size range' and particle size distribution is essential because they are frequently referred to in this study. In particular, the 'particle size distribution' is the major means of identifying/quantifying a powder.

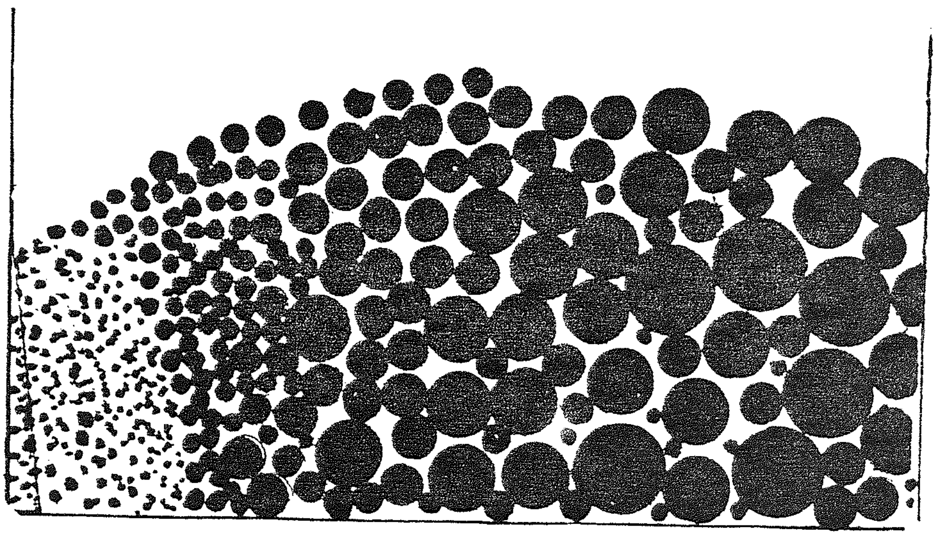


Fig. 2.2.1 A schem atic representation of a powder

TABLE 2-2a CHARACTERISTICS OF A POWDER PARTICLE

A. Material characteristics

1) Structure
2) Theoretical density
3) Melting point
4) Plasticity
5) Elasticity
6) Purity (impurities)

B. Characteristics due to the process of fabrication

1) Density (porosity)
2) Particle size (particle diameter)
3) Particle shape
4) Particle surface area
5) Surface conditions
6) Microstructure (crystal grain structure)
7) Type and amount of lattice defects
8) Gas content within a particle
9) Adsorbed gas layer
10) Amount of surface oxide
11) Reactivity

TABLE 2-2b CHARACTERISTICS OF A MASS OF POWDER

1) Particle characteristics (see Table 2-2a)
2) Average particle size
3) Particle size distribution
4) Average particle shape
5) Particle shape distribution
6) Specific surface (surface area per 1 gram)
7) Apparent density
8) Tap density
9) Flow of the powder
10) Friction conditions between the particles
11) Compressibility (compactability)

2.2.1 'Particle Size' and 'Size Range'

The size of the particle is defined as "the representative dimension that best describe the degree of comminution of the particle". For a spherically symmetric particle the diameter is that dimension and thus is its size (7)

Metal powder particles are found in a great variety of shapes as shown in Fig. 2.2.1.1.

For particles of shapes other than spherical, the choice of a 'quantity' to represent individual particle size becomes an acute problem.

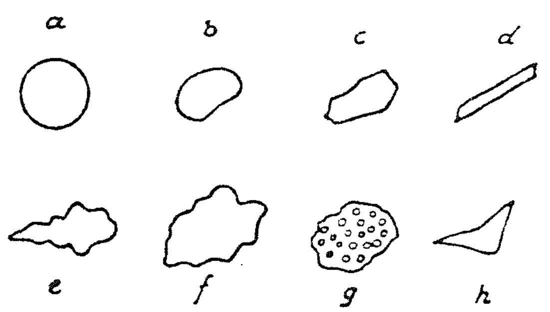


Fig. 2.2.1.1. Various shapes of metal powder(6):

(a) spherical, (b) rounded, (c) angular,

(d) acidular, (e) dendritic, (f) irregular,

(g) porous, (h) fragmented.

Fig. 2.2.1.2 illustrates the variety of methods used to measure the diameter of non-spherical particles (**8**).

Fortunately, various 'sizing' techniques are available today which provide parameters to represent the size of individual particles. These quantities and techniques by which they are derived are shown in Table 2-3.

In practice and particularly under the restrictions imposed by industrial production the determination of particle size is most commonly carried out by the technique of 'sieving'.

In this method the size of a particle is determined with reference to the size of openings in the sieve's screen. If a particle passes through the openings of the sieve's screen, it's size is less than that standard size of opening, and, if the particle retains on the top of the screen it's size is greater than the opening size.

Thus the sieving method does not permit the precise determination of particle size but rather it determines a 'size range' for the particles. For example those particles which fall through a 200 mesh (opening's size equivalence) screen, but are retained on a 230 mesh screen are of a size class which ranges from between 63 micron and 74 micron, and would be called size range.
Sieving in this sense is the classification of the sizes.

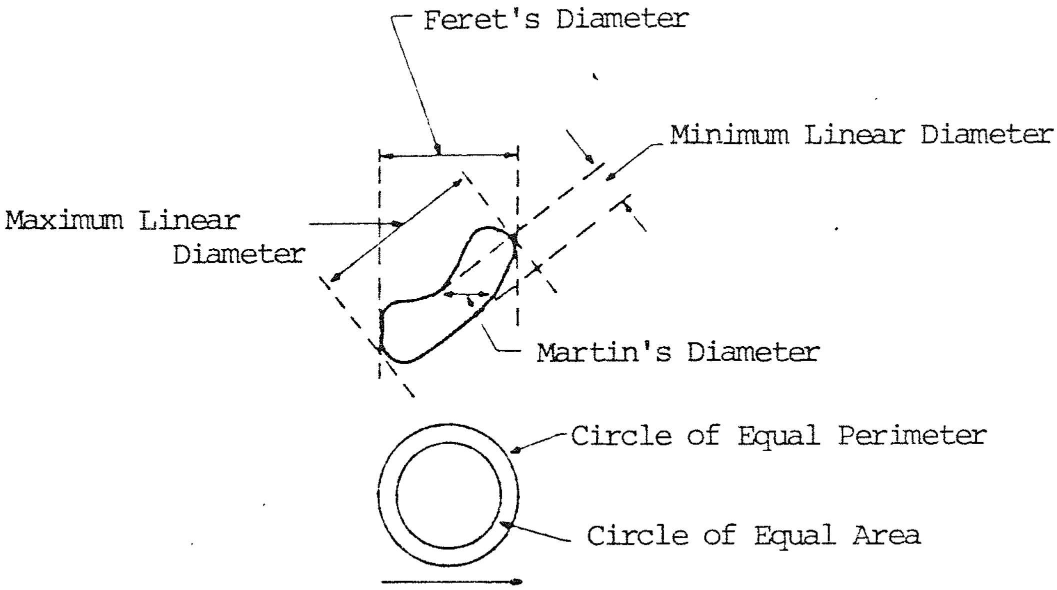


Figure 2.2.1.2 Methods used to measure the diameter of nonspherical particles(8)

TABLE 2-3 QUANTITIES USED TO REPRESENT SIZE OF INDIVIDUAL PARTICLES(8)

Derived from microscopy:

diameter
area
perimeter
Feret's diameter
Martin's diameter
maximum chord
minimum chord

Derived from other sizing techniques:

terminal settling velocity (in air)
Stokes' equivalent diameter
aerodynamic equivalent diameter
(unit density sphere diameter)
equivalent diffusional diameter
apparent optical diameter
sieve size

Two examples of 'size ranges' achieved through sieving are shown in Figs. 2.2.1.3 and 2.2.1.4.

In Fig. 2.2.1.3. the particles have been classified into only two broad 'size ranged'. In Fig. 2.2.1.4. a set of sieves has been used, and narrower 'size ranges' are identified to represent the 'size' of the particle.

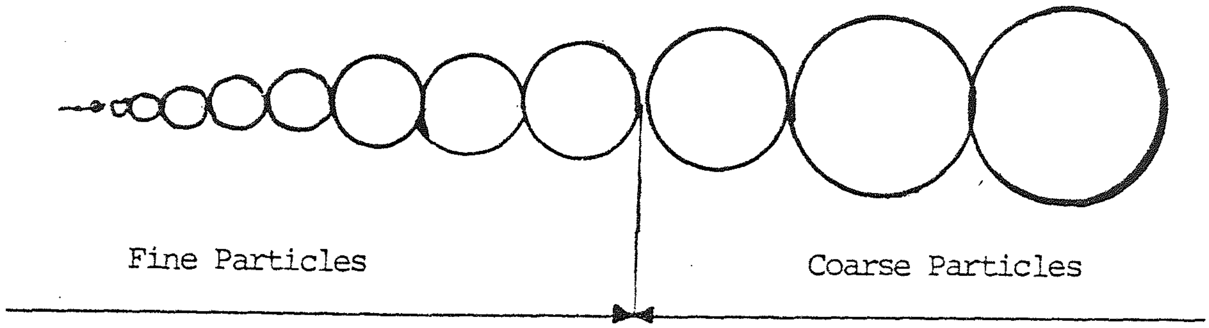


Fig. 2.2.1.3. Single stage classification of size

Two size range.

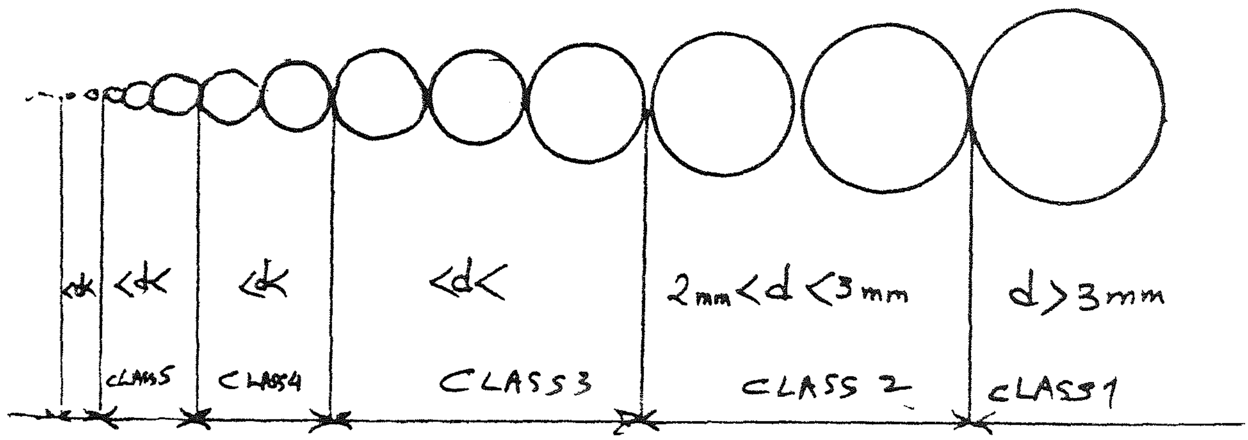


Fig. 2.2.1.4. Successive size classification

Many small 'size ranges'

2.2.2 Particle Size Distribution - A means of qualification of the powder

A powder comprises enormous numbers of particles of various sizes. One way to characterize or 'quantify' the powder is to determine the 'amount' of each particle 'size' present in it, <u>or</u>, in a more sophisticated way, to find a formula which shows the relative 'amount' of powder as a function of each size of particles present in it. The result which is obtained from this process is called the 'Particle size distribution' of the powder.

Several examples of such 'particles size distributions' are shown in Fig. 2.2.2.1.

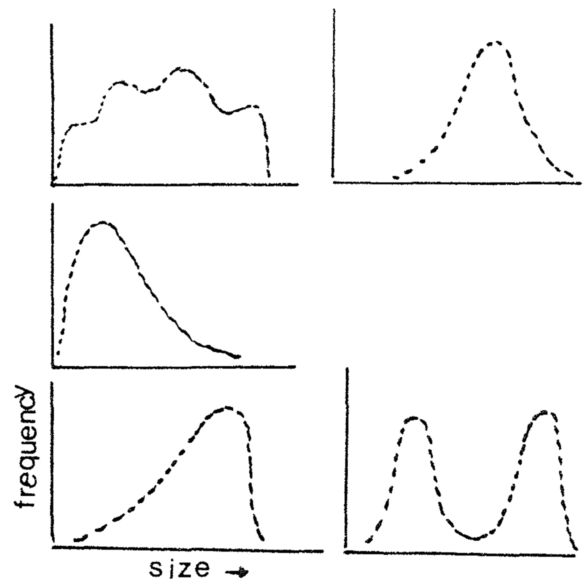


Fig. (2.2.2.1) Various types of powder particle size distribution

In practice, however, this characteristic of the powder is difficult to 'quantify' with certainty, because the actual counting and weighing of infinite number of particles in a particulate mass (powder) is not a practical proposition. These distributions therefore are the estimates of what actually may be the particle size distribution of the powders. They are normally derived through the use of statistical methods of analysis of 'sample data' of the actual powder.

The method used to find these distributions and the way these distributions convey the information on particle size characteristics of the powder is described briefly as follows.

In normal practice samples would be taken from the powder and would be analysed through the 'sieving method' described in the earlier sections. An example of the result of such analysis is shown in Table 2.4. Such data are often presented by means of some types of X - Y plots, the two versions of which are the histogram and the cumulative plot. In both cases one axis may be used to represent the particle 'size' and the other axis may be used to represent the particle 'amount' (Fig 2.2.2.2.)

On the X axis, the diameters of the particles are plotted. However, when dealing with large numbers of particles, which is the usual case, it is convenient to subdivide the particle size axis into size classes. These size classes are described by the methods used to obtain the particle size information. In the case where sieve analysis is used, the size class boundaries should be chosen to coincide with the mesh opening of the sieves.

The histogram presentation of this data is shown in Fig. 2.2.2.3.a. in which the 'Y' axis presents the 'mass' of particulate matter which belongs to a specific size classes on the particle size axis.

The cumulative plot of this data is shown in Fig. 2.2.2.3.b. in which the points entered show the amount of particulate material (in mass) contributed by the particles below the specified size.

The cumulative plot of (Fig. 2.2.2.3.b) can be approximated by the smooth curves provided that size intervals (size classes) are sufficiently small. This is shown in Fig 2.2.2.4.a.

The cumulative size distribution curve (Fig. 2.2.2.4.a), also called cumulative weight fraction curve, rises from zero to unity over the range from the smallest to the largest particle size present.

The distribution of particle sizes can be seen more readily by plotting a size frequency curve such as that shown in Fig. 2.2.2.4.b. in which the slope $\frac{dx}{d_d}$ of the cumulative curve (Fig 2.2.2.4.b) is plotted against particle size (d). The most frequently occurring size is then shown by the maximum of the curve. Any area under the curve and above any interval on the (X axis), $d_2 - d_1$, is the relative frequency with which the diameters of the particles will occur in that interval. The function corresponding to the curve is known as a distribution function. It will be shown later that for a single batch of powder produced by the powder manufacturing process the curve will generally have a single peak. For the mixture of two or many powders, however, the curve may have many peaks.

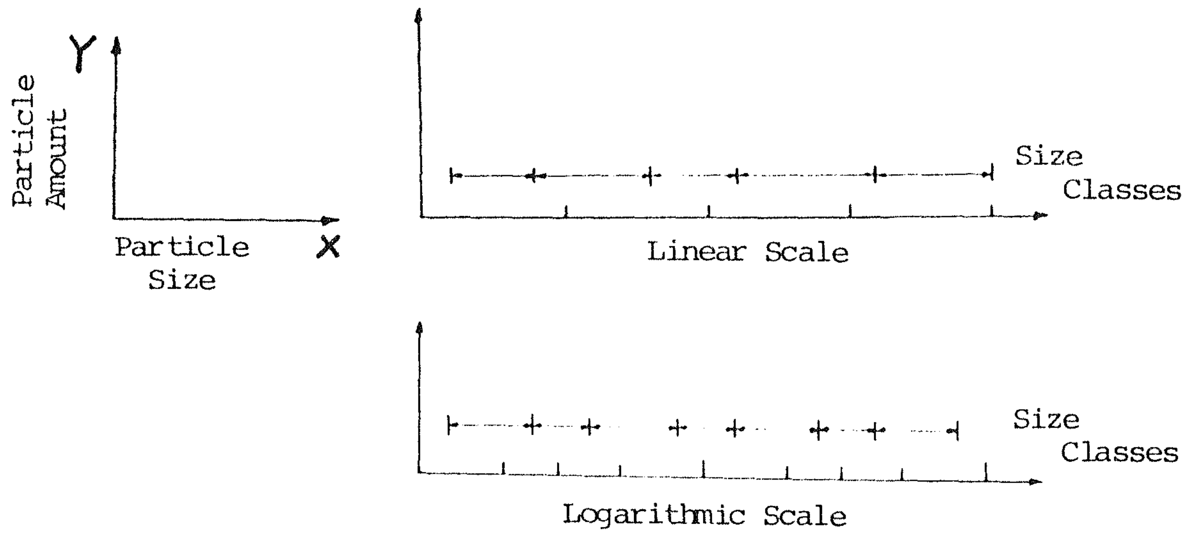


Figure 2.2.2.2. Linear and logarithmic particle size scales, with example size classes

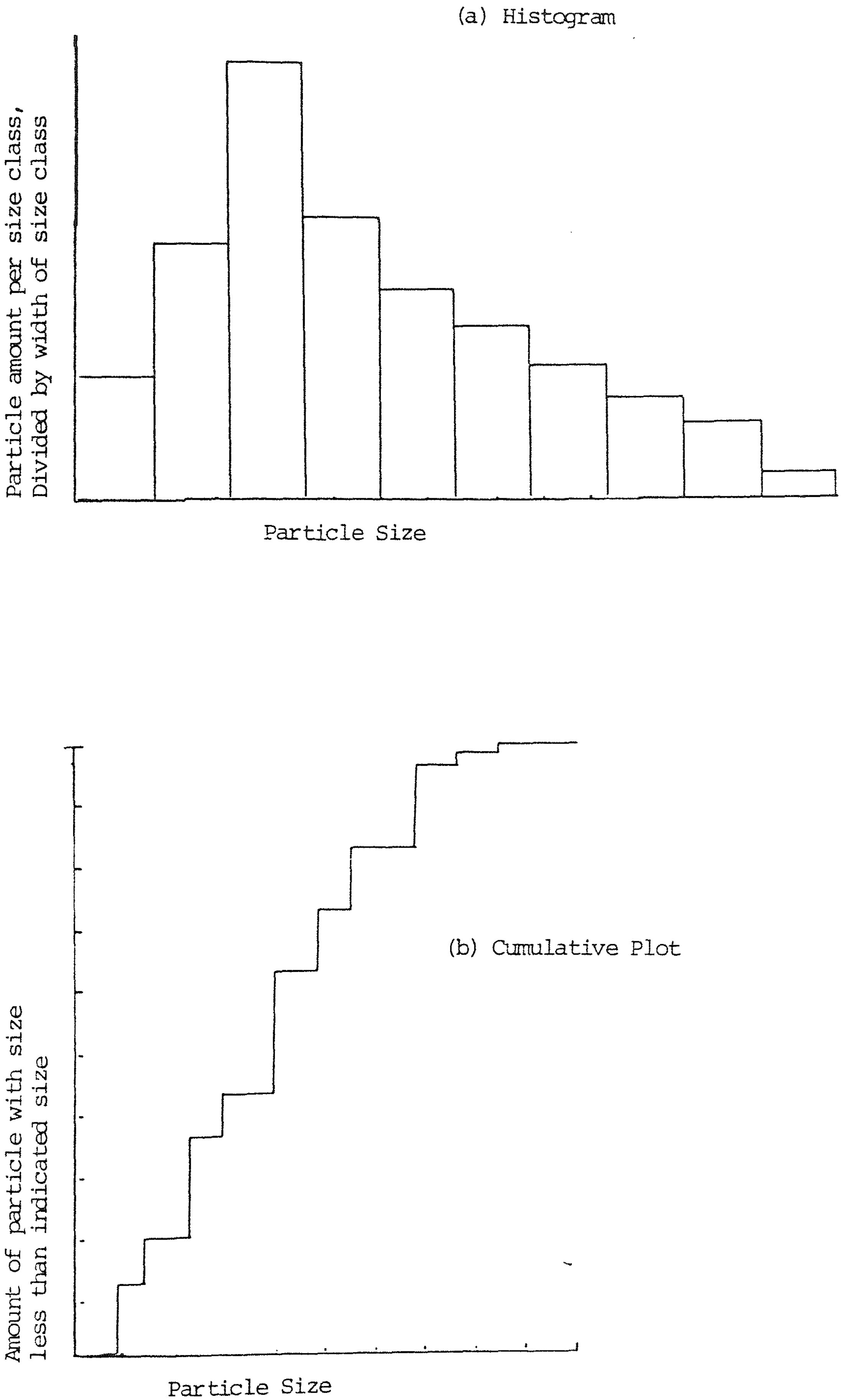


Figure 2.2.2.3. Histogram and cumulative plot

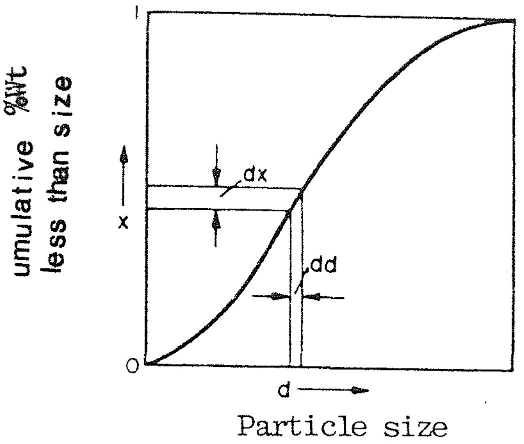


Fig. 2.2.2.4.a. Size distribution curve—cumulative basis

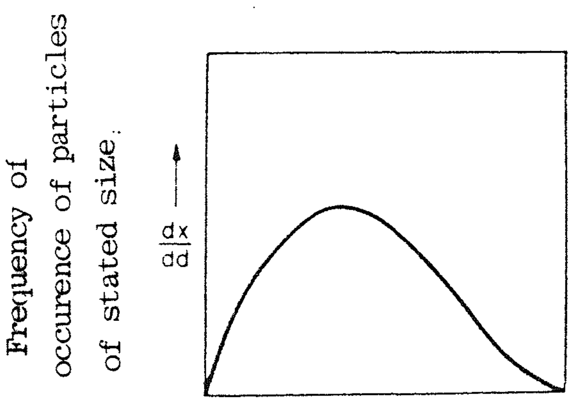


Fig. 2.2.2.4.b. Size distribution curve—frequency basis

Table 2.4 A typical data on particle size distribution (obtained by sieve analysis), after tapping by a 40 mesh screen

Particle size range x_1 to x_2	Mid Class	Amount of the particle matter laid in the class	*Fraction of total weight retained in class i	Cumulative wt% (less than) class i
+500			.46	99.99
-500+250			3.59	99.53
-250+180			6.61	95.94
-180+150			7.71	89.33
-150+106			12.49	81.62
-106+75			17.70	69.18
-75+63			9.24	51.48
-63+45			12.87	42.24
-45			29.37	29.37

* Fraction of total weight lying in the size range = percentage of total weight of powder lying in the size range x_1 to x_2

2.3 The Manufacture of Metal Powder

The production process in a powder making plant consists of several basic metallurgical and mechanical processes and various ancillary but nevertheless important activities which are necessary for the maintenance of powder quality as required by the customer.

The sequence of these operations can be seen from Figures 2.3.1 and 2.3.2 which are schematic diagrams of the process line in two different powder making companies. Both companies produce atomized steel powders.

The operation of both process lines, however, could be categorised into three distinct stages -

(a) Powder formation stage - in this stage the basic raw materials are transformed from their primary state (usually molten state) into their solid particulate forms, i.e. powder would be produced at this stage.

(b) Heat treatment stage - at this stage several metallurgical processes such as hardening, quenching and tempering are applied to the particles, to maintain and control their mechanical properties.

(c) Blending or classification stage - powders are screened so that the desired or standard fractions (size ranges) are separated from the whole. These fractions alone, or in combination with each other, may constitute the (hopefully) marketable products.

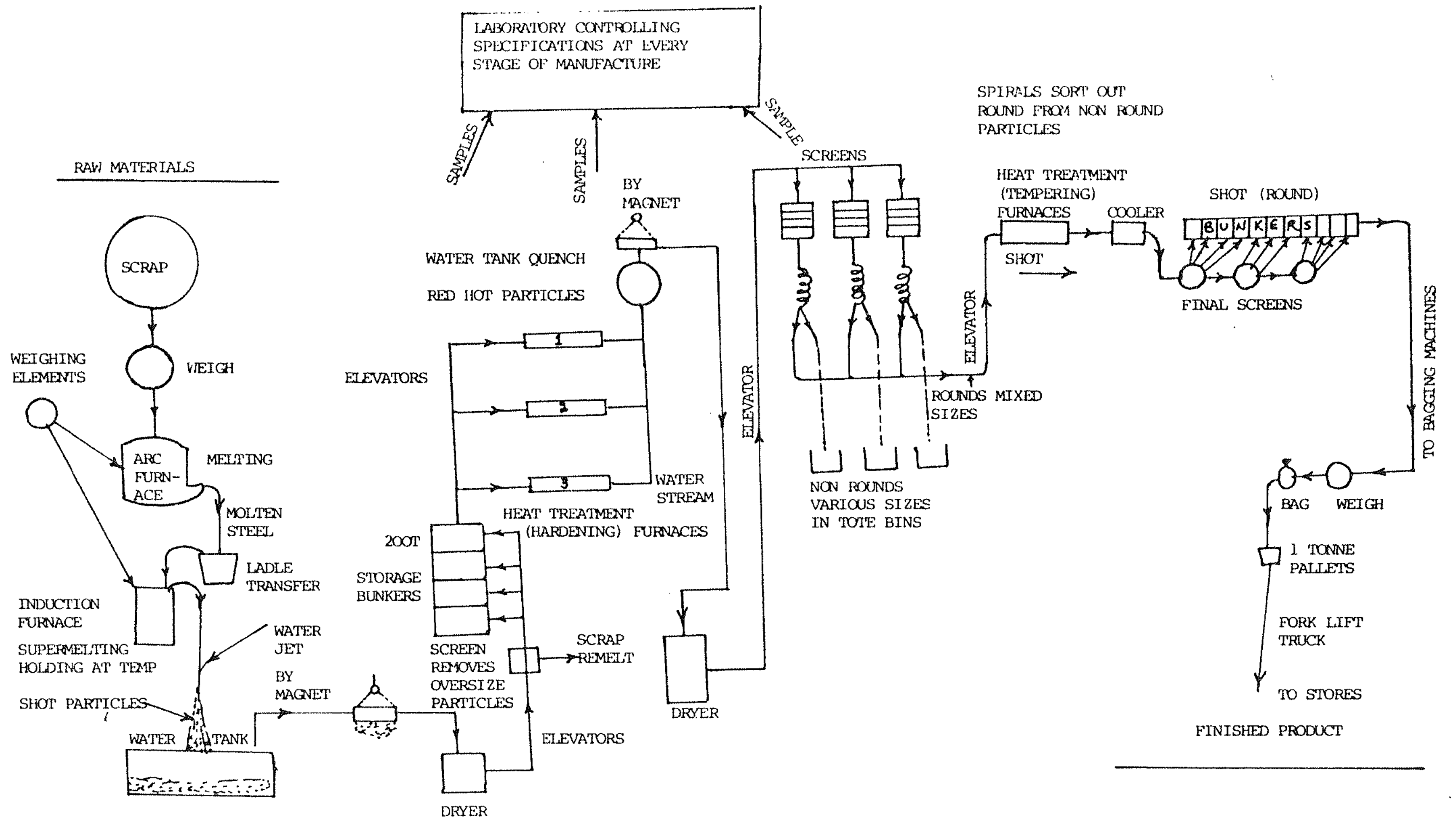
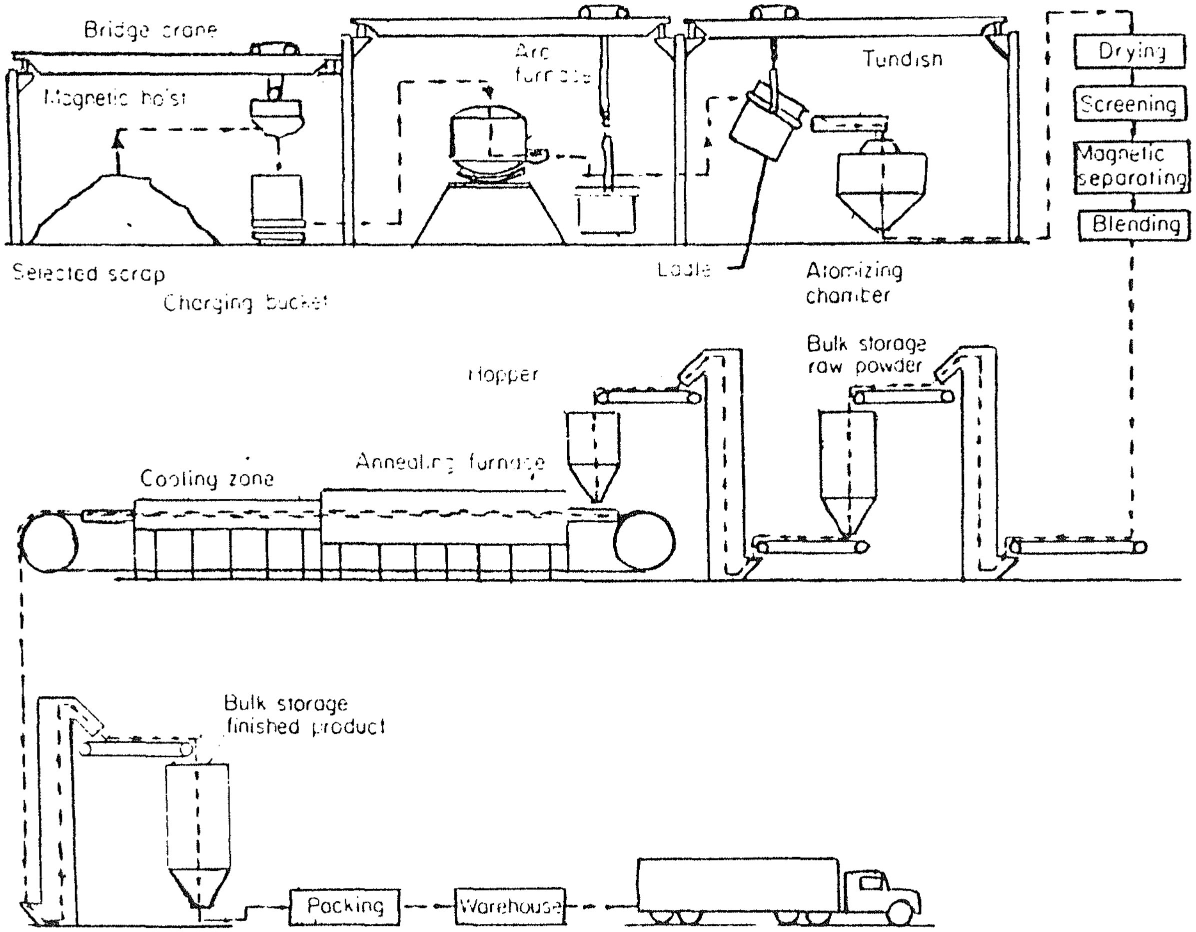


Fig. 2.3.1. Process line making atomized steel powder

Fig. 2.3.2 Schematic diagram of a process line making atomised steel powder



In practice, stages 1 and 3 are the major controlling influences on powder quantity and quality. As a result, most of the study presented here is concerned with these two stages.

2.3.1 Powder Formation Process - Atomization Method

The powder formation process, as the name implies, is a process whereby the basic raw material would be dispersed or disintegrated into it's particulate form, several methods are employed to produce the powders.

Some of the principal commercial methods are listed in Table 2.5 where comparisons are made according to the type of raw material used and the range of metal powders that can be produced.

The method of most interest in this project work is the 'atomization' method of powder manufacturing.

This method is most widely used in high tonnage production compared to the other methods (except the reduction process) which are used primarily for production of special materials in small quantities. (The reduction method is a special case via which iron powder is made direct from very pure iron ore).

2.3.1.1 Atomization Process

Atomization as applied to the production of metal powders, is a process which breaks up a tream of molten metal into individual droplets which subsequently solidify.

TABLE 2.5 Comparison of Principal Commercial Methods of Producing Metal Powders (5)

Method	Raw materials	Powders produced	Advantages	Disadvantages	Relative cost
Atomization	Scrap or virgin melting stock or metal or alloy powder desired	Stainless steel, brass, bronze, other alloy powders, Al, Sn, Pb, Fe, Zn	Best method for alloy powders. Applicable to any metal or alloy melting below 3000°F	Wide range of particle sizes, not all salable. Particles too spherical for some applications	Low to medium
Gaseous reduction of oxides	Oxides of metals such as Cu_2O, NiO, Fe_3O_4	Fe, Cu, Ni, Co, W, Mo	Easy to control particle size of powder. Good compacting powder	Requires high grade oxides. Restricted to reducible oxides	Low
Gaseous reduction of solutions	Ore for leaching or other metal salt solution	Ni, Co, Cu	Ore can be used. Purification during leaching. Fine particles	Applicable to few metals such as Ni, Co, Cu	Medium
Reduction with carbon	Ore or mill scale	Fe	Low cost. Control of particle size, controlled variation in properties possible	Requires high grade ore or mill scale. Applicable mainly to iron	Low
Electrolytic	Generally soluble anodes of iron and copper	Fe, Cu, Ni, Ag	High purity of product. Easy to control	Limited to few metals, cost	Medium
Carbonyl decomposition	Selected scrap, sponge, mattes	Fe, Ni, Co	Produces fine pure powders	Limited to few powders, high cost	High
Grinding	Brittle materials such as Be, high sulfur nickel, high carbon iron, Sb, Bi, Fe, Mn cathodes	Fe, Be, Mn, Ni, Sb, Bi	Controlled size of powder	Limited to brittle or embrittled materials. Quality of powder limits use. Slow	Medium

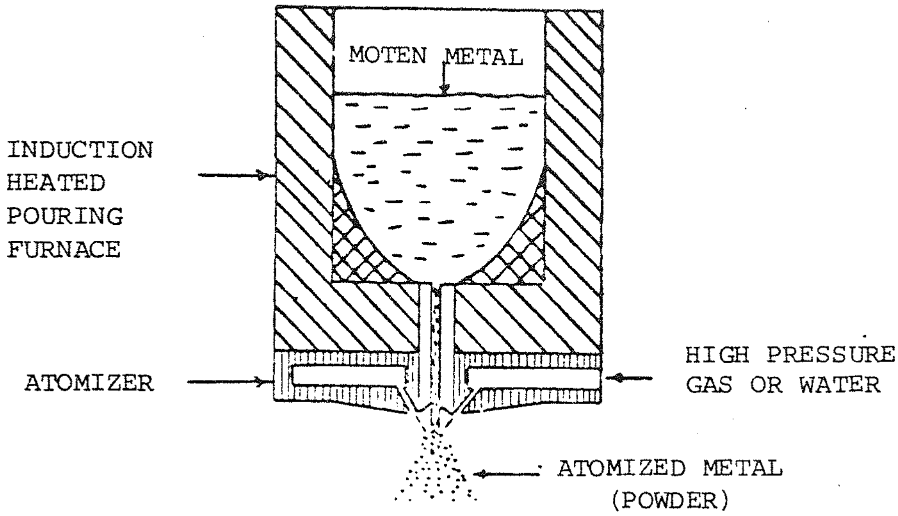


Fig 2.3.1.1.1 SCHEMATIC DRAWING OF TYPICAL ATOMIZING PROCESS (5)

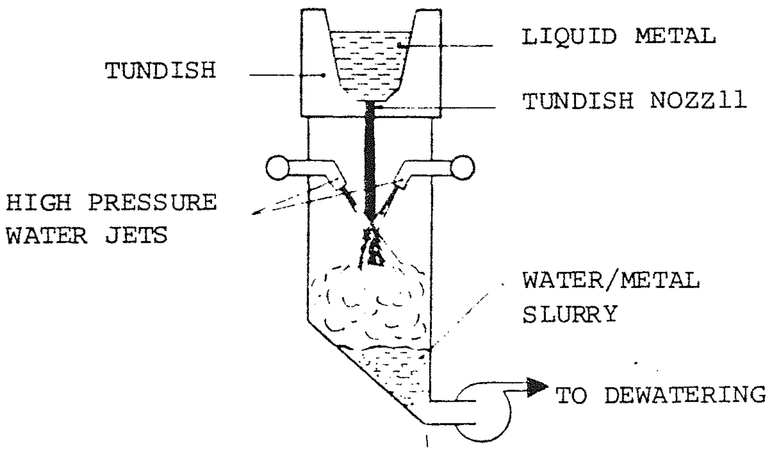


Fig 2.3.1.1.2 SCHEMATIC DIAGRAM OF WATER ATOMISATION (9)

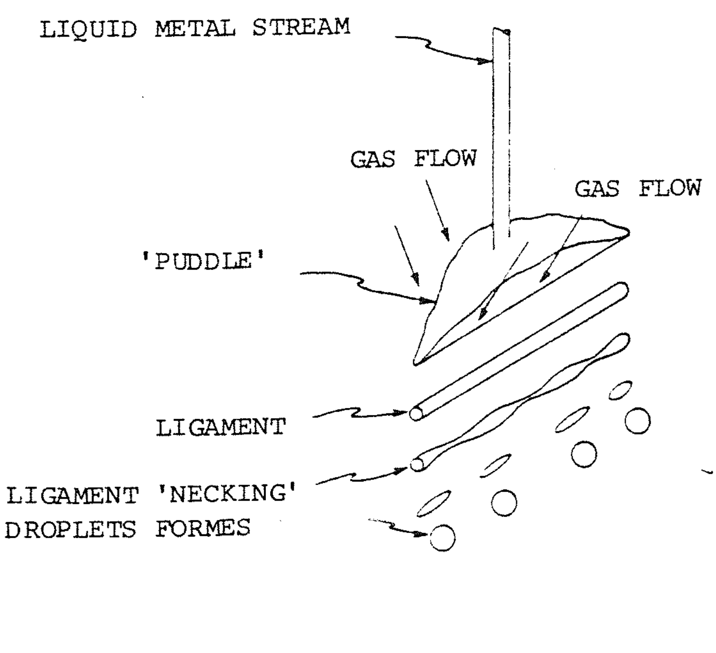


Fig 2.3.1.1.3 The break-up process which leads to particle droplet formation (4)

Atomizing is a simple operation and the number of facilities required for the accomplishment of the process are small.

A full diagram of an atomization plant can be seen in Fig. 2.3.1.1.4. and the details of the operation are as follows.

Molten metal is poured from the containers (ladle or an induction furnace) into a pre-heated tundish. The tundish contains an orifice or nozzle in the base, through which the molten metal flows downward in a smooth stream. This stream meets a high velocity jet of air or liquid from the atomizing nozzles which are held around the stream and below the tundish. The result of this interaction is that the molten stream breaks up into metal droplets which subsequently solidify to form solid particles.

A typical surface morphology of the mass of powder produced can be seen in Fig 2.3.1.1.5. (This particular powder achieved from an Argon Gas Atomization process of IN-792 powder.)[10]

The particle size distribution of this powder, in the form of cumulative % undersize, is illustrated in Fig. 2.3.1.1.6. As it was described in the previous sections a more quantitative information on size characteristics of this powder can be obtained from this distribution.

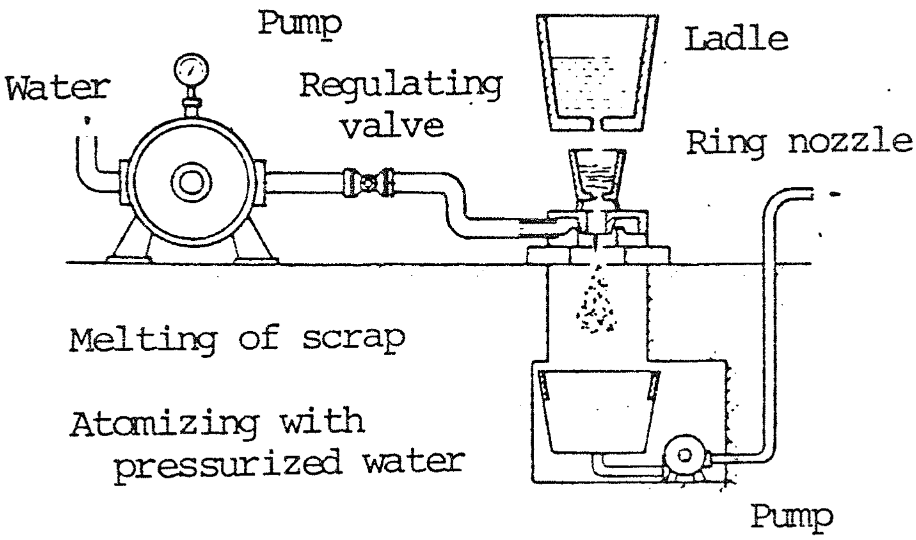


Fig. 2.3.1.1.4 Atomization plant (schematic)

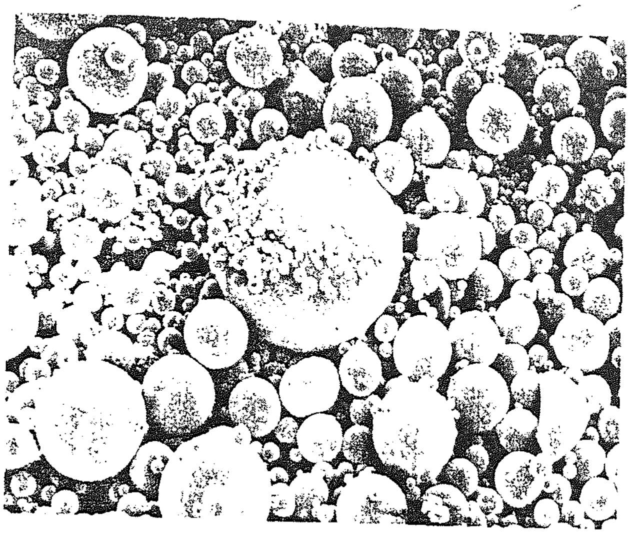


Fig. 2.3.1.1.5 Surface Morphology and Microstructure of Argon Gas Atomized IN-792 Powder (10)

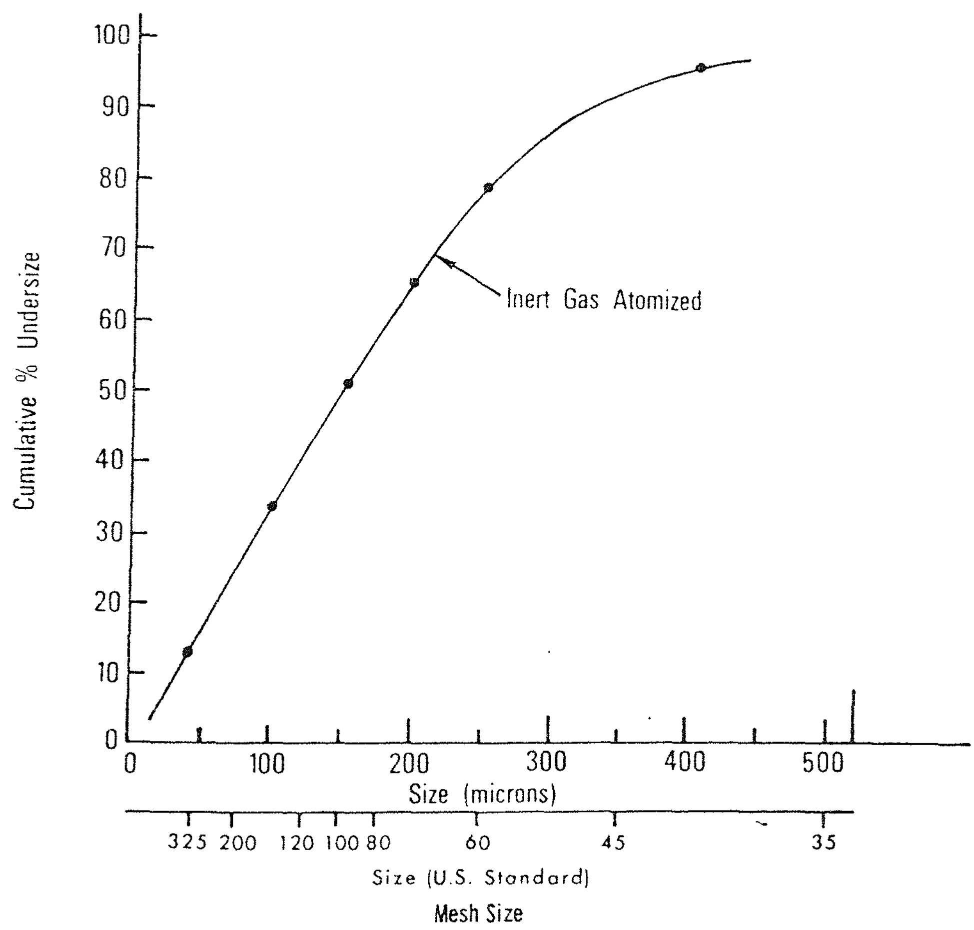


Fig. 2.3.1.1.6 Cumulative frequency distribution of particle size (10)

2.3.1.2. Atomization Process Control - Technological Limitations

Despite the simplicity of atomization operations, the process of atomizing itself is a complex process requiring the knowledge of and control of numerous variables for an effective result (4).
The major variables of an atomization process, whether using gas or water for atomization, are shown in Fig. 2.3.1.2.1. where they are categorised with respect to the entities involved in these processes namely:

1) molten metal properties (viscosity, surface tension, composition, superheat),

2) molten metal flow geometry (metal flow rate, stream length, flight path, manifold geometry),

3) jet geometry (apex angle, number of jets, jet location); and

4) jet flow (pressure, mass flow rate, viscosity, density)

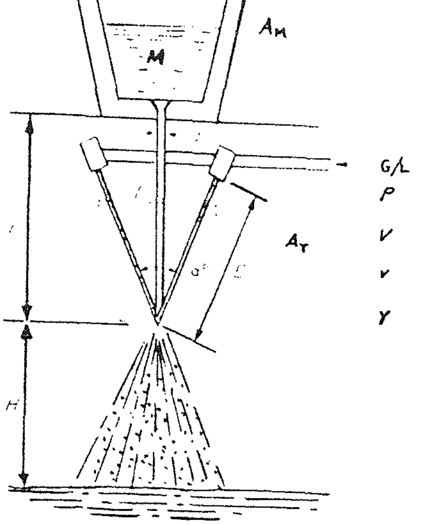


Fig. 2.3.1.2.1 Major Variables of Atomization Process[4]

ATMOSPHERE	During Melting (A_m) in atomising tank (A_t) Temperature Velocity
MOLTEN METAL	Chemistry (M) Viscosity (η) Surface tension (γ) Melting temperature range (Δ/m) Superheat (Δ/Q) Metal feed rate (V_m) Nozzle diameter (d) Specific gravity
ATOMIZING AGENT	Gas or liquid (G/L) Pressure (P) Flow rate, volume (V) Velocity (v) Viscosity (η)
JET GEOMETRY	Spread (D) Length (E) Metal stream length (F) Jet apex angle (a)
TANK PARAMETERS	Flight path (H) Quenching medium (Q)

The problem of finding how these many variables influence the quality of the end product (the powder) has been the most complex and attractive subject in the field of powder manufacturing industry. It has been the central theme of the work being carried out in this field by the various investigators from the fields of engineering and science. A comprehensive survey of these works can be found in the recent book of 'Production of powder by atomization' authored by J K Beddow (4), and in some of the references given in this thesis.

Since this project work is not directly concerned with such technological control problems of the manufacturing process a full discussion on these findings is not pertinent, but they are listed in the Appendix (1) for the sake of completion. However, a few notes are included here as to the apparent limitations that are involved in the problems of process control itself.

a) The atomization process does not lead itself to control for the production of a particular sized particle.

b) Due to the difficulties involved in the measurement of the parameters of the powder, such as, for example the particle size and particle shape which determines its various qualities, the effect of any control upon the quality of the powder is not predictable with certainty. Rather it can be evaluated only in statistical terms.

c) It has been shown (11) that the powders being produced on a specific atomization system have similar frequency distribution i.e. the spread of various sizes among the mean particle size is constant.

This is shown in Fig. 2.3.1.2.2. in which the particle size distributions of three powders being produced by an atomization system have the same shape. They are all versions of one type of distribution whose vertical axis is shifted left or right. This gives a flexibility to produce powders of the 'coarse', fine or medium mean size.

However, narrowing of the shape of this distribution is not possible on existing systems and is possible only by the change of atomization system itself (11). This constitutes a production rate constraint for a powder manufacturer who may desire to make a powder of particular mean particle size. In such a case a plant would not be efficient in producing a powder fraction which is only a small part of the particle size spectrum.

d) In some industries such as the aluminium powder making companies however, even the shifting of vertical axis is apparently limited. One leading company states that their plant can be adjusted to produce only <u>two</u> types of powders 'coarse' or'fine' (Appendix 2) this is achieved by slow or fast rates of air blasting for atomizing.

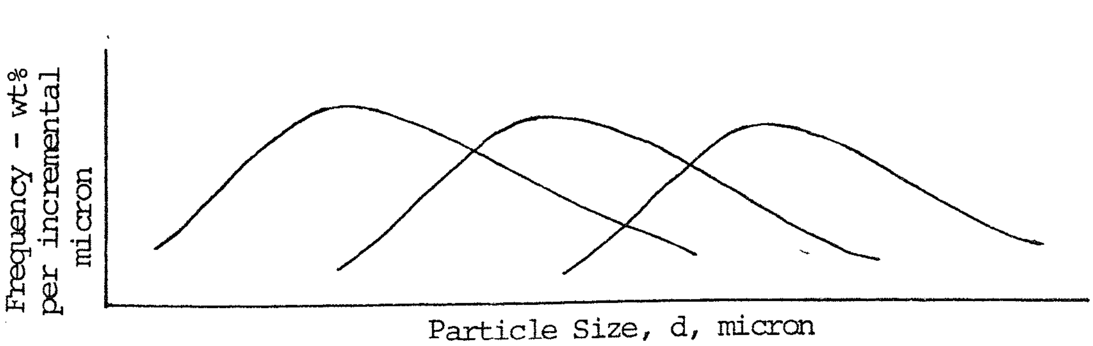


Fig. 2.3.1.2.2 A shift in particle size distribution as a result of changes in process variable.

These are those global technical problems of powder manufacturing at the process control level, which have been considered in this project work. It will be seen in the later sections how these limitations affect the operations of a powder manufacturing business.

2.3.2 Classification/Blending of Base Powders

Screening is the final stage on the process line in metal powder making operation. It is simply a mechanism for splitting the base powders into various fractions which contain the size specification requested by the customers or have a size specification determined by the company's standard. The company's standard is shown in Table 2.6.(12)

The classification of powders through screening is carried out by setting different cloth gauges between the screens. Each of these cloth gauges would permit some part of the powder to retain on them and some pass.

Screens are necessary in metal powder making operation because the production of a powder of the exact size specification as requested by the customer is not possible and thus it has to be made through the mixing of various powders and classifying them into fractions which match to customer-requested products. The cloth gauges among the sieves allow the interchange between products.

There is legitimate flexibility during screening to transfer material from one grade (groups) to the next, as follows:

TABLE 2.6 FULL SPECIFICATION OF PRODUCTS (12)

				FINAL PRODUCTS (j)						
	Size Classes	Sieve Opening mm	(Mesh Size)	Product No 1 660	Product No 2 550	Product No 3 460	Product No 4 390	Product No 5 330	Product No 6 230	Product No 7 170
CONSTITUENT MATERIAL (PARTICLES)	Size Class No 1	2.00	8	Min	All Pass					
	No 2	1.68	10	87%	Min	All Pass				
	No 3	1.40	12	Max 13%	87%	Min	All Pass			
	No 4	1.20	14		Max 13%	85%	Min	All Pass		
	No 5	1.00	16			Max 15%		Min	All Pass	
	No 6	.850	18				Max		Min	All Pass
	No 7	.710	22					Max		

S. 660 S. 550	Manipulation ± 25%
S. 550 S. 460	Manipulation ± 25%
S. 460 S. 390	Manipulation ± 25%
S. 390 S. 330	Manipulation ± 25%
S. 330 S. 230	Manipulation ± 10%
S. 230 S. 170	Manipulation ± 7%
S. 170 S. 110	Manipulation ± 10%
S. 110 S. 70	No manipulation

The above manipulation, of course, could be seen from Table 2.6.

CHAPTER THREE

MANAGERIAL PROBLEMS OF PRODUCTION CONTROL AND DECISION MAKING IN METAL POWDER MANUFACTURING INDUSTRY

3.1 Introduction

It was shown in the previous chapter that metal powder manufacture involves a complex technological process which is controllable only to a limited degree — The production rate response of the process for individual particle sizes or particle size ranges can be changed only to a certain limited degree. A change in the plant setting (i.e. control variable) results in the achievement of a different size distribution spectrum in the powder and thus, different production rates for each individual particle size. This variation in the production rate of individual particle sizes however, takes on only limited value because the size distribution spectrum cannot be changed to any desired extent.

It was also shown in the same chapter that a precise 'qualification' of the process output (i.e. the powder) is not possible because the actual measurement of the infinite number of particles of the powder is impractical, and the size characteristics of the powder only, are identified through a statistically drawn frequency distribution of various sizes that are present in it . Thus the production rate-response of the process for individual particle sizes are only a statistical estimate of the actual production rates and are not the exact values.

This chapter describes the problems and difficulties that the managers in this type of industry are confronting in their tasks of organising and controlling production in these circumstances.

These features of this industry particularly when considered along with the lack of precise information on market demand, which is partially allied to these features of the industry and partially related to the diversity of the qualities required from the powders' various applications, bring about increased difficulties in planning and controlling production in this type of industry. The managers in this industry have many problems in deciding upon the quantities of various grades/size distribution of powders to be produced at each planning period to satisfy the requirement of the order book. Their problems are mainly related to the lack of precise information on demand, on current stock level and on the utility of each of their powder products in a multi-choice situation - all of which are difficult to obtain because of the possibilities of 're-seiving' of powders, and the continuous monitoring of the products specifications, both of which are necessary for increasing the production efficiency.

These difficulties, which have led to the need for the approach taken in this work, are considered in more detail in the next few pages.

3.2 The Nature of 'Production' in Powder Making Industry and the Basic Problem Involved

Before describing the problems of production control in any manufacturing situation it is required that the production should be clearly defined - What is the work to be planned and controlled?

Considering the characteristics of metal powder as a product, the production in metal powder manufacturing industry is typified by manufacturing in batches of continuously variable products whose charactistics are described only by a statistical probability distribution. Fig 3.2.1 illustrates an oversimplified schematic diagram of the batches which have been produced at a process run.

The products shown in this diagram are in essence made by various combinations of the particles of various sizes drawn from a continuous spectrum of such particle sizes produced by the process in a production 'run' or 'campaign' using a particular plant setting. In this simple diagram the number of particles of each size that are present in each product can be counted and thus the products can be identified. This measurement, however, is not practical in the 'real' situation. Rather, these products have to be identified through the particle size distribution of the whole batches of the powder being produced. This identification takes the following form:-

<u>"The probability that the powder contains the product$_1$ is......"</u>

Thus the production-rate response of the process for each product that can be made through the process is uncertain.

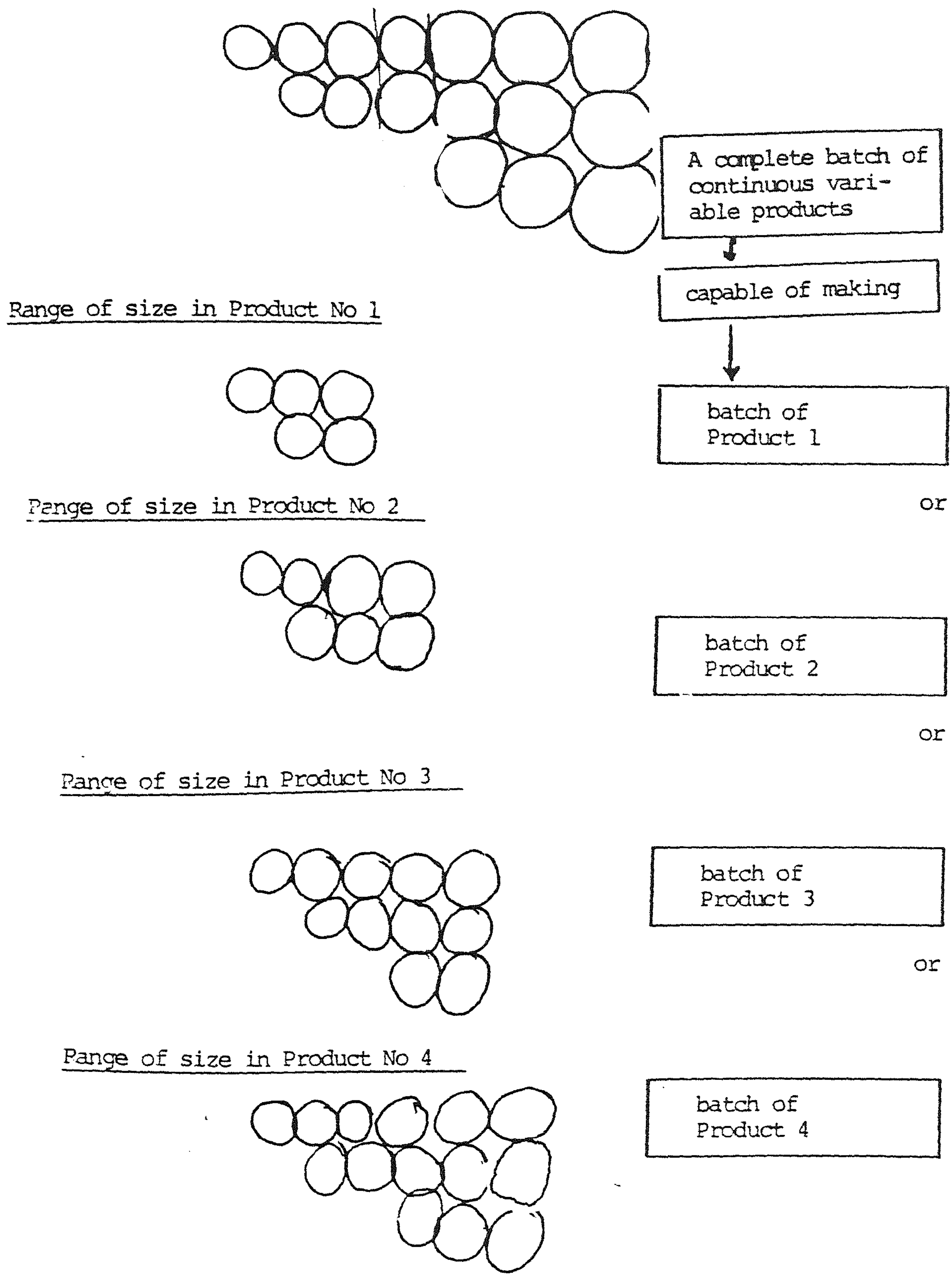


Fig 3.2.1. The various batches of products that can be produced in a process 'run'

This problem, however, is complicated even more by the fact that, from the several powders that can be produced through the process (each having different occurrence probabilities for individual particle size or products) none of them would match the customer-requested powders exactly, except on very infrequent occasions. And the powder manufacturer has many difficulties in finding the exact combination of powders which can best match the requirements of the many customer orders that he must supply every day.

An example of the mismatch between the two (product and request) is shown schematically in Fig. 3.2.2. in which the curves 'B' and 'C' are representing the size distributions of the two different batches of powders produced by the process and curve 'A' represents an assumed size distribution for a customer-requested powder.

The nature of this mismatch can be described either with respect to the mean particle size of the powder or with respect to the several particle size ranges included. The first case is a less rigorous measure than the latter, but describes the mismatch more easily therefore it is considered here first and explained as follows:-

It can be seen from the figures that curve 'A' represents a powder whose median particle size equals to d_M. This implies that such powder requires that 50 per cent of its weight be contributed by the particles whose sizes are below the size d_M.

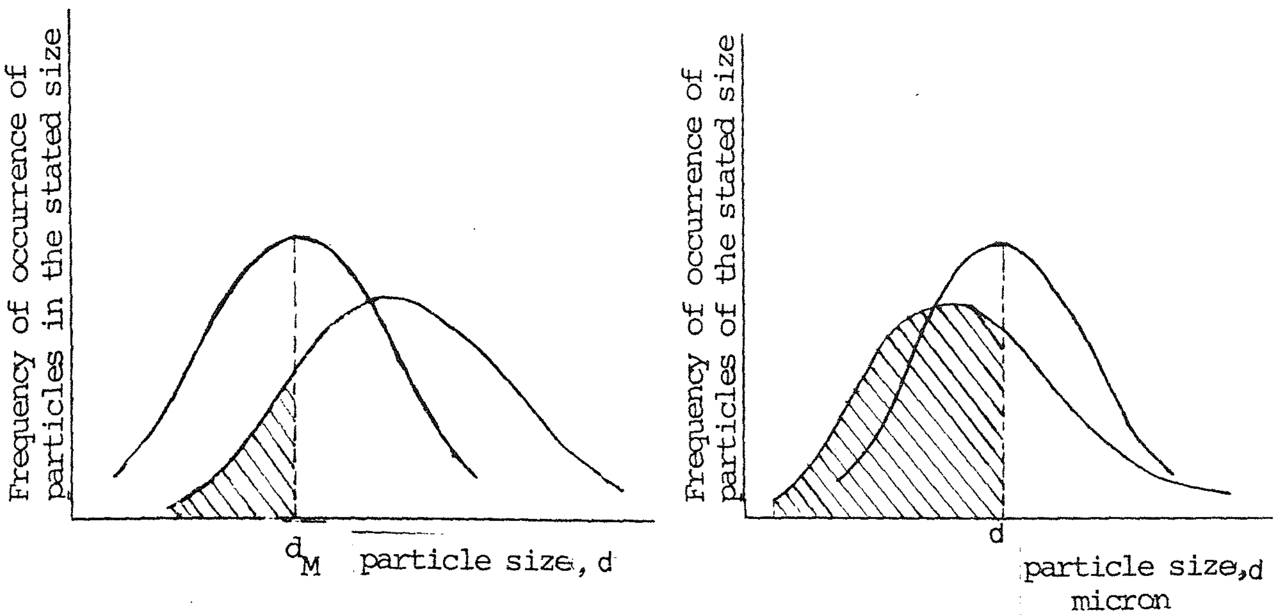


Fig. 3.2.2 : Comparison between the size distribution of powders that are produced through the process (B and C) and the customer requested powder (A).

If considered in probability terms, the probability that any particle drawn from this powder having a size equal to or less than d_M should be 50 per cent.

Considering the curve 'B', which represents one of the powders being produced by the process, it shows that the probability of a particle drawn from this powder (Powder B) having a size equal to or less than d_M is only 20 per cent (the dashed area shown under this curve represents this probability, the whole area under the curve being 100 per cent.)

The powder of curve 'B' therefore cannot be accepted by the customer. But if this powder is going to be used to make the powder of curve 'A' the production of more than one batch may be necessary in practice. These batches should be mixed and sieved in order to generate a powder having the size distribution consistent with the powder of curve 'A', ie. having a median size equal to size d_M.

In this respect the powder represented by curve 'C' has a better chance of matching the powder of curve 'A' because the probability that a particle drawn from this powder has a size equal to d_M is greater than that of powder of curve 'B'.

However, in practice, the size specifications given by the customers' orders are more rigorous and includes the limitations for several size ranges. For example, the powder represented by curve 'A' in Fig. 3.2.3 may be required to be made to match the following specifications:-

a) It should have a size range between d_1 and d_5 (d_1 is the size of the finer particle and d_5 is the size of the coarser particle in the powder.

b) At least 85 per cent of its weight should be contributed by the particles whose sizes falls between d_3 and d_4 (ie. being smaller than d_4 but greater than d_3).

c) Only 12 per cent of its weight is allowed to be contributed by the particles whose sizes fall between d_2 and d_3.

d) And only 3 per cent of its total weight is allowed to be contributed by the particles of the size smaller than d_2. Characteristic is illustrated in Fig. 3.2.3.

This requirement would make the mismatch between the powders more clear. Both powders of curves 'B' and 'C' have different overmatch or undermatch fractions of the particles in this respect.

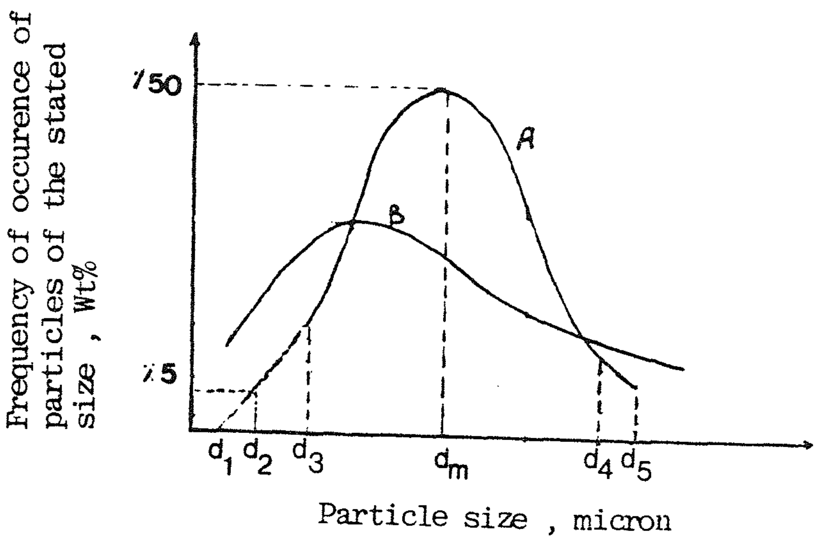


Fig. 3.2.3. Comparison between the size distribution of powder product(B) and the customer-requested product (A)

The two above simple examples revealed the <u>basic</u> problem encountered by metal powder manufacturers namely, the difficulty in comparing the products that they can achieve through the process with what the customer might request. And the difficulty they would have in modifying the process output to match the request.

These examples described the comparison between the powders achievable through the process and only <u>one</u> customer-requested powder. However, in practice the powder manufacturer must every day examine the products that he can achieve through the process against at least 100 customer-requested powders each having a completely different size specification. This would obviously be a difficult task.

3.3 Planning and Controlling Production in Metal Powder Making Industry/Operation - The Problem

3.3.1 The Production Planning Decision

The mismatch between the powder products that can be produced through the process and the customer requested products would often result in production deficiency because it requires more batches of base powders to be produced to satisfy the requirements of the customer-requested products.

The situation would be worse in the cases where the customer-requested products demand for small definite proportions of the base powders and in particular when the fractions, demanded by these products, overlap on each other. An example of this case is shown in Fig 3.3.1.1.where areas under the curves are related to the amount required.

In each planning period the manager is faced with this type of problem and he must decide upon the total quantities of the base powders to be produced to satisfy the requirements of these order.

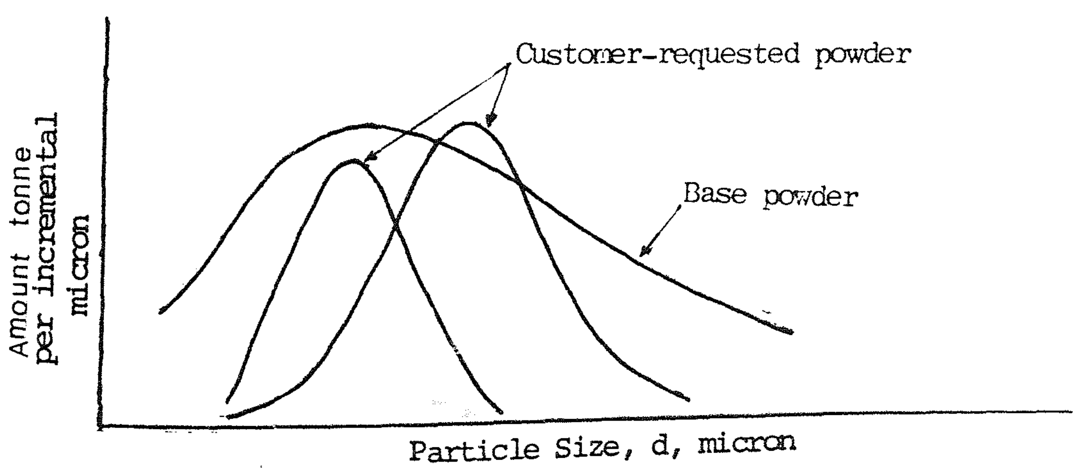


Fig.3.3.1.1 The overlap of customer-requested products.

It is this problem of metal powder making industry which is of most concern in this study.

Production which exactly duplicates individual customer demands would not be economic , hence the manager has to examine the following possibilities before he can make a final decision on production requirements :

i) to integrate the various customers' orders which are due at various due dates so that the economic production runs could be achieved.

ii) to ask the customer to accept the products of slightly different size specification but of a closer performance quality to what they requested in order to make use of wider fractions of base powders.

iii) to check the possibility of 're-sieving' the stock of 'slow mover' or 'undesired fractions' which have remained in stock from previous production periods in order to fill some portion of the requirements.

iv) to check the materials which are yet in the process and are either allocated to some less significant orders or have not been allocated to any orders., i.e. those fractions which would be generated as a result of producing and classifying base powders to meet the requirements for desired fractions.

The consideration of the third and fourth options(i.e.using stock materials and in-process materials) are part of the managers dision-making process because the 'amount'of these materials is relatively high in most metal powder making operations. As a result 'stock' consumes a large amount of company cash.In particular in those powder-making companies who operate continuously at an output rate of 100 tonnes per day, the considerable amount of these materials would accumulate quickly and must be used before new portions are added during the next production runs.

3.3.2 The Problem - Lack of Precise Information and the Complexity of the Decision Problems

The managers in metal powder making industries cannot make the potential use of the options which were outlined in the previous section and which are the major source of increase in their production efficiency. The reason for this is that they have many difficulties in obtaining up-to-date and accurate information which they need to use these options more effectively. For example, he has no access to the information on which products the customer has been accepted in the past instead of this-requested product, and he has no accurate information on the actual level of stock materials that he can use to fill the requirements of his order book.

The stock materials are often difficult to specify precisely, because the exact record of the materials are not kept and because these materials have been subject to continuous and irregular changes which are caused by the manager's decision to 're-sieve' them. Since these decisions are not often recorded and because the state of the material has not been up-dated after each decision, an exact

specification of the material is impossible.
However, since the stock materials are not always specified, the manager has no chance to make potential use of them.

In the case that information on stock material is available, the allocation of available material to the requirements is itself a difficult problem. The difficulty arises due to the fact that the manager has to make a decision on simultaneous allocation of several limited available materials to many customer orders who are competing for these limited materials and who have various priority or value to the company. An efficient allocation requires the computation of,and solution to, many simultaneous quations which is something beyond the capability of the decision maker and the time available.

However, some customer demands can be met from stock whereas other demands may be pushed into the future for supply from future manufacturing capacity. In manufacturing,the manager (decision maker) faces the original problem which has been stated in the previous section - He must select from amongst a number of powders that he can produce through the process, that powder or combinations of powder which will meet the production requirements <u>and</u> satisfies multiple criterias of plant performance. In this stage of decision making he must be able to evaluate the utility of each powder against these requirements.

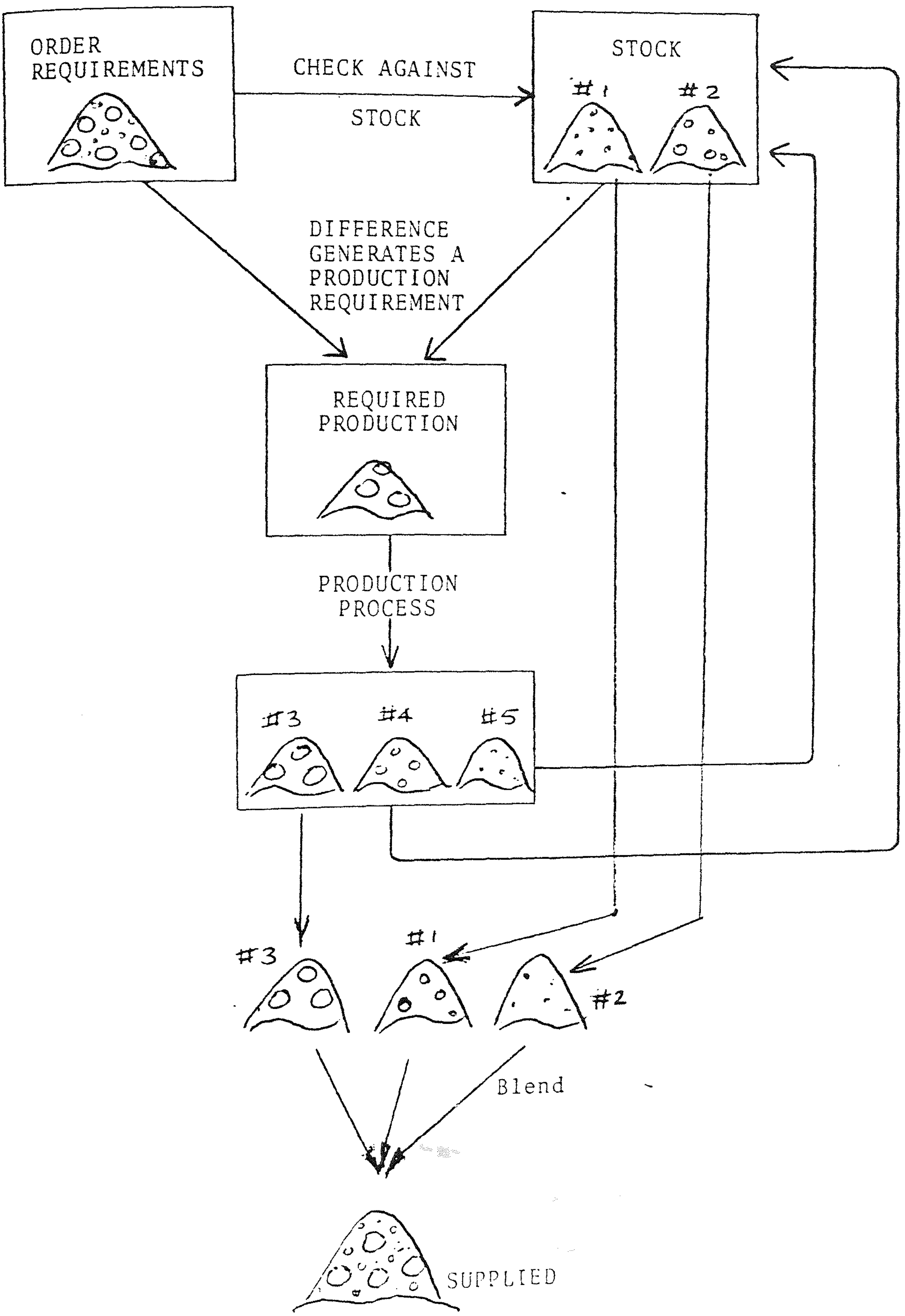
The selection of powders to be produced to meet the present requirement should take into account the fraction which would be generated as a result of classifying the powder to satisfy the requirements.

An example of a case where the requirements of the order book could be met partially through the use of stock material and the rest of it should have been made by the manufacturing is shown in Fig. 3.3.2.1.

As can be seen from this diagram, the excess fractions which would be generated might not be of immediate use but the question is whether they will be of use in filling the future requirements of the order book.

When the level of requirements are high and the production of various base powder in different combinations should be decided, the determination of the cumulative result of such schedule presents great difficulty. It requires again many computations of and solutions to a number of simultaneous equations.which is difficult for human decision-maker.

FIG 3.3.2.1. Schematic diagram of order processing in Metal Powder Manufacture Industry.



3-4 Summary of the problem

The managers in metal powder making company may have difficulty in determining:

i) Whether a particular customer requirement will be "in stock" at the time it is required as a result of production of complementory fractions for other customers in the same class of quality.

ii) If not, when can a production be fitted in?

iii) What production settings ?(Those which produce course, medium, or fine)- is desirable for this specific requirements .

iv) What other fractions will be generated by the sieving operation necessary to give the customer the fraction he wants?

v) What quantities of these fractions will be in stock as a result of this when these powders have been produced etc.

So far the manager has had to do many tedious calculations and computations to answer these questions and by this process he was not always sure of the consequences of the final decision. On occasions he did not involve himself with making these decisions because it was too tedious and time consuming. In this circumstance the operations are left either uncontrolled, or left under the control of the Forman, who is not always aware of the policy of the manager. The consequence of inconsistent decisions were often costly. These are exemplified in a high level of stock of the 'wrong' or undesirable fractions, and a low level of stock of products in more demand.

These tactical problems of powder making industry have not yet been approached, as far as the literature survey of the author is concerned, by any previous works which are carried out in this sector of the industry.

CHAPTER FOUR

ALTERNATIVE APPROACHES TO THE MANAGERIAL PROBLEMS OF PRODUCTION CONTROL AND DECISION MAKING IN METAL POWDER MAKING INDUSTRY

4.1 Introduction

The previous chapter has revealed that managers in metal powder making industry have to make their various planning and controlling decisions in a complex and uncertain environment, i.e. in a situation where they can not have access to up-to-date and accurate information on demand, and on current stock level. Also they have to make their decisions in a situation where they have difficulty in assessing the utility of each of their powder products in a multi-choice situation.

It was also shown in the same chapter that all these problems are caused by the attempts of the manager himself to utilize the many options which are possible to him and are the major sources of increase in efficiency of his plant production. The options were:

- 're-sieving/modifying' of the stock materials
- influencing the specification of customer ordered products.
- integrating and postponing various customer products so that an economic production was achievable.

Making decisions in an uncertain environment would certainly result in inefficient production. The consequences would be more costly when the manager turns away from making the decision because it is too difficult for him to understand the system which he controls (this normally happens in most metal powder making companies.)

It is obvious that in these circumstances the managers in this industry should see the solution to their problems coming from an approach which could provide them with this information and make their environment more certain.

There are two approaches which would immediately suggest themselves as solutions to this managerial problem.

The first approach is to provide the manager with a computer information system. One such system which suits the metal powder manufacturing industry would comprise a stock file, an order file and a 'customer intelligence file'. A schematic view of this system is shown in Fig. (4.2.1) in Section 4.2.

This approach would consider a decision making process similar to the one used by the managers at present, but their decision making would be aided by the ready availability of information.

The second approach to the managerial problem of production in metal powder making industry is the 'mathematical programming' approach. This approach would both mechanise the decision making process of the manager and would make the use of an operation-research optimizing technique to solve the problems in the 'best' possible way. This approach, therefore, would be concerned with the complexity of the decision-making process of the manager. It recognizes that in each of his decision problems the manager has to work out the vast number of alternatives which are possible to him and make a choice from among them. This approach would release the manager from this difficult task by giving it to the computer which can do the job with high accuracy and speed.

Both approaches have a great impact on the decision making tasks of the manager and significantly contribute to the efficient utilization of the plant resources and capacity.

These approaches are outlined in this chapter and a choice is made by the author to deal with the one which appears most 'suitable'. The full details and applications of the approach to managerial problems of metal powder-making industry is illustrated in the next chapter.

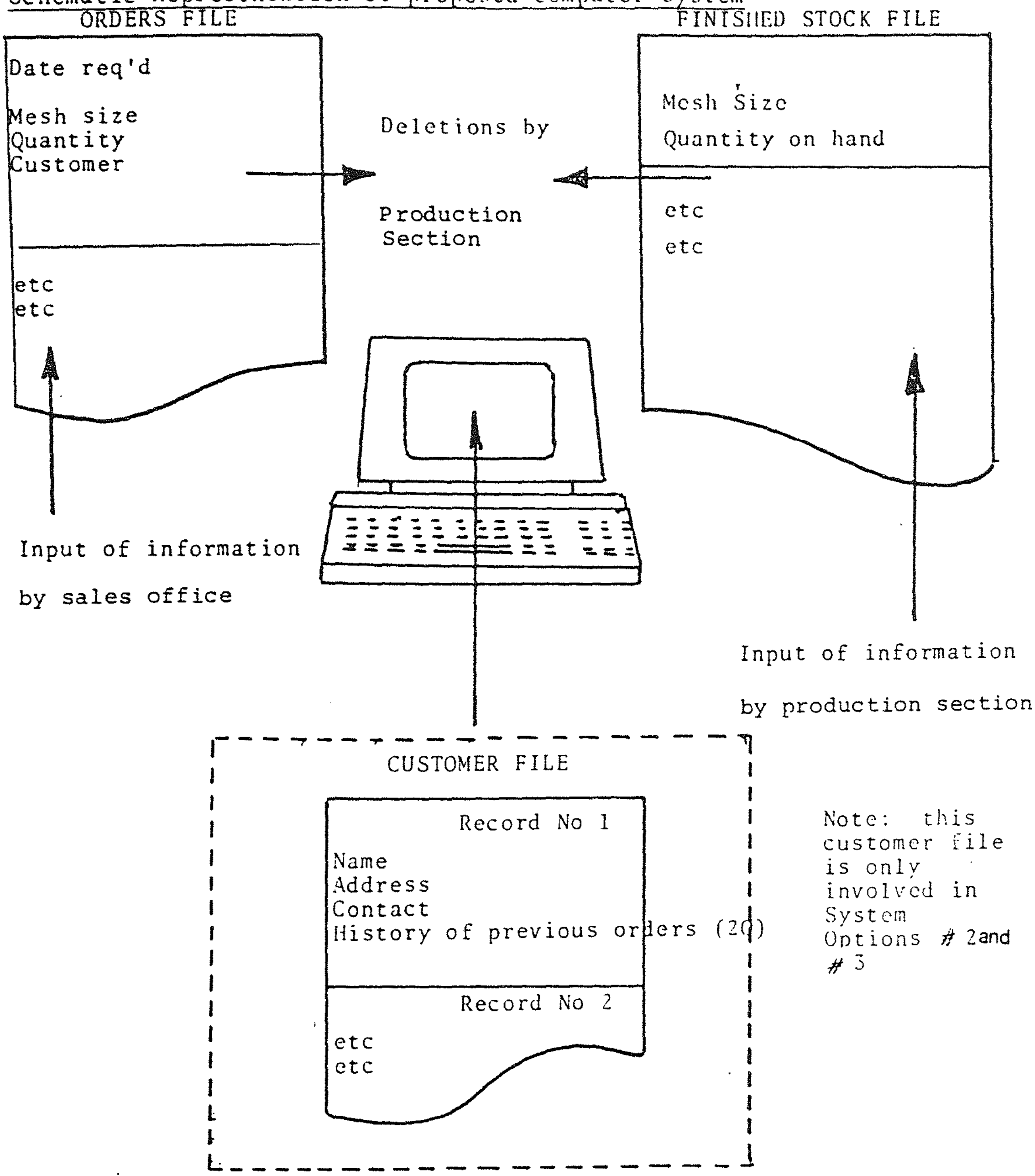
4.2 - The Computer Information System - The First Approach

The computer is an ideal data-storage agent. In addition to this it has the capability of processing the information in many permutations at high speed. Both characters are what a metal powder-making company requires if it is to operate more efficiently. To run a metal powder-making operation more profitably (efficiently) it requires that the manager has access to up-dated and accurate information on the current order book, current stock levels and production output. The system shown in Fig. (4.2.1) would facilitate this. Indeed, a feasibility study being carried out by the author in conjunction with a consulting company who have experience in this field revealed that this approach can be successfully applied to the problems met in metal-powder making companies. A few schemes were proposed which could cover the whole necessary flow of information and decisions for planning and controlling production in metal powder-making industry.

A brief outline of these schemes is given in the following sections. However, these schemes consider the flow of information between the office which may be called the 'management' side of the company who make the production decisions (usually the sales office may be responsible for this decision making), and the production section which execute the decisions and informs the management section on the status of stock and production output.

FIGURE 4.2.1

Schematic Representation of proposed computer system



The schemes are separately discussed to show their degree of complexity.

Scheme I - This scheme uses only the two files shown in Fig. 4.2.1.

An ORDERS file - containing details of individual customer orders - Required Date, Powder Mesh Size Range, Quantity Required.

A FINISHED STOCK file - containing full information on finished stock levels - Powder Mesh Size Range, Quantity on hand.

The ORDERS file would have items added by the sales office (i.e. new orders or alterations) and items deleted (or archived) by the plant manager (i.e. completed orders that have been dispatched).

The FINISHED STOCK file would be maintained by the production plant and amended every time a stock movement occurs (more likely this would be 'batched' and actually accomplished on a daily basis).

Whenever a production programme is required, the system will first sort the orders into 'required date' sequence, with 'overdues' the head. A manual decision would next be made to indicate which orders were to be included (i.e. satisfied) in the production programme. The system would then scan the order requirements, and sum the total quantities needed for each powder quality/mesh size range. The available stock would be automatically referenced and the balance printed in the form of a list of production requirements.

Based on these 'batch' requirements the sales manager would notify the production section on the production programme to implement for the period under consideration.

During the period, production section would be amending both the ORDERS file and the FINISHED STOCK file. At any time, the manager at sales office could enquire as to the state of the order book, levels of finished stock etc.

Scheme 2

Here, a further source of information in the form of a customer file would be added to aid decision making. Such a file would consist of records on individual customers containing such data as: Customer Name and Address, Contact Name, History of Previous Orders (say, the last 20), etc.

Before instructing the system to 'batch' the Order Book requirements, each order could be reviewed in turn. The system would simultaneously display (on a computer VDU) the corresponding customer details from the CUSTOMER file. The sales manager would then have the opportunity of overriding the actual order details by substituting an alternative mesh size range - because it would be known (from the recorded details displayed from the CUSTOMER file) that the customer had previously accepted this compromise. The decision to override could be based on several criteria, and might vary from time to time. For instance, it might be necessary (or'desirable') to use up an existing stockpile of a particular mesh size. It is fully realised that on occasions a 'better quality' specification might have to be supplied for what is in effect a lower price. Nevertheless, such a course of action may be preferable (all things considered) than, say, having to organise a manufacturing run for just one order item, and as a result, being left with quantities of mesh sizes not immediately saleable.

Scheme 3

All preceding schemes take as their basis the order book between two given dates, and tenaciously assume that 'required delivery dates' have been met.

On reflection, it would appear sensible to review the entire Order Book in certain circumstances to establish whether the 'surplus' finished stock generated by satisfying 'immediate' orders could be used up by orders already in the pipeline.

Alternatively, delaying the production of certain orders that are known to give rise to unacceptable finished stock levels with the present order mix, may alleviate the problem when they are slotted in with a different (i.e. future) batch.

Thus, it would appear to be desirable to have the facility to either widen or narrow the 'window' of required delivery dates on orders to be included in the Production Programme for a given period. Consequently, certain orders would be made earlier, and others later, than the requested delivery dates.

As with other decisions discussed, such alterations can only be made by management on an individual basis. Much will depend on the customer concerned, and again, the information stored in the CUSTOMER file will prove to be extremely useful as an aide-memoire.

If properly structured, the CUSTOMER file could also act as a very effective Marketing System in its own right. For example, if every customer is coded according to the usual products purchased, it would be possible for the computer to locate potential sales for any given mesh size of powder. Such a feature would prove very useful if stocks built up to high levels, by directing the sales efforts at good prospects (possibly by making 'offers' if order are placed quickly).

4.3 - Mathematical Programming - The Second Approach.

The previous approach assumed that the manager will still make his own decisions and it provides him with a facility which enables him to obtain the information which he requires for his decision making. It did not, however, concern itself with the problems that the manager faces in his actual process of decision making. Nor could it assure the manager that the decision he has made is the best possible one.

In each decision making situation, there are several alternative decisions, among which the decision maker has to make a choice. The selection of a decision which is apparently the 'best' requires a thorough evaluation of these alternatives before the final choice is made.

In the case of metal powder manufacturing operations, each decision which should have been made by the manager involves several alternatives, the consequences of which are difficult to evaluate by the human decision maker. For example, in his decision to allocate the available stock of specific 'mesh size' to the customer orders there are vast numbers of possible routes for blending these materials into the final products. These possibilities arise due to the fact that the different customers' orders have different values to the company and/or they have different size range flexibility which permits the various proportions of that 'mesh size' to be allocated to that order. Each of these possibilities when selected is a program of action or a strategy. Obviously, the manager would like to know which is the best of these alternate possible actions. The 'best' is the one which may incur the least cost or may be the one which yields the highest profit.

In such problems, often with only a small number of products and a small number of raw materials (here mesh sizes), the computation of the best allocation programme would be very difficult and needs a powerful computational device.

Another example of the manager's decision making problem can be observed in his decision making on the quantities of each base powder (those powders which can be produced through this process are called base powders) to be produced to satisfy the production requirements. This equally means the decision to allocate the various level of plant available capacity to the various 'blowing rates'.

In this decision making his main difficulty is in the evaluation of the utility of each basic powder against the requirements. The reason for this difficulty lies in the fact that various basic powders would generate different amounts of undesired fractions. On the other hand, they contain different quantities of the desired fractions which means they require different levels of production capacity and thus incurring different production costs to satisfy a specific amount of production requirements.
Obviously some combinations would be much better than others in terms of some criteria or objective function applied. Here again, the manager would like to know which schedule of 'blowing' would yield the best profit or economic outcome to the company's operation.

This evaluation certainly involves more difficult computations than the previous example and would require the consideration of more technological and economic factors.

Recognizing the complexity of the decision making process of the manager in metal powder making operation, the second approach would try to formulate each of the decision problems in terms of a mathematical model. When these models are programmed for the computer, the computer handles the difficult tasks of computations. It calculates at a high speed and with great accuracy how the different courses of action would work out. Then the manager can choose what appears to be the 'best' course. The computer can also be programmed to reach the final 'best' course of action.

In the circumstances that prevail in metal powder making industry the manufacturer has to resolve upon the optimized maufacturing and the optimized blending of the powders if he is to provide a reasonable return on the capital he invested in his company's operation. Indeed this is what the managers in this industry would try continuously but the model upon which they work out the situation is their intuition or experience. The decision problems which are involved in metal powder making operation are too complex to be handled by intuition or managerial experience.

Fortunately, these problems are already known to the management scientists and the techniques have been developed to provide a best solution to them.

This type of problem which deals with the efficient use or allocation of limited resources, to reach special goals in the best fashion, are defined generally as 'programming' problems (45). These problems are best solved through the mathematical techniques called the mathematical programming. Most advanced amongst these techniques is Linear Programming, which is used in this study and which can find the best of all possible solutions in a stated problem (48) providing that it satisfies the conditions and assumptions used in this method.

4.4 The Selection of the 'Appropriate' Approach

The two approaches which were outlined in this chapter would both aid the decision making task of the managers in metal powder making companies. Both provide the information which they need for making suitable decisions which certainly result in more profitable operation than otherwise would be achievable by the decisions which are taken by 'hunch' or by guesses.

In making a choice between the two approaches (computerizing the information and the optimization of the plant operations) it was thought by the author that the first approach is a matter of programming (computer programming) and can be done by the company whenever it wishes to do so and it takes a programmer a few months to develop the programme suitable for their operations. But the mathematical modelling of the operations of powder making plant might yield findings and insights, pointing out a potentially more profitable use of plant resources. The managers in this industry have continuously been attempting to make an optimum decision, but the complexity of the problems did not permit them to reach a 'rational' decision. The mathematical modelling of various operations would allow them to examine various courses of action in a matter of minutes and select a best strategy in each case. In particular the problems of allocating the stock material to make best use of them and the selection of the base powder to be produced, and their quantities, are best solved by the application of mathematical programming techniques.

This optimization approach would therefore be selected by the author to be the approach to the managerial problems of production in metal powder making industry.

This approach has been described in more detail in the next chapter where it is directly applied to the problem.

CHAPTER FIVE

MATHEMATICAL PROGRAMMING APPROACH TO MANAGERIAL PROBLEMS OF PRODUCTION CONTROL AND DECISION MAKING IN METAL POWDER MAKING INDUSTRY

5.1 Introduction

The operation of the powder making process can be summarised as containing three levels of decision making:-

(1) The problem of allocating the stock of various fractions of powders which remain from previous periods towards the final marketable products required by customers in this period

(2) The problem of scheduling plant 'settings' so as to give 'efficient' utilisation of capacity against those customer demands which cannot be satisfied from inventory

(3) Selection of suitable gauges of mesh to be used in sieving, so as to maximise the financial 'return' from the use of basic powder by satisfying customer demand while limited by customer-created constraints upon the size composition of the products.

These decisions represent the major routine decisions by means of which the manager of a powder making plant, balancing the productive capacity of his manufacturing plan against the requirement of the market demand in a short interval.

It is illustrated in this chapter that the decisions of stage 1 and stage 3 can be approached by linear programming, and the decisions at stage 2 can be made by dynamic programming. It is also shown that when these programmes are used as a system of models, it can be highly successful in advising the manager of his decisions regarding the optimum setting of cloth gauges and schedule of plant settings which should result in achieving a high level of customer satisfaction and an optimum level of resource utilisation.

Before illustrating how these programmes can be applied however, it is essential to introduce a conceptual model of the product and the plant operations. The reason for this is that the powders being produced, the products requested by the customers and those stored in the plant warehouse as the stocks of 'supposedly saleable' products are in composite forms and specified only in statistical terms. This level of quantification is not adequate for inclusion in mathematical models required for the programming approach.

On the other hand the solutions proposed for various decision problems require reference to a model of total plant operation. This identifies the <u>exact</u> specification of the materials at each stage as they move through the production process. i.e. it is necessary to define precisely the form of the 'fractions' at various process stages as they will vary with stage

The following section introduces a conceptual model of the products and the plant operations.

5.1.1 Powder as a combination of particles of closer 'size classes'

When powder is produced, one of the problems of production recording is that a spectrum of particle size is made, and although they are arbitrarily classified (by ability to pass through, or be retained upon, particular mesh screens), the true picture of a continuous distribution of sizes.

This has been illustrated previously (in the section relating to the output of the atomization process) and is shown in Fig. 5.1.1a. In this figure the product (output) of a single process 'run' is represented by a single continuous distribution of particle sizes and the outputs of two process 'runs', using different plant settings, are shown together by a double distribution constituting a bi-modal distribution of particle sizes.

When the actually occurring continuous distribution (Fig. 5.1.1a) is passed through a series of sieves (Fig. 5.1.1b) it is arbitrarily classified into fairly broad mesh categories (Fig. 5.1.1c).

Each of these categories is called a 'size class' or a small 'size fraction'.

5.1.2 Conceptual Model of the total operations of a powder making plant

The normal practice in many powder making plants is that several appropriate powders are produced daily, whose qualities are known only through the proportions of their mesh categories. These are subsequently sieved in order to provide customers with the desired

FIGURE (5.1.1.a) Distributions of particle sizes for a single process 'run' output and for the output of two combined process 'runs'.

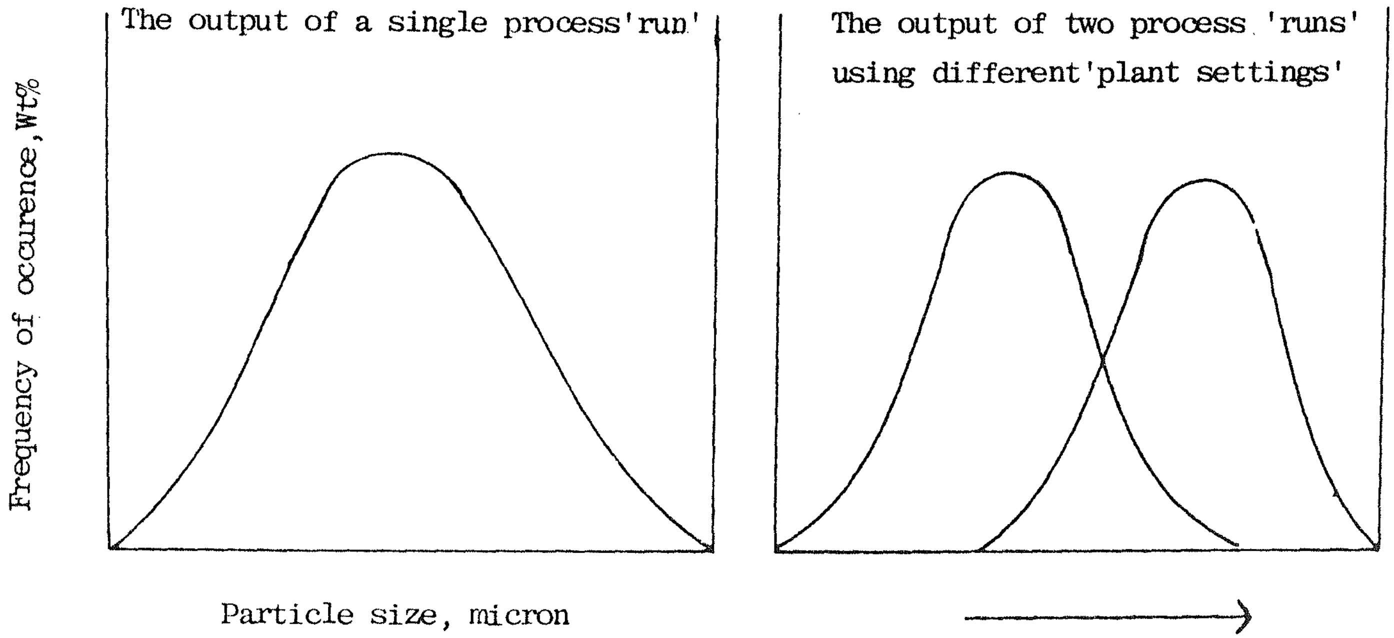


Fig. 5.1.1.b Schematic diagram of classification process via which a particulate matter(powder) is split into a group of particles of different size classes.

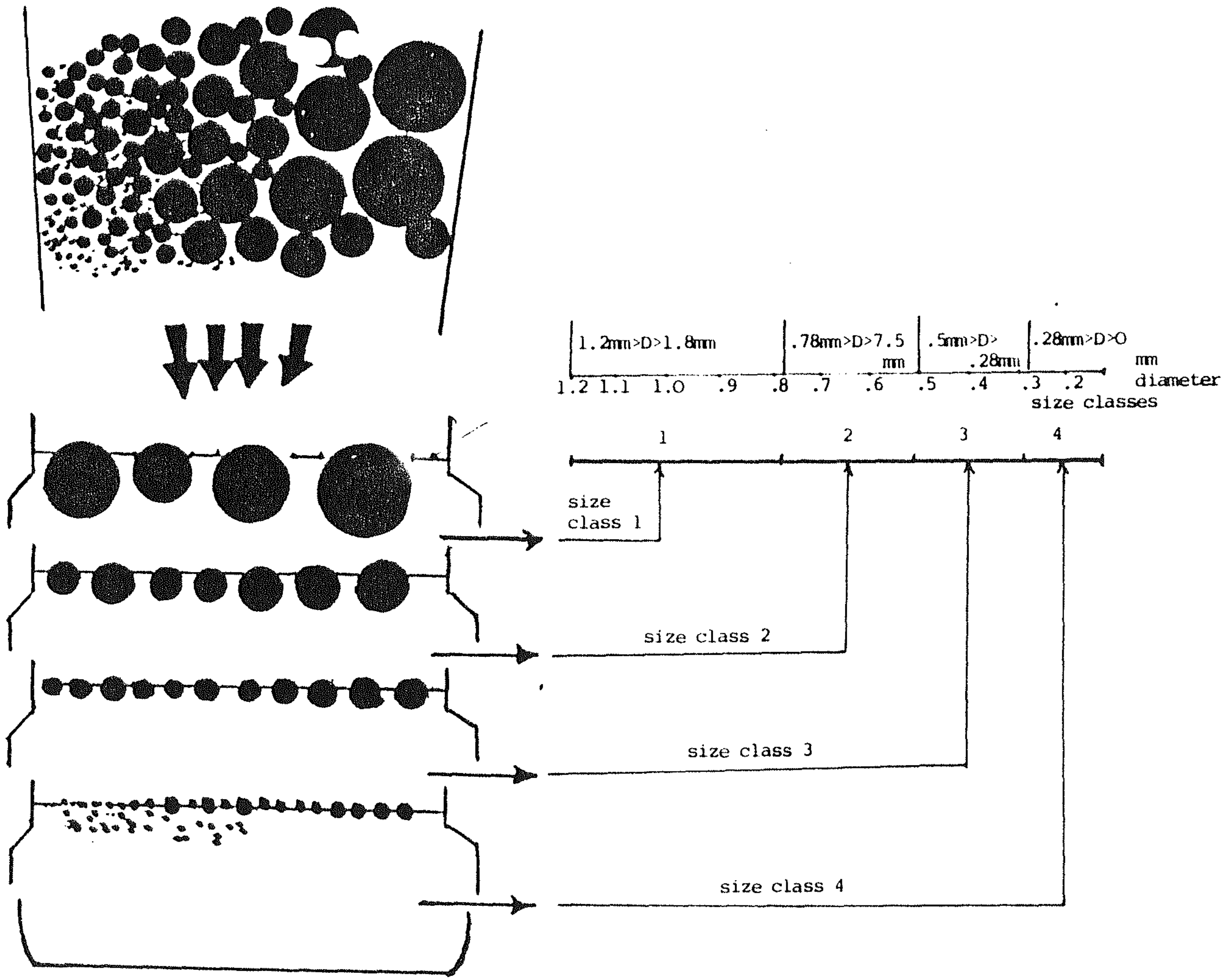
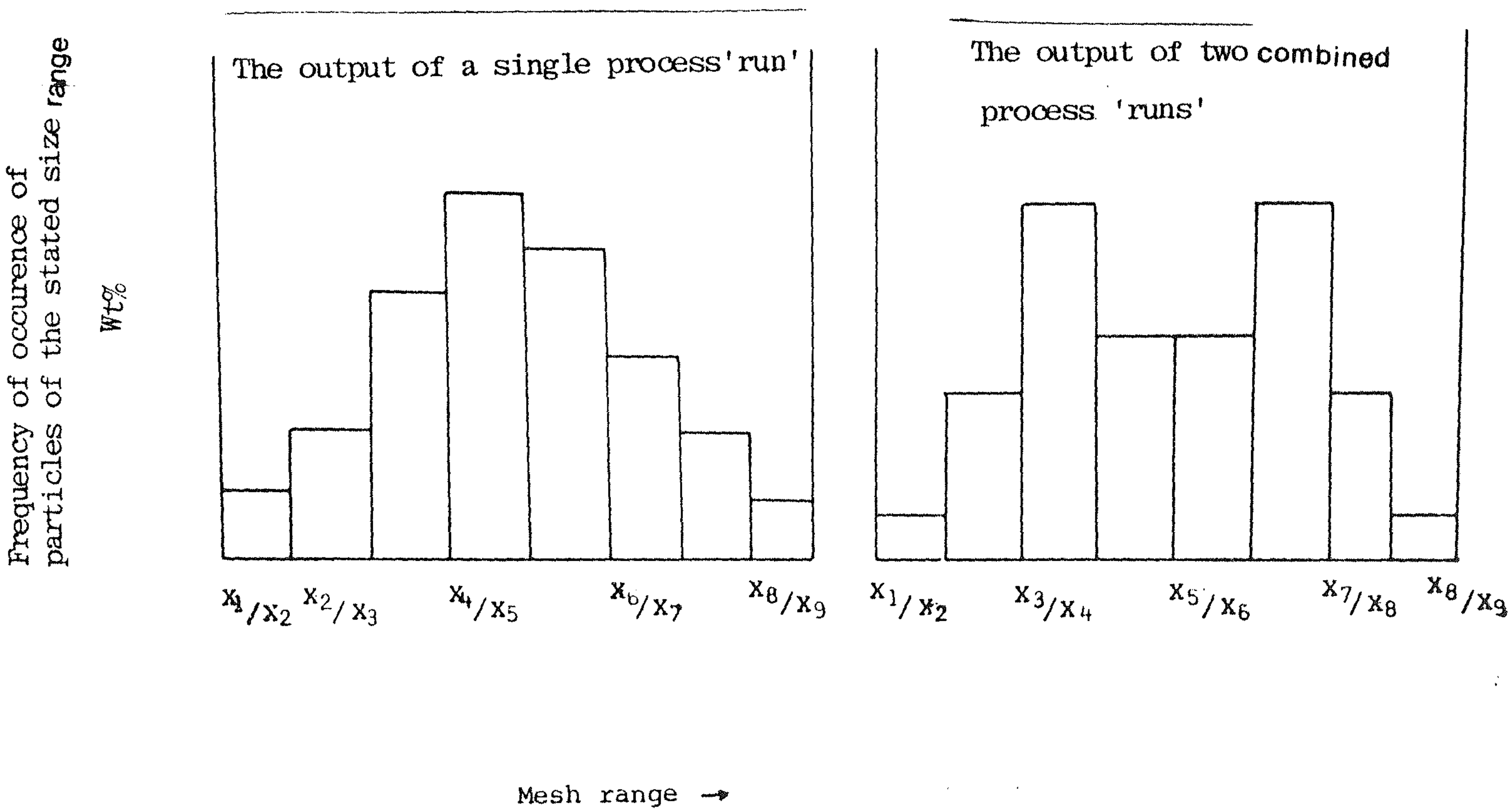


Fig 5.1.1.c COARSE CLASSIFICATION BY MESH GRADE



fractions. Such a fraction will be 'retained' on a sieve mesh of the appropriate size. Three types of fraction would be obtained from a batch of basic powder. These are shown in Fig. 5.1.2.1 and identified as follows:

(1) Fraction A, which goes to stock, is supposed to contain the saleable products as being forecast or on the basis of previous experience.

(2) Fraction B goes immediately to customers since it possesses the 'exact' or 'near to exact' specified size characteristics.

(3) Fraction C is the remaining part of the powder which is not desired (at least for the present) by any customers. It would remain either in the store or somewhere within the process.

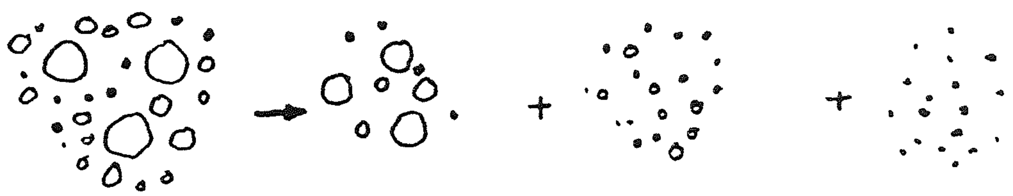
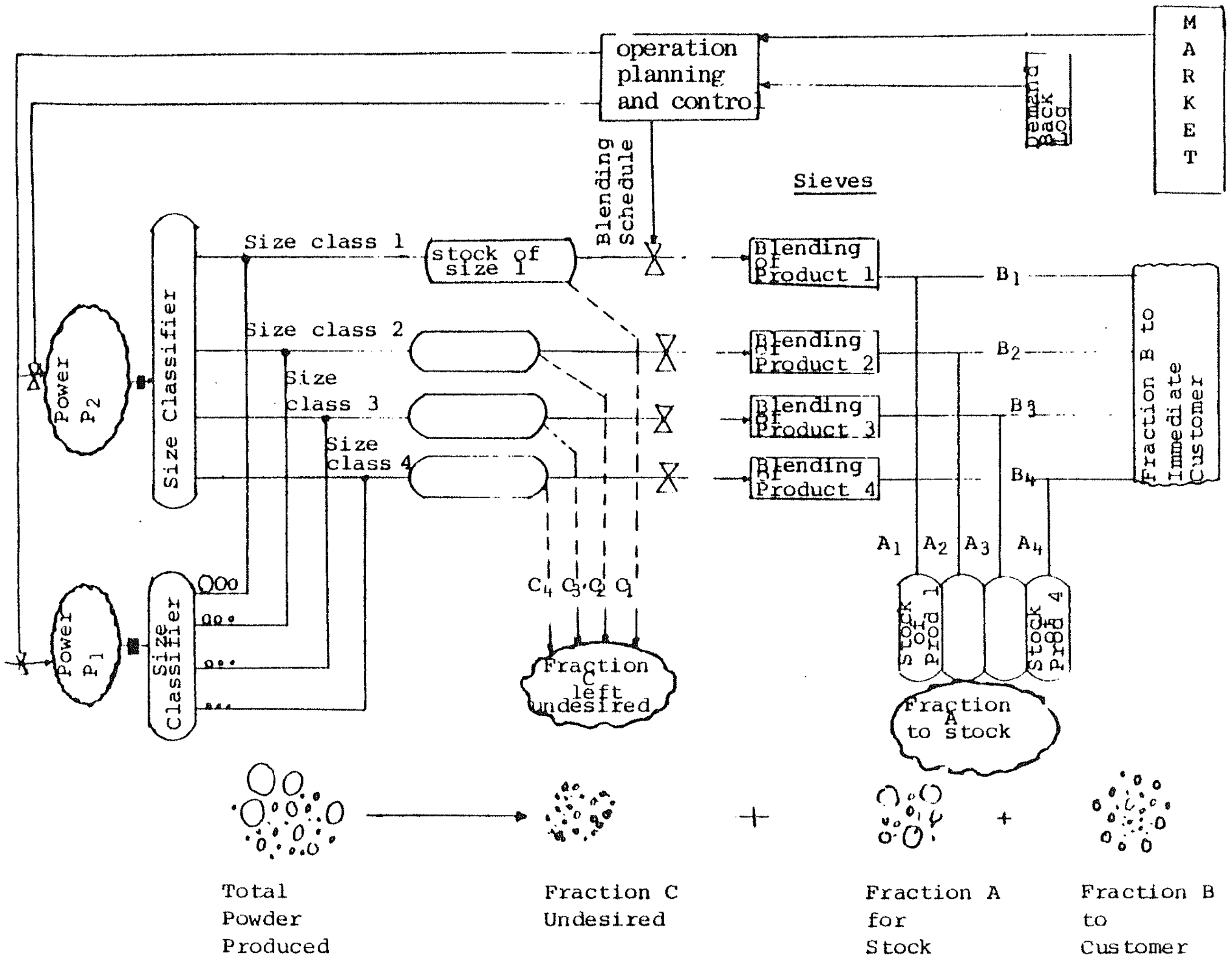


Fig. 5.1.2.1 Classification of Base Powder.

A conceptual model of the type proposed will show us exactly where the various 'fractions' are at any given time (Fig. 5.1.2.2.) - A snapshot of the current material/process status. As can be seen from this model, the basic powders are assumed to be split firstly into their constituent 'size classes' of particles, these classified particles would then be sent to their relative 'conceptual tanks' to form the stocks of particles of various size classes. Secondly, the various fractions would be made from these stocks as shown in Fig.5.1.2.2. For example the necessary amount of particles of size classes No 1, 2 and No 3 are removed from their relative stocks and blended to produce a given amount of final product No 1 which would be packed for immediate sales (B_1) and a given amount of the same product which would be left in stock (A_1). This model (Fig. 5.1.2.2.) is now more capable of assisting the translation of the decision problems into a mathematical form.

Fig. 5.1.2.2. Schematic diagram of the proposed model for illustrating the operational planning and control of powder making plant.



5.2 Stock Allocation by Linear Programming

5.2.1. The Problem

The stock allocation problem which is encountered in metal powder making industry is that the size composition of individual stock material do not conform exactly with that of customer-requested products for most of the time and the manager has difficulty in using these materials effectively to fill the customer orders. There is often a huge amount of these stock materials which have remained unused for a long period of time and they are responsible for absorbing a large amount of the company's cash.

The stock of finished products was shown in Fig. 5.1.2.2. as the sum of fractions labled A_1, A_2, A_3 .... In real situations, however, there are also some certain amounts of undesired products (i.e. fraction 'C') in stock which should be considered too. Here it is possible for convenience to suppose that the stock consists of fraction 'A' only.

The present practice of matching and allocating these materials with customer orders is either to give the customers the products of higher qualities instead of what they have requested, or to mix and 're-sieve' the powder fractions of closer size range to provide the customers with fractions that contain the specified size characteristics. While the first process is easy and needs no complex calculations, the second process of matching requires many computations and the considerations of many technological and economic factors for an effective result. These computations are something beyond the capability of the manager and his available time. For this reason the manager would often recourse on some rough calculations and can make decisions on interchange between the specifications of only a few powder fractions to match with the customer's order, for example, if the fractions A_1, A_2 and A_3 are assumed to comprise the following mesh size categories:-

	A_1	A_2	A_3
mesh no	7	8	10
mesh no	8	10	12
mesh no	10	12	14

the manager can make a decision on taking some amounts of particles of mesh size No 10 from fraction A_1 and some amount of particles of mesh size No 12 from fraction A_3 to add to fraction A and make a change in the specification of this fraction to match it with 'a' customer-requested product. This matching process, however, requires extensive computations and the consideration of many economic and technological factors as the number of powder products and the customer-requested products increases. In this case it would be doubtful if the manager could solve this problem effectively by the present method.

A more precise and accurate procedure is needed to match the unallocated stock materials with customer orders. This procedure, if developed, would result not only in releasing a significant amount of capital being tied up in stock materials and giving more satisfaction to customers by quicker delivery, but it also prevents the waste of plant available capacity which otherwise should be employed to produce the already available material.

5.2.2 The Approach - Linear Programming

This problem, however, can be solved by the mathematical technique called "Linear Programming" more effectively. Linear programming is a mathematical technique for seeking optima(32). The main feature of this technique is that by using a mathematical model which describes the operation of a process or an allocation problem, it allows the reaching of a solution which is the best strategy for that process or allocation problem(33). This technique has been described in Appendix (III) and here it is showing how it solves the stock allocation problem.

The Linear Program Allocation Procedure requires that the following conditions are met first:-

(i) The stocks are reclassified into the 'size classes'.

(ii) The final products are specified in terms of size classes.

(iii) Variables and constraints are defined.

(iv) The objective function is formulated.

(i) Reclassification of Stocks

The coarsly graded powder fractions (or stock materials) are reclassified (at least computationally) into the closely graded particle sizes. These latter grades are the standard 'size classes' described earlier as 'mesh categories'. The principle of this is shown in Fig. 5.2.2.1. and this process converts the stocks of finished products into the stocks of standard, defined 'size classes' which are more precise for inclusion in the linear program in terms of final products.

(ii) Product Specification

The final products requested by the customers are specified (either by the customer or by the Company) in terms of this 'size classes'. This is shown in Tables 5.1. and 5.2.

Table 5.1 shows, for instance, Final Product No 2 (shown across top of chart) should consist of a spectrum of particle sizes ranging from 1.20 mm to 1.68 mm (or passing the mesh category 8 and retaining upon the mesh category 14).

Table 5.2 shows a more precise specification of this product which indicates that the final blend should be such that

a) The particles of mesh categories or 'size classes' No 2 and No 3 should consitute at least 87% of weight of the final blend.

b) The amounts of particles of size class No 4 should not exceed 13% of the total weight of the product.

(iii) Defining the Variables and Constraints

The results of stage i and stage ii can be summarised in Fig. 5.2.2.2 which represents a schematic/pictorial model of the allocation of

Stocks of various sizes to the final products. This model allows the variables and constraints to be defined more precisely than was possible before.

a) Variables or activities

b) constraints or equations.

a)- Variables

Variables in this allocation problem may be expressed as

- using stock of size class No 1 in the blending of final product No 2.
- using stock of size class No 2 in the blending of final product No 1.,etc,

A diagram which represents all of these variables is shown in Fig.5.2.2.3 which is the conversion into algebraic form of the information given in Fig.5.2.2.2. In this diagram a matrix is being set up which uses the notation X_{ij} to represent variables.

b)- Constraints

Constraints in this case are the limits set for the variable X_{ij} by

- final product size range
- final production size speciation
- the material balance
- the customer demand or market limitation

b-1 Size range limitation

Table 5.1 shows that in blending a particular final product only particles of a few size classes would be acceptable. For this reason the variable X_{ij} might be positive, ie. acceptable, or zero, meaning not allowed to be blended in a final product. This information is given in a small Table at the bottom of Fig.(5.2.2.3).

b-2 Product size specification (size proportion limits)

Table 5.2 shows that for a given final product blend, which proportions of each constituent size class particles are acceptable.

b-3 Material balance

The quantity of each size class being used in blending various final products should, in total, be equal or less than the available stock of that 'size class'. This means that, for example, all quantities of size class 2 which goes to product 1 and 2 should not exceed the total amount of the 'size class' available in its relative stock.

b-4 Product demand and market limitation

This is either a 'sales constraint' on the product types which is the maximum quantity of each final product demanded by the market or the 'demand constraint' which is the minimum quantity of the final products which must be manufactured to satisfy the orders of the regular customers.

Both cases put limitations on the amount of a particular size class which can be used or must be used in producing a definite product type.

Each of these constraints when expressed in mathematical terms forms a mathematical equation. The complete mathematical equations are given in Appendix(III-a) and a summary of these equations is presented in Fig.5.2.2.4.

Fig.5.2.2.4 forms the L P model for allocating available stock into the size classes requested (implicitly if not explicitly) by the customer. This model, to be used to identify the 'best' solution, requires that the criteria of 'best' solution be specified and included in the model.

(iv) Objective function

The criteria for the 'best' solution would normally have the forms of

maximize the return

or minimize the cost

or maximize the cash flow (sales revenue)

In the case of Powder manufacturers they have to decide upon the conditions they meet.

However, the final stage in solving a realistic sized L P problem is always to code it for computer solution - in this simple example into a simple 2-dimentional matrix. Only coefficients (e.g. O, 1 and

0.85) are used, representing algebraic function in particular columns and/or rows. This matrix is shown in Fig 5.2.25 which forms the input data for the computer programme. Typically, solution of a problem of the size illustrated, might take 3 - 4 minutes on a small micro-computer and a few seconds on a larger computer.

This might involve trying 17 - 18 different solutions to the problem, such as is shown in the example on the following page (ie page 96).

Fig. 5.2.2.1. Modified diagram of the operatioal planning and control of powder making plant.

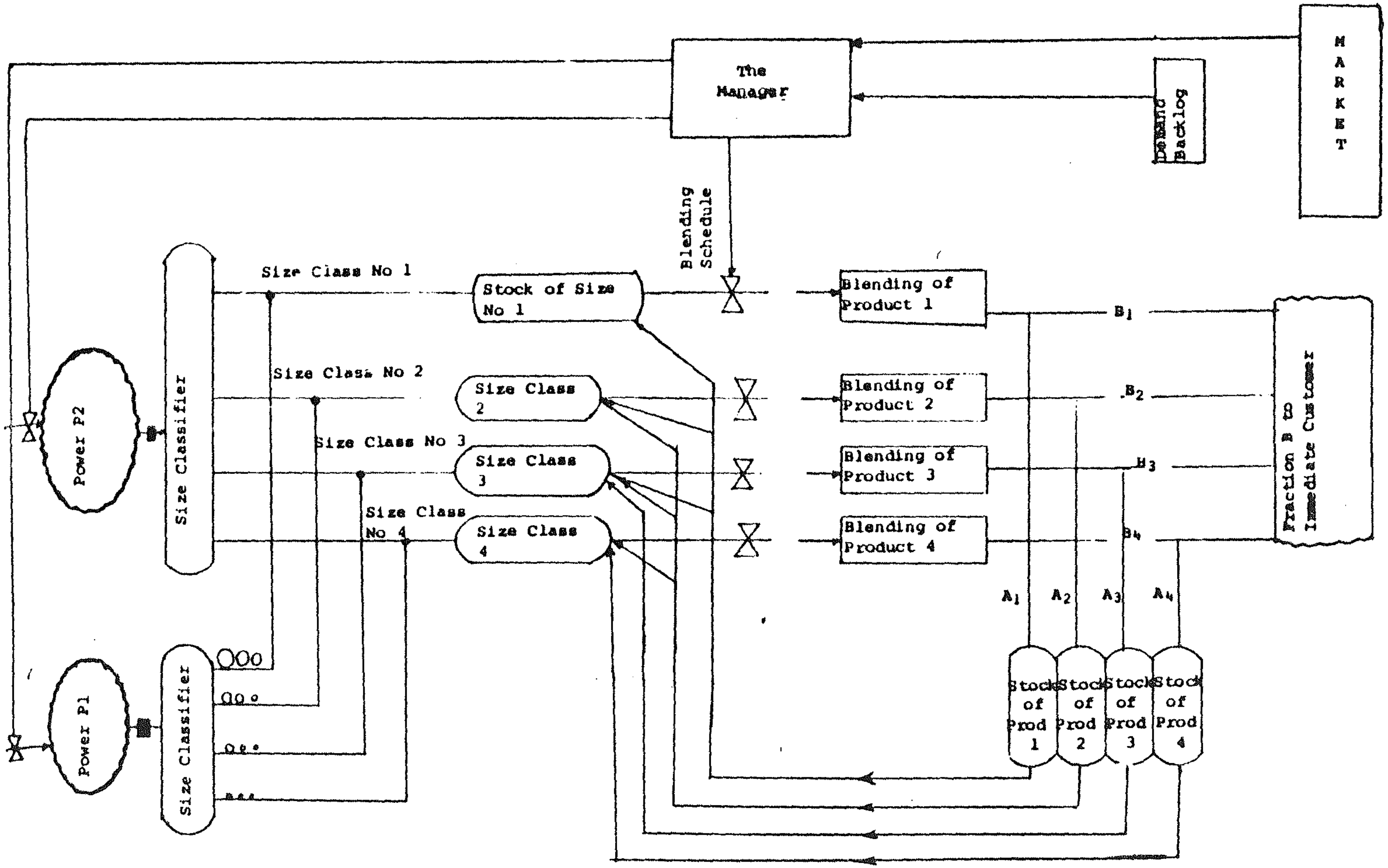


TABLE 5.1. FINAL PRODUCT SPECIFICATIONS SHOWN IN TERMS OF THEIR PARTICLE SIZE RANGE.

	Size Classes	Sieve Opening mm	Tyler Equivalent Mesh Size	FINISHED (FINAL) PRODUCTS						
				Product No 1 S660	Product No 2 S550	Product No 3 S460	Product No 4 S390	Product No 5 S330	Product No 6 S230	Product No 7 S170
CONSTITUENT MATERIAL (PARTICLES)	1	2.00	8	*	All Pass					
	2	1.68	10	*	*	All Pass				
	3	1.40	12	*	*	*	All Pass			
	4	1.20	14		*	*	*			
	5	1.00	16			*	*	*		
	6	.850	18				*	*	*	
	7	.710	22					*	*	*

TABLE 5.2. FULL SPECIFICATION OF PRODUCTS

CONSTITUENT MATERIAL (PARTICLES)			FINAL PRODUCTS (j)						
Size Classes	Sieve Opening mm	(Mesh Size)	Product No 1 660	Product No 2 550	Product No 3 460	Product No 4 390	Product No 5 330	Product No 6 230	Product No 7 170
Size Class No 1	2.00	8	Min	All Pass					
No 2	1.68	10	87%	Min	All Pass				
No 3	1.40	12	Max 13%	87%	Min	All Pass			
No 4	1.20	14		Max 13%	85%		All Pass		
No 5	1.00	16			Max 15%	Min		All Pass	
No 6	.850	18				Max	Min		All Pass
No 7	.710	22					Max	Min	

Fig. 5.2.2.2. FINISHED PRODUCT STOCK SHOWN IN TERMS OF SPECIFIC PARTICLE SIZES.

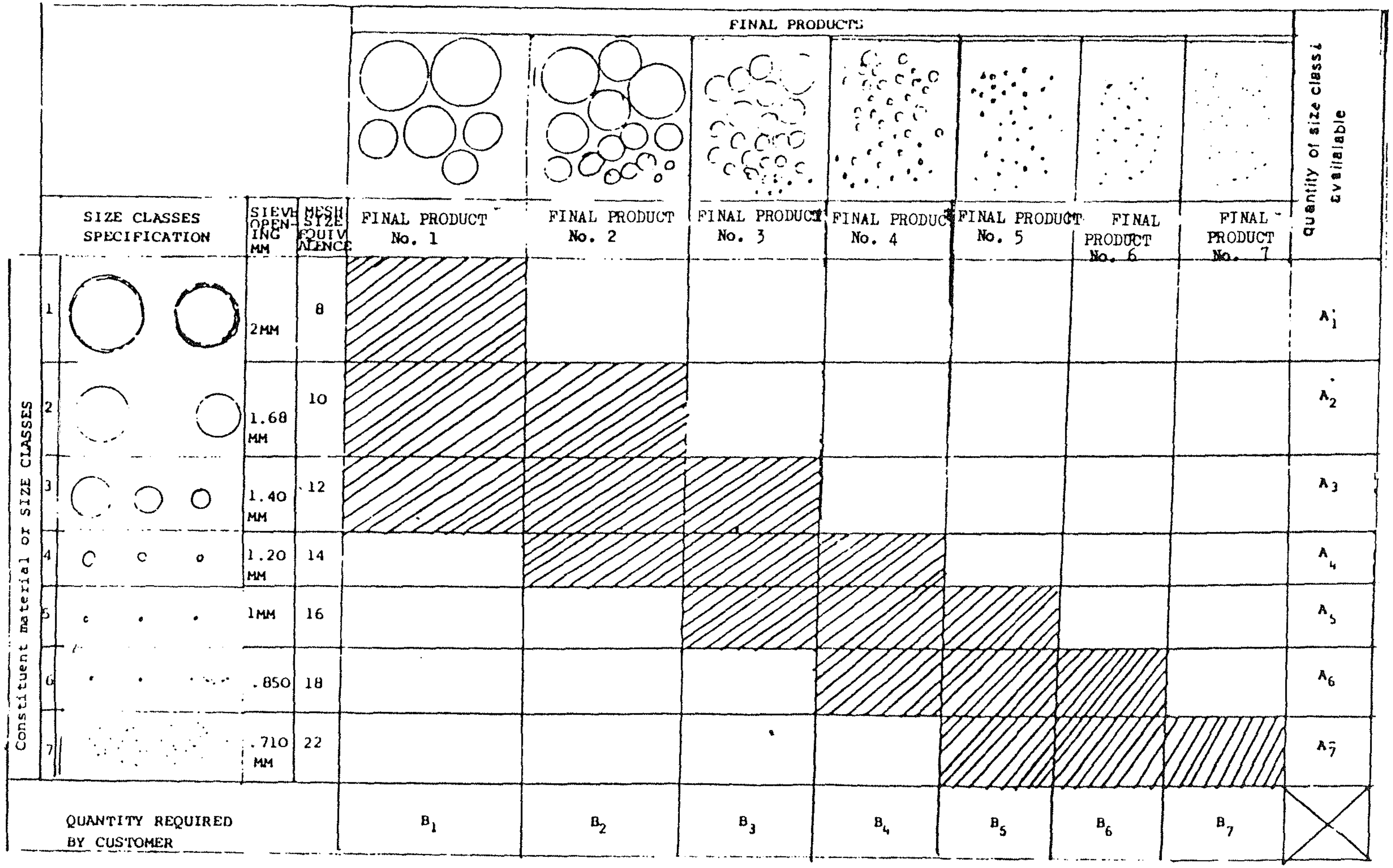


Fig 5.2.2.3. ALGEBRAIC INTERPRETATION OF FIG (5.2.2.2)

PARTICLE size classes	Sieve size in MM	Mesh Size	FINAL PRODUCTS No 1	No 2	No 3	No 4	No 5	No 6	No 7	No 8
			Product Name S 660	S 550	S 460	S 390	S 330	S 230	S 170	
1	2 mm	8	X_{11}	All Pass						
2	1.687	10	X_{21}	X_{22}	All Pass					
3	1.40	12	X_{31}	X_{32}	X_{33}	All Pass				
4	1.200	14		X_{42}	X_{43}	X_{44}	All Pass			
5	1.003	16			X_{53}	X_{54}	X_{55}	All Pass		
6	.850	18				X_{64}	X_{65}	X_{66}		
7	.710	22					X_{75}	X_{76}	X_{77}	

	No						
variables No.s related to Final Products	X_{11} 1 X_{21} 2 X_{31} 4	X_{22} 3 X_{32} 5 X_{42} 7	X_{33} 6 X_{43} 8 X_{53} 10	X_{44} 9 X_{54} 11 X_{64} 13	X_{55} 12 X_{65} 14 X_{75} 16	X_{66} 15 X_{76} 17	X_{77} 18	

Fig 5.2.2.4 SUMMARY OF LINEAR PROGRAMMING MODEL FOR ALLOCATION OF STOCK INTO SIZE CLASSES FOR CUSTOMER DEMAND

SIZE CLASS	SPECIF'N OF RANGE	FINAL PRODUCT SPECIFICATIONS																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
		X_{11}	X_{21}	X_{22}	X_{31}	X_{32}	X_{33}	X_{42}	X_{43}	X_{44}	X_{53}	X_{54}	X_{55}	X_{64}	X_{65}	X_{66}	X_{75}	X_{76}	X_{77}	

SIZE CLASS	SPECIF'N OF RANGE	Constraint		
1		X_{11}	$<A_1$	AVAILABILITY OF PARTICLES IN VARIOUS SIZE CLASSES
2		$X_{21}+X_{22}$	$<A_2$	
3		$X_{31}+X_{32}+X_{33}$	$<A_3$	
4		$X_{42}+X_{43}+X_{44}$	$<A_4$	
5		$X_{53}+X_{54}+X_{55}$	$<A_5$	
6		$X_{64}+X_{65}+X_{66}$	$<A_6$	
7		$X_{75}+X_{76}+X_{77}$	$<A_7$	
		$-.13X_{11}-.13X_{21}+.87X_{31}$	<0	SPECIFICATION OF FINAL PRODUCT
		$-.13X_{22}-.13X_{32}+.87X_{92}$	<0	
		$-.15X_{33}-.15X_{43}+.85X_{53}$	<0	
		$-.15X_{44}-.15X_{54}+.85X_{64}$	<0	
		$-.15X_{55}-.15X_{65}+.85X_{75}$	<0	
1	PRODUCT SALES LIMITATION	$X_{11}+X_{21}+X_{31}$	$<D_1$	SALES CONSTRAINTS
2		$X_{22}+X_{32}+X_{42}$	$<D_1$	
3		$X_{33}+X_{43}+X_{53}$	$<D_3$	
4		$X_{44}+X_{54}+X_{64}$	$<D_4$	
5		$X_{55}+X_{65}+X_{75}$	$<D_5$	
6		$X_{66}+X_{76}$	$<D_6$	
7		X_{77}	$<D_7$	
8				

Fig 5.2.2.5 'TECHNOLOGY MATRIX', RELATING PARTICLE SIZE CLASS CONSTRAINTS TO DESIRED OBJECTIVES - (OBTAINED FROM FIG 5.2.2.4 data)

VARIABLE NUMBER → / CONSTRAINT NUMBER	VARIABLES (K=18)																		AVAILABLE OF EACH SIZE CLASS R.H.S
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	X_{11}	X_{21}	X_{22}	X_{31}	X_{32}	X_{33}	X_{42}	X_{43}	X_{44}	X_{53}	X_{54}	X_{55}	X_{64}	X_{65}	X_{66}	X_{75}	X_{76}	X_{77}	
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	A_1
2	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	A_2
3	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	A_3
4	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	A_4
5	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	A_5
6	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	A_6
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	A_7
8	-.13	-.13	0	.87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	-.13	0	-.13	0	.87	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	-.15	0	-.15	.	.85	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	-.15	0	-.15	0	.85	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	-.15	0	-.15	0	.85	0	0	0
13	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	D_1
14	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	D_2
15	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	D_3
16	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	D_4
17	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	D_5
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	D_6
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	D_7
	P_1	P_1	P_2	P_1	P_2	P_3	P_2	P_3	P_4	P_3	P_4	P_5	P_4	P_5	P_6	P_5	P_6	P_7	

An example of input and output for a microcomputer-based LP powder model

Inputs

a) Technology Matrix (Figure 5.2.2.5)

b) Available stock levels of various size classes

eg size class 1	weight 40 tonnes
size class 2	weight 80 tonnes
size class 3	weight 120 tonnes
size class 4	weight 160 tonnes
size class 5	weight 180 tonnes
size class 6	weight 80 tonnes
size class 7	weight 60 tonnes

c) Demand Backlog and product prices

Output (calculated optimal solution)

a) The particular quantity of each powder size fraction used in each product (xij)

eg x11 = 40 (tonnes)	x53 = 0 (tonnes)
x21 = 0	x54 = 180
x22 = 80	x55 = 0
x31 = 5.977	x64 = 0
x32 = 114.023	x65 = 80
x33 = 0	x66 = 0
x42 = 28.99	x75 = 14.117
x43 = 0	x76 = 0
x44 = 131.01	x77 = 45.88

b) The total quantity of each final product to be provided from stock

Weight of product 1 = 45.977 tonnes

Weight of product 2 = 223.014 tonnes

Weight of product 3 = 0 tonnes

Weight of product 4 = 311.008 tonnes

Weight of product 5 = 94.118 tonnes

Weight of product 6 = 0 tonnes

Weight of product 7 = 45.882 tonnes

c) The (optimum) sales value achieved (from stock) is £9518.07.

5.3 - Scheduling the Plant Settings via Dynamic Programming

5.3.1 The Problem

In this stage of the modelling, the problem to be solved is which is the most efficient combination of plant settings to produce base powders capable of satisfying the proportion of customer demand not met from stock.

This situation is illustrated in Figs 5.3.1.1 and 5.3.1.2 which show respectively the demands of an order book and the response of two specific atomisation plant settings

Various combination of base powders could be produced to meet the requirement. For example, it might be necessary to produce two batches of base powder No. 1 and 5 batches of base powder No. 2 to satisfy the requirements. Since each base powder is produced under a specific plant setting, this would equally mean a combination of two process 'runs' using plant setting No. 1, and 5 process 'runs' using plant setting No. 2 is required. Any combination of plant settings which is chosen to produce the base powders to meet the production requirements (those proportion of customer demand which are not met from stock) is called in this study a 'schedule'.

Each schedule, in addition to satisfying the production requirements, result in production of some excess amounts of 'overstocked' material or 'undesired' fractions. These excess materials cause an increase in the cost of inventory and are responsible for the waste of the plant capacity and the money. This may be called here as the 'negative'

Figure 5.3.1.1 Specification of products required by customers (order book)

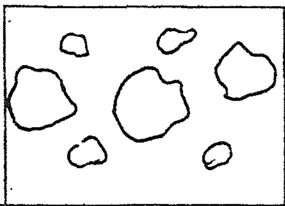
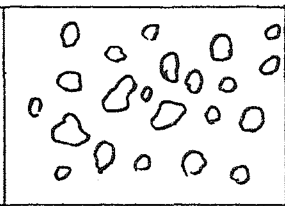
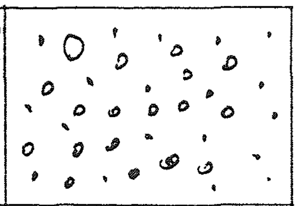
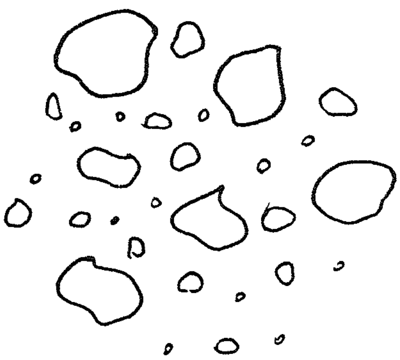
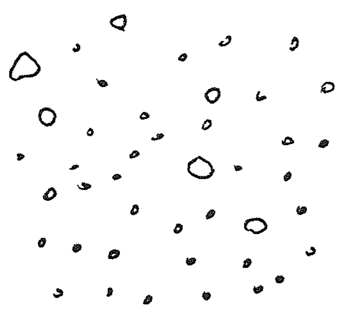
				
No	Mesh	Product A	Product B	Product C
1	8	Minimum 85%	Maximum 20%	All pass
2	10		Minimum 65%	Maximum 10%
3	12	Maximum 15%		Minimum 85%
4	14		Maximum 35%	
5	16			Maximum 5%
Requirement (tonne)		10	30	30

Figure 5.3.1.2 Illustration of powder produced by 2 atomisation plant setting.



Coarse Powder produced by plant setting No. 1



Fine Powder produced by plant setting No. 2

responses of a schedule. The 'positive' response of a schedule is the amount of sales that can be achieved from the sales of the total production output which results from applying this schedule. This includes the sales of the bye-products which result from applying this schedule.

The positive and negative responses of a schedule when considered together define its utility.

The efficient schedule is that schedule which while meeting the production requirements, produces the maximum utility.

The problem is to find this schedule.

5.3.2 The Approach

In approach to this problem, a similar size classification to that performed on 'stock' material is possible. However because the outcome of allocating various levels of capacity to production of a specific powder can not be assured as a linear function of the level of capacity being employed,Linear programming can not be used to optimise the choice of settings. Instead Dynamic programming (DP) appears the most suitable method(34)

This (more sophisticated) method models the scheduling problem as a multistage decision process where each decision is taken when all the consequences of previous decisions are assessed. Such model conforms with the actual manufacturing situation. In a manufacturing situation, a decision made on, say, the use of plant setting No.1 would result in production of some powder fractions which alters the state of the plant and this affects the 'choice' of next blow. The next plant setting to be chosen must be capable of either compensating for powder fractions which have not been produced enough by the first 'blow' or must not add to the amount of excess fractions already produced. In the same manner a schedule must consider the accumulative results in terms of other parameters. For example, a sequence of plant setting chosen must result in a maximum cumulative profit or sales revenue etc. that can be achieved.

Dynamic programming is especially designed for solving such multi-stage decision problems. (34,35 This method is described in Appendix (IV) In the following section it is shown how it computes an optimum plant setting schedule.

5.3.2.1 Dynamic Programming As Applied to Scheduling Problem

To illustrate how Dynamic Programming (DP) would solve the scheduling problem in metal powder making operation, a simple case would be considered first. In this case the objective is to find a schedule which is optimum with respect to only one of it's responses such as, for example, its sales outcome. In later section the scheduling problem would be solved by considering its total responses.

5.3.2.1a Finding a Plant Setting Schedule which Optimises Sales Outcome

In the process of computing the optimum schedule by DP the following view is given on the scheduling problem:

The manager knows that his plant capacity permits six 'blows', (i.e. six process'runs'). This capacity should be distributed among, say, 3 plant settings.

He knows (it is assumed here that he has the information) that if he allocates K_j blows to plant setting$_j$, the resulting output would bring him a total sales value equal to $Y_j(K_j)$. One such information is shown in Table 5.3. As it is seen in this table by allocating 2 blows to plant setting No. 2, the manager achieves a total sales equal to £96. While for the same level of capacity allocated to plant setting No. 1, he achieves a total sales of £88. (It will be shown in later section how this information can be prepared).

The manager wants to find a distribution of the available capacity among the 3 plant setting that result in maximum overall sales that can be achieved.

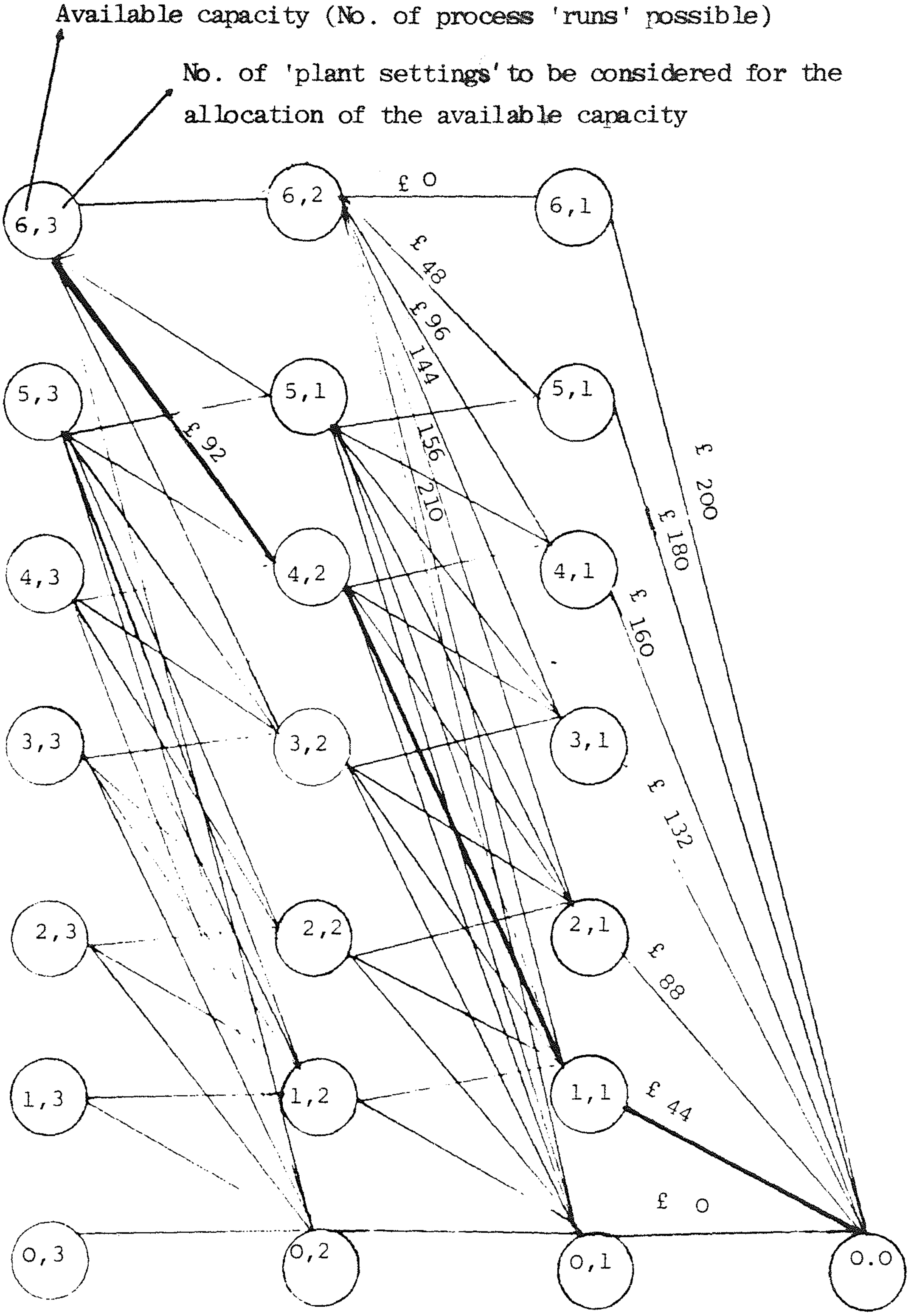
The dynamic programme would simply work out the many combinations of the entries of the Table 5.3 and finds that combination which gives maximum 'total sales achievable'. Having found this maximum value it goes backward and finds the distribution which leads to this maximum value.

The complexity of this task can be best illustrated through a network model (Fig.5.3.2.1.a.1) which is called an acyclic network and would best represent any DP problems i.e. any multistage decision problems (36). The symbols of this model would be explained in the Appendix (IV-b) It is, however, sufficient to say here that each of the series of arrows which join the circles of various columns represent a 'route' or a schedule and the values they carry are corresponding to values of entries of Table. 5.3 . Thus, the various combinations of these

TABLE 5.3 Independent return function for different levels of capacity(i.e.0,1,2,..,6'blows') being allocated to each plant setting.

	Size Distribution 'A' resulted from using plant setting No. 1		Size Distribution 'B' resulted from using plant setting No. 2		Size Distribution 'C' resulted from using plant setting No. 3	
	Number of blows (K_j) performed with this plant-setting	Value of sales $Y_j(K_j)$ achieved (£)	Number of blows (K_j) performed with this plant setting	Value of sales $Y_j(K_j)$ achieved (£)	Number of blows (K_j) performed with this plant setting	Value of sales $Y_j(K_j)$ achieved (£)
For all products considered together and 6 blows possible	1	44	1	48	1	46
	2	88	2	96	2	92
	3	132	3	144	3	122
	4	160	4	186	4	136
	5	180	5	210	5	150
	6	200	6	218	6	164

Fig (5 3 2 1 a 1) COMPANY'S SALES ACHIEVABLE NETWORK



values can be computed.

For example Fig.5.3.2.1.a.2 below showes a 'route' which indicates that from six blows possible;

1 blow is allocated to plant setting No. 1 Sales achieved= £ 44

3 blows are allocated to plant setting No.2 Sales achieved= £ 144

2 blows are allocated to plant setting No.3 Sales achieved= £ 92

the total sales that can be achieved from this route equales to £44+£144+£92=£280

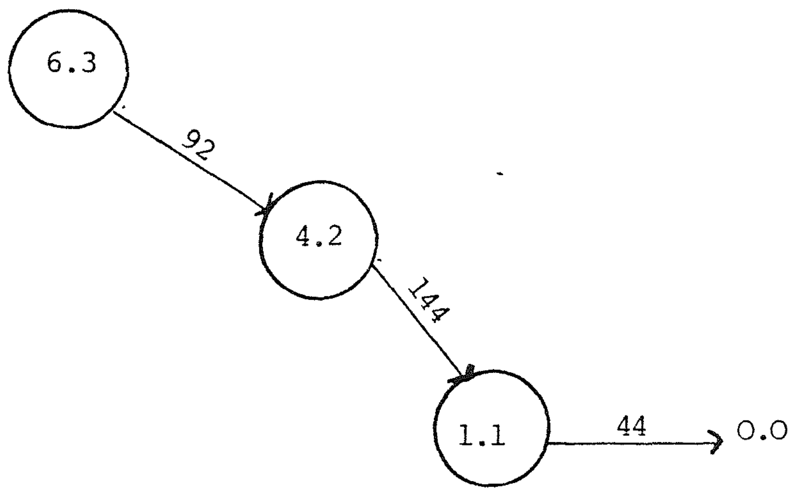


Fig.(5.3.2.1.a.2)A set of arrows representing a schedule.

As can be seen from this model the computation of values of all routes and the selection of the 'best'one is very difficult and time consuming for a human decision maker , particularly as the number of plant settings and the available capacity increases. Dynamic Programming computes the values of various routes of distribution and compares them with each other at a high speed and from this comparison it will identify the maximum route for each situation.

The information on each route can be achieved from the output of this programme which is in matrix forms as shown in Fig. 5 3 2 1 a 3
Each of these matrixes identify a strategy and includes the outcome of each action (schedule) within that strategy.

For example, Fig(5 3 2 1 a 3c)shows a strategy of allocating the plant capacity among three plant settings and in this strategy the result of any decision can be seen from the matrix. If the maximum route is to be selected from the policy of using '6' blows, then it is best to allocate 2 blows to plant setting No. 3. Going back to the matrix of Fig. 5 3 2 1 a 3b it is seen that from the 4 Blows left it is best to allocate 3 blows to plant setting No. 2, and referring to Fig.5 3 2 1 a 3 a there is only one blow left for plant setting No.1. Thus, the 'best' schedule which maximises the achievement of sales values is :

2 blows with plant setting No. 3

3 blows with plant setting No. 2

1 blow with plant setting No. 1

Maximum sales achieved = £ 280

The full details of the network model which is used here is given in Appendix IV-b

	No. of blows allocated to plant setting No.1						
No. of blows (i.e. process 'runs') possible	0	1	2	3	4	5	6
0	0						
1	0						
2	0	44	88				
3	0	44	88	132			
4	0	44	88	132	160		
5	0	44	88	132	160	180	
6	0	44	88	132	160	180	200

Allocation of possible blows when only one size distribution (No. 1) considered

	No. of blows allocated to plant setting No.2						
No. of blows (i.e. process 'runs') possible	0	1	2	3	4	5	6
0	0						
1	44	48					
2	88	92	96				
3	132	186	140	144			
4	160	180	184		186		
5	180	208	228	232	230	210	
6	200	228	256	276	274	254	218

Allocation of possible blows when 2 plant settings are examined (No.1 & No.2)

	No. of blows allocated to plant setting No.3						
No. of blows (i.e process 'runs') possible	0	1	2	3	4	5	6
0	0						
1	48	46					
2	96	94	92				
3	144	142	140	122			
4	188	190	188	170	136		
5	232	234	236	218	184	150	
6	276	278		266	232	198	164

Allocation of possible blows when 3 plant settings are examined (No.s 1,2&3)

Fig. 5.3.2.a.3 The output of dynamic programming computation presented in matrixform.

5.3.2.1b The Solution to Scheduling Problems Considering the Total Responses of the Schedule

In the previous section a 'route' or 'sschedule' was determined based upon the desire to meet the production requirements and to satisfy only one objective of the manager, namely, to maximise the sales that can be achieved from applying the chosen schedule.

In real practice, however, there are several objectives or criterias of performance which are applied to this schedule, and the schedule which maximises sales outcome may not be satisfactory with respect to other objectives. For example, if this schedule produces some excess amounts of 'overstocked' materials or some fractions which may not be saleable in the near future, it would result in an increased inventory cost which may outweigh its advantages of maximising the sales outcome. Thus the manager would like to know the various responses of the schedule before he makes his decision on the schedule to be applied at manufacturing.

To obtain information on the various responses of the schedules the effects of using each individual 'plant setting' to meet the requirement will be examined first. This involves the calculation of costs and revenues associated with each production campaign in which a specific plant setting is used for a specified number of runs. The final result obtained from this calculation will be presented in a table similar to that shown in Table 5.3 but the entries in the new table will represent the 'utilities' of each individual plant setting at conditon of using several runs.

Assuming that the following amount of various final products are not met from stock and should be produced through the manufacturing

Product i	Requirements for Product i DF(i)
P_1	20 tonnes
P_2	30 tonnes
P_3	10 tonnes

the following conditions may arise when various level of capacity are being employed and when various 'plant settings' are being used:-

a - the quantity produced for product i is equal to the requirements

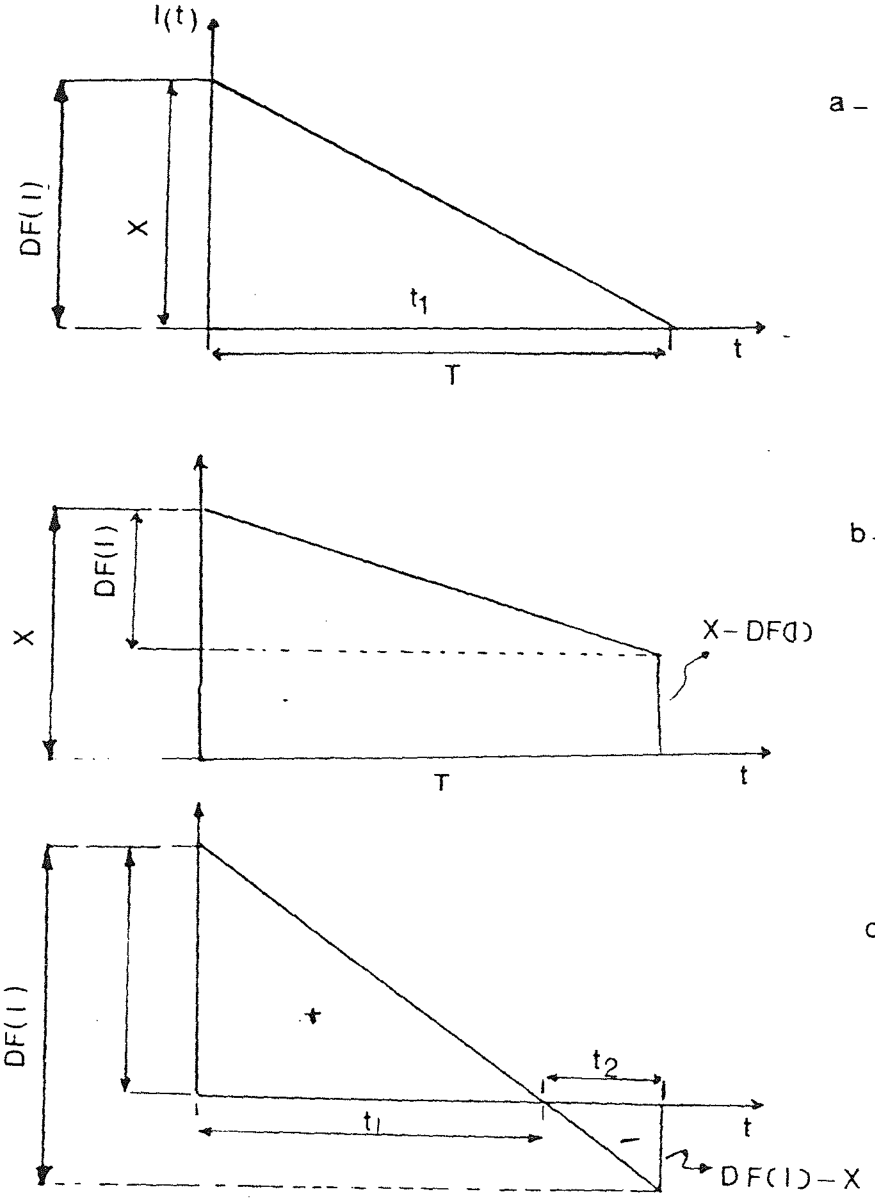
b - the quantity produced for product i is less than the requirements

c - the quantity produced for product i is greater than the requirements

(It is assumed that the production would be achieved immediately after being planned , no change is to occur in the manufacturing programme, and the requirements are to be satisfied immediately.)

During this period, the manufacturer may face a problem of excess material for some products and shortages for others. In both cases he incurs some costs.

The excess and shortages and the associated costs are shown in the schematic diagram of Fig.5.3.2.1.b.1 which represents the inventory curve for the above cases.



a – Production equals to demand

No shortage cost
No excess cost

There is a sales revenue

b – X>DF

Production exceeds the requirement

Cost, excess cost, inventory cost

c – X<DF

Production is less than requirements

shortage cost (penalty)

Fig 5321b1 Inventory Curve

An algorithm is developed and has been programmed for the computer to calculate the costs and revenues at conditions where different levels of capacity being allocated to each individual plant setting. In addition to these a very detailed information on various items such as

- quantities of each final product being produced,
- total sales achievable by products,
- amount of over production achieved/amounts of excess stock,
- amount of under production/amount of shortage occurred,
- amount of cash which would be tied-up or wasted in the production of undesired quantities,
- cost of carrying inventory,
- penalty - the cost of shortage, etc.

can be obtained from the computer calculations. A full list of such information is illustrated in Table 5.4 which would be an example of the computer print out.
(The information on Table 5.3 presented in the previous section is the output of this computer calculation).

The mathematical formulas of this algorithm is given in Appendix IV-b

Having achieved these calculations the total result is then input into a formula called here "utility formula" which sums all the positive and negative responses of each individual plant setting to determine its utility against meeting the requirements.

The principle of this process is shown in Fig 5 3 2 1 b 2 which shows the input and output to the algorithm and the utility formula. Table 5.5 shows the utility of each plant setting when it uses several levels of plant capacity. This table is similar to Table 5.2, but it has been prepared with full consideration of production and inventory costs and other parameters which have not been considered for the sales maximization criteria. In the case of utility criteria, the manager can influence the schedules by shifting them towards production of products in a manner more consistent with his policies regarding various products. For example, the manager can assume some high penalty costs for the desired products and a high inventory cost for the undesired products and then determine the utility of each plant setting against this situation. An optimum combination of these plant settings which result in the achievement of higher utility would in fact be more consistent with the manager's policy regarding the problem of controlling the inventory of products. This is itself an advantage to the case when only one criteria of sales maximization is considered.

This intermittent process of finding the 'utility' of each plan setting gives the information required for a Dynamic Programming-computation of an optimum schedule. When this information is input to the dynamic programming it indicates(in a manner similar to that explained in the previous section) the optimum schedule.

An example of the schedule which has been computed by the dynamic programme and maximizes the utility can be seen from the network model (Fig.5.3.2.1.b.3) .The solution(i.e.optimum schedule) is traced through the output of the dynamic program which is presented (printed out) in a matrix form and is shown in Fig.5.3.2.1.b.4.

This schedule involves the following allocation set

2 blows with plant setting No.1

4 blows with plant setting No.2

0 blow with plant setting No.3

The sales achievable = £ 276

The maximum utility = £ 174

The sales value resulting from this schedule is slightly less than the sales value of a schedule which is obtained under the criterion of sales maximization(the sales achieved by the latter was £280 and the sales achieved by the present schedule is £276). However the present schedule,obtained under the utility maximization, is more consistent with the manager's policy since it has considered more constraints and objectives of the manager.

Table 5.4 List of information that would be pinted out by the computer when it calculates the 'utility' of each individual plant settings.

NOTATIONS					
I=	Product No	Prod 1 I=1	Prod 2 I=2	Prod 3 I=3	All Products Considered Togeth[e]r
DK(I)	Quantity Demanded				
J=J	Plant Setting Being Used				
KJ	No of 'Blows'				
X(I)	Quantity of Product Produced				
M(I)	Shortage Accured				
P(I)	Penalty (Shortage Cost)				
EX(I)	Excess Produced				
A(I)	Cost Of Excess				
P(I)+A(I)	Total Cost (Excess for Shortage) Per Product				
S(I)	Potential Sales				
Y(I)	Achievable Sales				
U	Gross Utility for Product				
SU	Total Gross Utility for All Products Together				
C	Cost of Melt or One Blow				
SU-C	NET TOTAL UTILITY				
SY	Total Gross Sales Achievable				
SY-C	Net Sales Achievable by All Products Together				
SM	Total Shortages Occured				
SP	Total Penalty				
SO	Total Excess				
SA	Total Excess Cost				
SS	Total Potential Sales Expected				
SY	Total Sales Achievable				
SY-C	Total Net Sales Achievable				
SD	Total Demand				
SX	Total Supply (Production)				

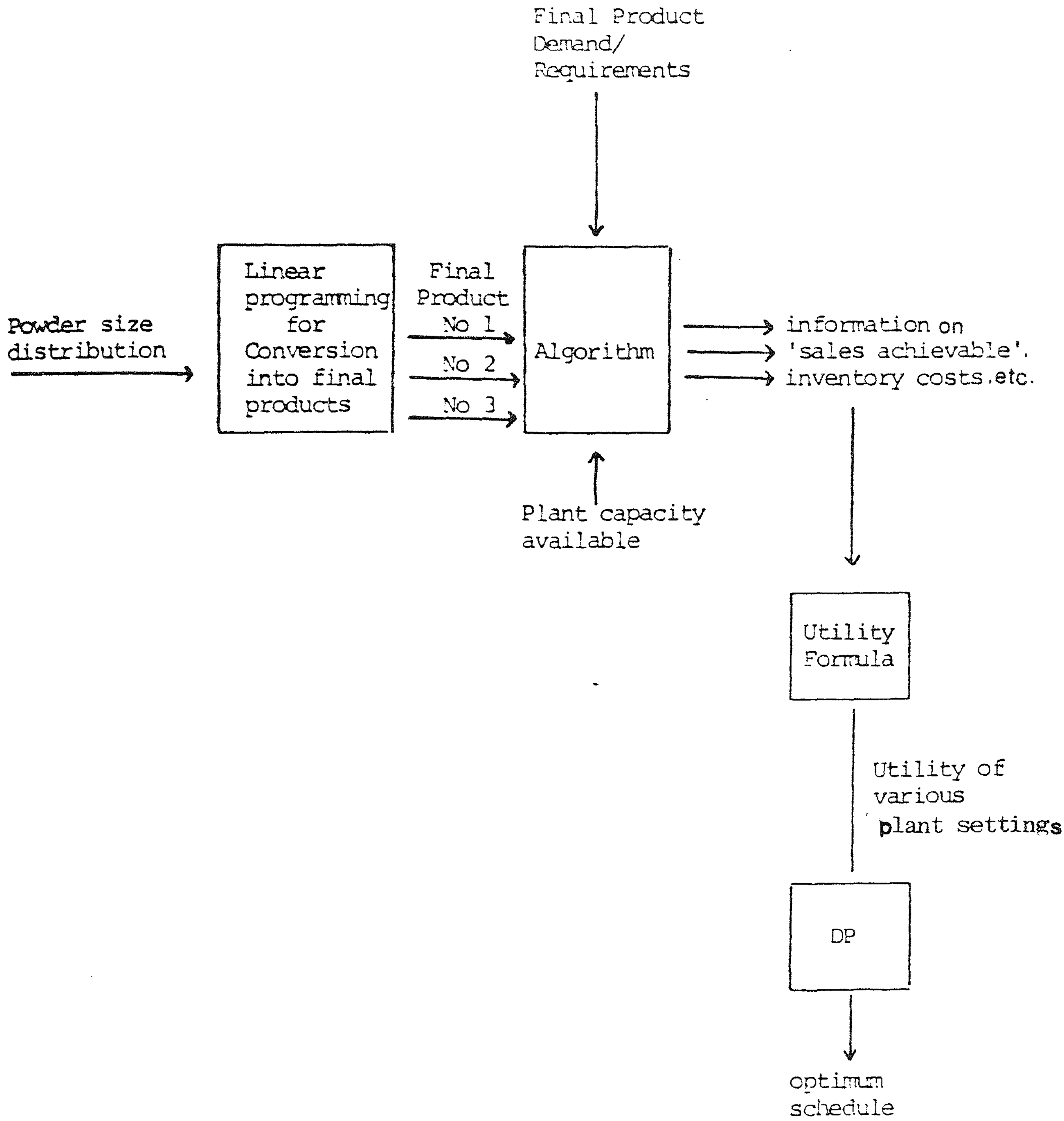


Fig. 5.3.2.1.b.2 Flow chart illustrating the input and output of the computer programs and the Algorithms developed for determining the optimum plant-setting schedule.

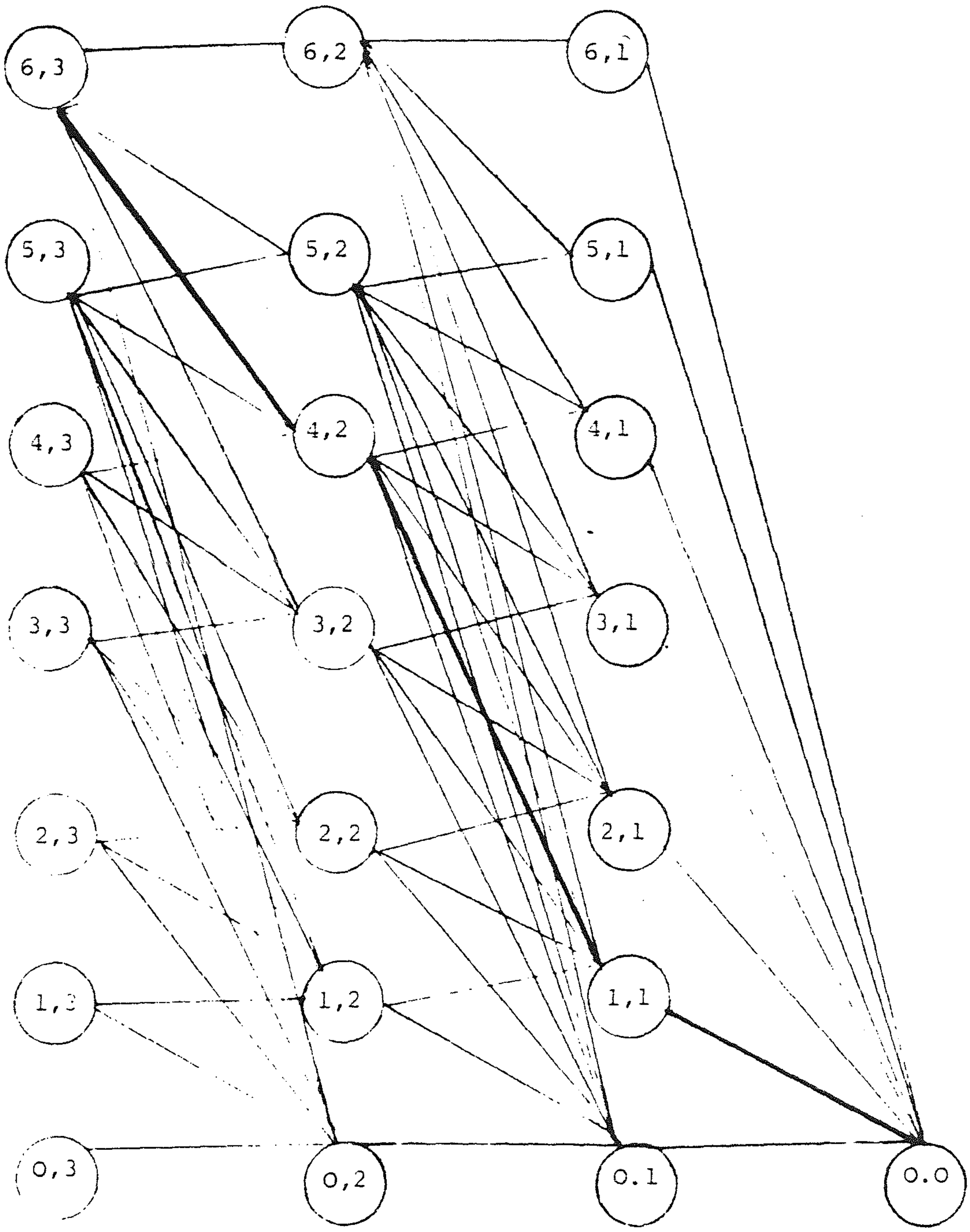
Table 5.5 Independent retun function for different level of capacity being allocated to each plant setting .

	Size distribution 'A' resulted from using plant setting No. 1		Size distribution 'B' resulted from using plant setting No. 2		Size distribution 'C' resulted from using plant setting No. 3	
	No. of blows (K_j) performed with plant setting No. 1	Return (utility) $Y_J(K_J)$	No. of blows (K_j) performed with plant setting No. 2	Return (utility) $Y_J(K_J)$	No. of blows K_j performed with plant setting No. 3	Return (utility) $Y_J(K_J)$
6 Blows are possible and should be allocated to 3 plant settings.	1	10	1	12	1	6
	2	48	2	54	2	43
	3	77	3	90	3	67
	4	102	4	126	4	61
	5	99	5	151	5	54
	6	94	6	119	6	46

Fig. 5.3.2.1.b.3   UTILITY NETWORK MODEL

Available capacity (i.e. No. of process 'runs' possible)

No. of plant settings to be considered for the allocation of the available capacity



Total blows possible	No. of blows allocated to plant setting No. 1						
0	0	1	2	3	4	5	6
0	0						
1	0						
2	0	10					
3	0	10	48	77			
4	0	10	48	77	102		
5	0	10	48	77	102	99	
6	0	10	48	77	102	99	94

Allocation of possible blows when only one size distribution (No. 1) considered

Total blows possible	No. of blows allocated to plant setting No. 2						
	0	1	2	3	4	5	6
0	0						
1	10	12					
2	48	22	54				
3	77	60	64	90			
4	102	89	102	100	126		
5	102	114	131	138	136		
6	102	114	156	167		151	119

Allocation of possible blows when 2 plant settings are examined

(No.s 1&2)

Total blows possible	No. of blows allocated to plant setting No. 3						
	0	1	2	3	4	5	6
0	0						
1	12	6					
2	54	18	43				
3	90	60	55	67			
4	126	96	97	79	61		
5	141	132	133	121	73	54	
6		147	169	157	115	66	46

Allocation of possible blows when 3 plant settings are examined

(No.s 1,2&3)

Fig. 53.2.1.b.4 The output of Dynamic Programming Computation presented in Matrix form.

5.4 Selection of Cloth Gauges to be Used in Sieves

This problem is concerned with the fractioning of an existing powder production (base powder) to give maximum utility to the powder fractions of a base powder.

As was shown in the previous section the customer-requested product would often overlap on each other and compete for a definite proportion of the powder. An example of this is shown in Fig. 5 4 1 where the base powder has a size range from 0.050 mm to 2.50 mm and there are four products which demand for various fractions of this product.

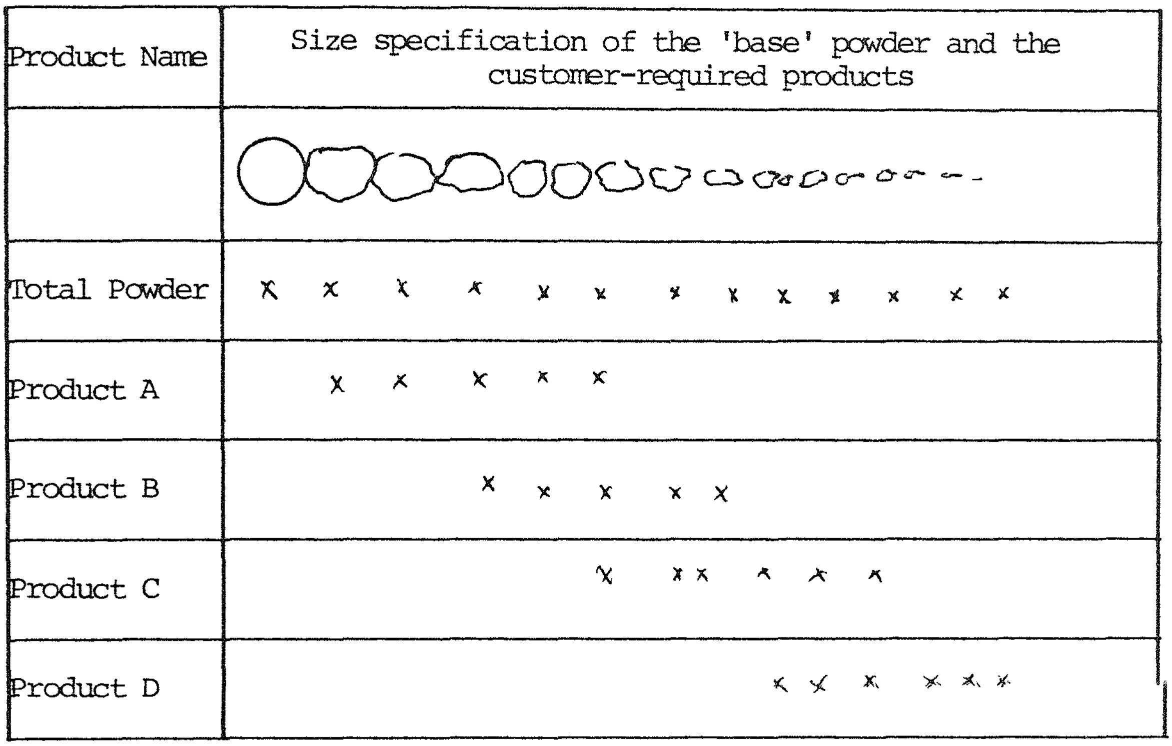
It was shown in the previous chapter that the screening stage is a control point on the process line which permits the monitor of the split of base powders to various mesh categories or standard products through the setting of various cloth gauges in the screens.

The problem at this section assumes that there are various possible cloth gauges which can monitor this split as desired. If this assumption is valid then it is possible to solve this problem of split (most efficiently) by LP which recommends those cloth gauges which maximize the utility of various fractions of a base powder. Even if this selection of cloth gauges is limited the LP solution will be of most guide in selecting the right cloth gauges.

This problem is analogous to the problem of 'cracking' oil to achieve a maximum yield of petroleum and other products.

The problem of fractioning a base powder to meet a given order book is a problem akin to fractioning of stock material discussed in section 5-1. The same basic considerations apply. The technology matrix, similar to that in (Fig. 5.4.1 is drawn-up and used as the basis of decisions for the sieve-cloth choice situation.

Fig. 5.4.1 The 'base' Powder and the Order Book Requirements



Customer requested product	size range of the product
Product A	from 0.050 mm to 1 mm
Product B	from 0.075 mm to 1.25 mm
Product C	from 1 mm to 1.75 mm
Product D	from 1.10 mm to 2.50 mm

5.5 Summary of the Approach and the Procedure for its Use in Controlling the Operations of Powder Making Process

The previous sections described how the decision problems of various stages of powder making process can be modelled and solved by mathematical programming techniques. These models would permit rational decisions to be made by the managers in metal powder making companies in controlling the production of their respective companies. By using a low cost microcomputer for which these models are programmed the manager can, at every moment, examine (check) the availability of the customer-requested products in the unallocated stock materials and load the plant more economically than otherwise would be possible through the decisions made by 'intuition' or by 'hunch'.

This section introduces a new procedure for controlling the production in metal powder making process which places these decision models in the context of total plant operation.

A schematic diagram of total operation of a powder making plant is shown in Fig. 5.5.1. This diagram contains two decision centres which control the flow of materials through the plant. The Decision Centre No. 1. would represent the manager responsible for making production decisions and the Decision Centre No. 2. represents the manager responsible for selling the products which are being produced.

In the existing management system the Decision Centre No. 1. would make all of the production decisions. As it is seen in Fig. 5.5.1 the production decisions are based upon the previous history of sales of the individual products which may be obtained in the form of

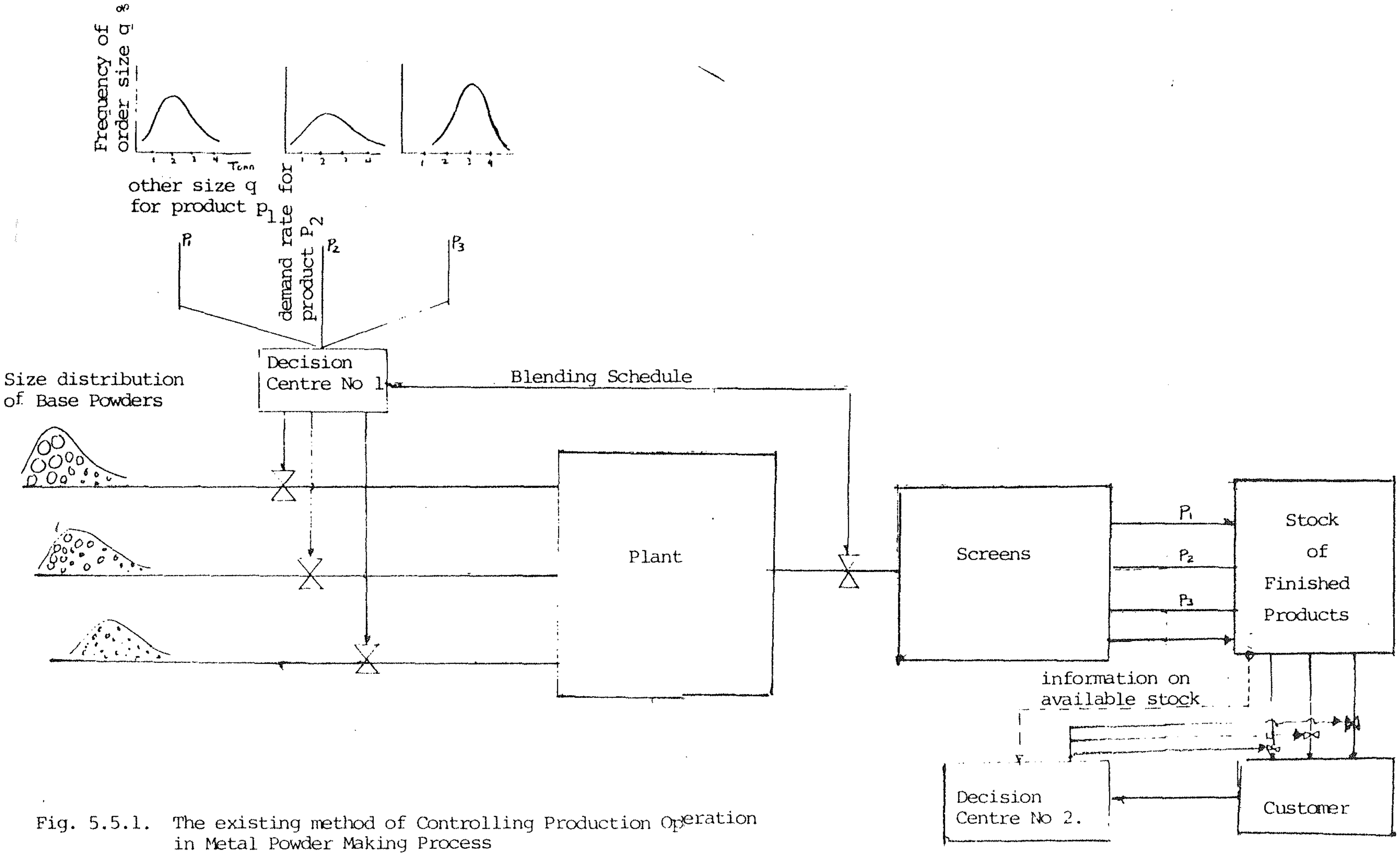


Fig. 5.5.1. The existing method of Controlling Production Operation in Metal Powder Making Process

probability distribution for individual products. This information may be given by the sales manager(decision center No.2) or the accountant. The decision center No.1 uses this information and make decision on the quantities he would like to produce for each individual products so that the expected demand is satisfied and some amounts are produced for stock.Based upon this decision, he makes a decision on the batches of various base powders to be produced.As it was stated before this decision is very difficult to make since it requires many simultaneous equations to be solved for reaching a reasonable decision.Because of this difficulty the manager would make his choise by considering the outcome of decisions with respect to only a few probably more demanded products or with respect to those products which he is obliged to produce for the incoming period. Parallel to this decision, he would select the cloth gauges to be used in the screens so that the 'should be production' would be classified into the final products which he has planned in the chosen planned rate. The second Decision Centre (i.e. the sales manager) would then be informed on the expected resulting level of stock of products which would be available to be sold. The sales manager (Decision Centre No. 2.) upon receiving the actual and current customer orders would compare the stock materials (finished products) with the customer-requested products and simply assign them to the customers orders provided that they match with the customer's requested products. And, of course, he would put intensive efforts to sell the other products too.

This process of decision making, however, has not been successful because it produces a high level of 'wrong' products which means waste in materials, energy and time.

The approach which is presented in this chapter would improve the process by facilitating the making of rational decisions at both decision centres. It assists the production manager in making more economic and more consistent decisions on the batches of various powders to be produced, and allows the sales manager to participate more effectively in the making of production decisions, and, in particular, it allows the sales manager to play the role of the final controller of production.

The schematic diagram of the proposed system for controlling the production is shown in Fig. 5.5.2, which is a modified version of Fig. 5.5.1. The new procedure is explained below.

The production manager (decision centre No. 1) by using the information on expected product demand, would go through the following stages to reach a final decision on the batches.

As a first step, he (the production manager) would convert each individual base powder into its final product equivalence in such a manner that for a given pattern of demand the profit or sales value of each base powder is maximized. This would mean that the production-manager attempts in fact to maximize the profit or sales outcome of each process run. For the purpose of this conversion the manager makes use of the LP as previously described in the section on 'stock allocation' and 'cloth gauge selection'. A simple example of such conversion is shown schematically in Fig. 5.5.3 below.

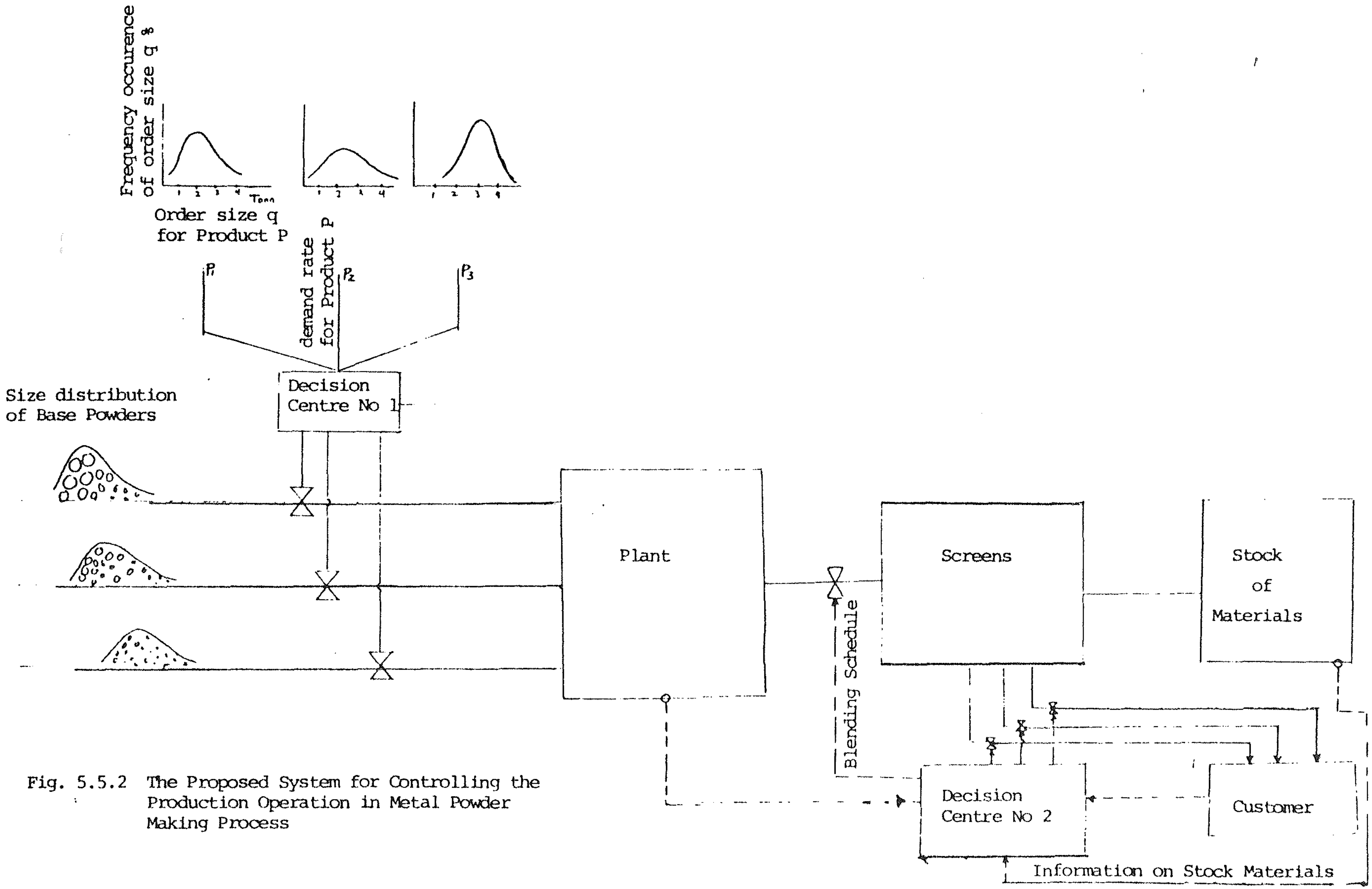


Fig. 5.5.2 The Proposed System for Controlling the Production Operation in Metal Powder Making Process

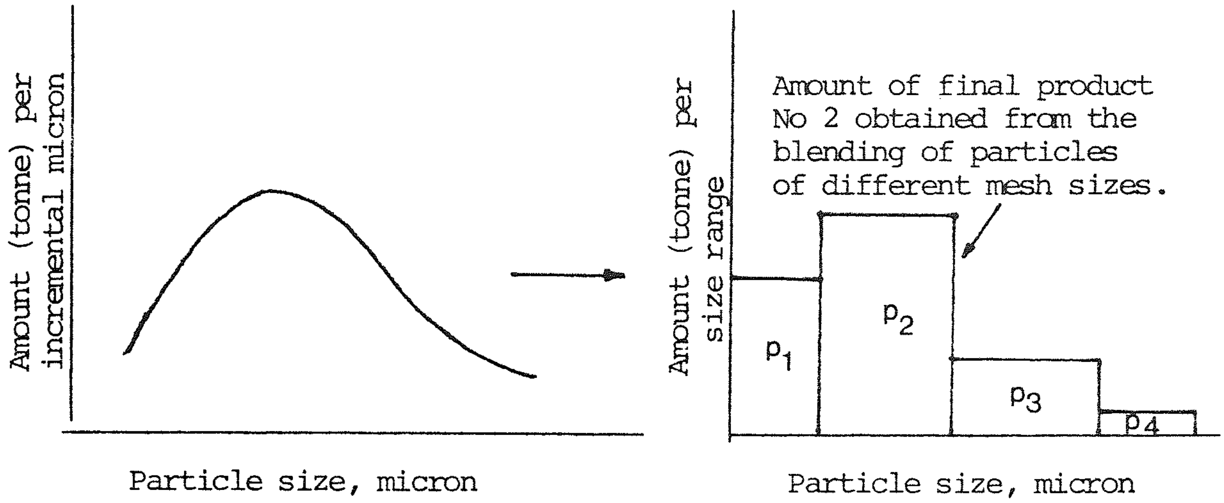


Fig. 5.5.3 The Conversion of the Size Distribution of a Base Powder into its Final Product Equivalence

In the second step, the production manager, having obtained the results of the first step, now solves the problem of selecting among the various base powders and determining the quantity of each to be produced by considering it as a simple classic scheduling problem. The converted base powders are by analogy the machines which produce several products at different rates and the production manager's problem is to decide on the level of capacity (plant capacity) which he should allocate to each machine in order to meet the expected demand for each of the final products. To solve this problem the production manager would use the dynamic programming technique which is the most appropriate method for solving such scheduling (allocation) problems (36).

The end result of these two steps will be a "production schedule" which indicates the batches of various base powders to be produced and the expected quantities of each final product. (The process of finding this schedule has been described in the previous section on 'plant setting schedule').

On the basis of this schedule the sales manager (decision centre No 2) would obtain information on the availability of the materials in terms of both the expected finished products and the particles of various 'mesh categories' that would enter the system. The sales manager, upon receiving the information on actual level of demand for each final product and their exact size specifications, would be able to make a comparison between the available materials and the customer-requested products. If they match one another he assigns the expected finished products to the customers; in other cases he runs a Linear Program to determine the allocation scheme for blending the available materials into the currently demanded products. Based upon this allocation sheme he would prescribe the cloth gauges to be put in the screens. In this way, selecting the cloth gauges or blending schedule by the sales manager is a second control on production operation and results in more effective utilization of production capacity and resources.

The proposed system allows both the production and the sales managers to determine easily, after each cycle of decision-making, the exact specification and quantities of unused materials. This information would be used by them in the next cycle of decision-making and might have a significant effect upon the economics of the production operation. The minimum effect would be a saving in plant capacity which otherwise may be used for production of already available materials. Even in the current cycle of decision-making it is quite possible that the sales manager could influence the customer orders (within limits acceptable to the customers) and make a slight change in the specification of the requested products so that some portion of the unused materials can be used.

CHAPTER SIX DISCUSSIONS AND THE CONCLUSIONS

a) DISCUSSION

The managerial problem of production control and decision making in the metal powder making industry is a title covering a wide problem area which includes the full hierarchy of decision problems of the managers in this type of industry. It includes problems ranging from the making of lower level operating decisions which control day-to-day operations of powder making processes, to the problems of the higher level of control. Typical of the latter if the designing of policies which should maintain the stability of operation of the powder making company under the various stimuli of the outside world (eg. The influence of overseas suppliers who by their aggressive strategy might enter the home market and cause a contraction in the volume of the market demand for the company's products).

The author originally believed that simulation would be the most direct approach to the managerial problems of this industry. Initial impressions gained by the researcher were that a dynamic 'company model' developed from historical data could be used to evaluate manufacturing policies. However, the observation of plant operation revealed that the metal powder making companies involved complex decision problems at the plant process control level which should be dealt with first before any decisions of the 'higher' level could be approached.

THE MAJOR DECISION PROBLEM OF A POWDER MAKING PROCESS AT PROCESS CONTROL LEVEL IS THE DECISION OF FRACTIONING OF THE BASE POWDER INTO THE SIZE CLASSES WHICH YIELD MORE QUANTITY OF FINAL 'SALEABLE' PRODUCTS AND, THE SCHEDULING OF PLANT SETTING TO YIELD THE COMBINATION OF BASE POWDERS WHICH MEET THE REQUIREMENTS OF THE ORDER BOOK, AND BRING ABOUT MORE UTILITY OUTCOME FOR THE LEVEL OF CAPACITY BEING USED.

IN ADDITION TO THESE THE PROBLEM OF ALLOCATING STOCK OF 'UNSUITABLE' POWDERS OR 'RE-ALLOCATION' OF 'OVERSTOCKED' MATERIAL TO THE CUSTOMER ORDERS WOULD BE OF GREAT IMPORTANCE SINCE IT WOULD RELEASE A SIGNIFICANT AMOUNT OF CAPITAL WHICH WOULD OTHERWISE BE TIED-UP IN THESE MATERIALS AND WOULD SAVE THE AVAILABLE PLANT CAPACITY WHICH MIGHT HAVE BEEN USED TO PRODUCE THE ALREADY AVAILABLE MATERIALS.

In each of these decisions the manager has difficulty in considering a number of economic and technological factors. These are quantified in this work by means of mathematical models and the models are programmed for the computer to provide a mechanism for the manager to assist him in effective short term matching of the available plant capacity and resources to the requirements of the market demand.

The mathematical models developed in this work are the optimising techniques of the operations research such as Linear Programming for stock allocation problems and the fractioning of base powders to increase its yield, and the Dynamic Programming for the determination of the optimum scheduling of plant settings.

The use of linear programming as an optimal decision-making technique for production decisions is well established in the petroleum cracking industry where a complex hydrocarbon is broken down into a series of simple hydrocarbons. In powder making a raw product, having a wide range of particle sizes, is broken down into more 'precise' fractions (at least in concept). In the same way, sales demands are translated into similarly precise fractions and an 'allocation' takes place.

Since only small computers were available to the author the example of allocating particles of various mesh sizes to the final products include only a few size classes. However, with computers of larger size,solution of larger, more complex, problems is possible. For the objective function of Linear Programming either the minimization of cost or the maximization of sales value could be considered. However, because the precise evaluation of the cost of each size-classified particle is not possible and because 'value' in terms of final product price can easily be included in the program, most of the LP solutions involve the sales maximization criteria. Where the objective is to minimize the backlog of demands the relative value of the backlogs are considered as the coefficients of the objective function.

The selection of the best combination of plant settings or base powders could probably be done through the use of Linear Programming which has been developed for stock allocation problems. It would, however, be necessary to assume that a linear relationship exists between the values of the output (for instance the sales' value of the output against a given pattern of demand) and the level of the output (ie. the number of batches of each base powder to be produced). This assumption is not always valid because there can arise a level of output for each base powder after which the production of that powder brings about negative results by either adding to the amount of undesired materials or increasing the level of 'overstocked' materials.

Even if a linear relationship could be assumed between the values and the levels of the output for each base powder, the resulting linear programming model of this problem would involve a large number of variables and require larger scale computer capacity for it's execution.

To avoid these difficulties (ie. making invalid assumptions and putting large numbers of variables in LP), the Dynamic Programming technique was adopted. Using this technique, the outcome of various choices of combinations of base powders are computed rapidly and the results are presented in a matrix form that allows the optimum solution to be traced quickly.

The models and the computer programs described in the preceding paragraphs have contributed enormously towards the solution to the managerial control problems of production in the metal powder manufacture industry. The complex routine manufacturing decisions of the industry,at one time responsible for occupying much of the managers time and being the major cause of frequent isolation of the management from the manufacturing function of the industry, are now easily dealt with, by the manager, through the use of mathematical models which simplify their presentation and through the use of the associated computer programs which are specifically developed for their solution by the computer. Furthermore, these models and the associated programs enabled the managers to plan an optimum production output and to determine, at any given situation, the organization of production that is most effective in terms of matching the plant resources and the requirements of the company's order book. In short, the work has facilitated a greater control of the management over the manufacturing function of the industry and assisted a closer tie between these two functions in the metal powder making industry.

In addition to assisting the manager in solving the manufacturing organizational problems of the industry, the work presented in this thesis has provided a basis for future investigations into a number of areas, examples of which are quoted in the following paragraphs.

The immediate problem of more concern to the management in the metal powder making industry is the determination of inventory to be held at the start of each planning period so that a steady level of service to the customer can be guaranteed. As was previously explained in this thesis, there will always be a need for this type of inventory. Plant capacity in this industry, although equal to, or even greater than the tonnage requirements in the companys order book, is often unsuitable for making the exact products needed (the reason for this is the inevitable mismatch that exists between process output qualities and the specifications of the customer-requested products).

It is possible to simulate the production operation of a power making plant to find out whether the plant capacity will be able to meet the companys' future delivery commitments, and if not, adopt the policies to supplement the existing resources, eg: getting rid of misallocations ie. remelt or sell off non-saleable fine materials and buying in size grades which are not economic to produce.

Any simulation model to be constructed for this purpose would involve the major events and activities as shown in Table 6.1 and illustrated in Fig. 6.1 As can be seen from Table most of the activities listed in this Table are the ones already explained and modelled in this thesis (for example the 'checking of the stock material against the backlog of orders' has been modelled as the 'stock allocation' problem and the 'generating of a production schedule' has been modelled as 'plant setting scheduling' problem).

The above simulation can therefore be carried out with ease, even by hand, using only pencil and paper to record the results obtained from the calculations and computations at each of the consequent events.

The use of a computer to carry out the simulation, however, is of greater advantage than hand simulation, as it allows more accurate and much faster analysis of the situation. In practice this would require considerable additional programming work which is outside the scope of the present work.

The next chaper on Future Work, suggests that future research into the managerial control problems of the metal powder making industry should extend the control problem area to deal with the dynamics of the operation of a metal powder making industry. In particular it suggests that the future research should aim at providing management in this industry with the tool that can assist them in designing policies that

Fig. (6.1) Activities carried out in a cycle of plant production operation simulation

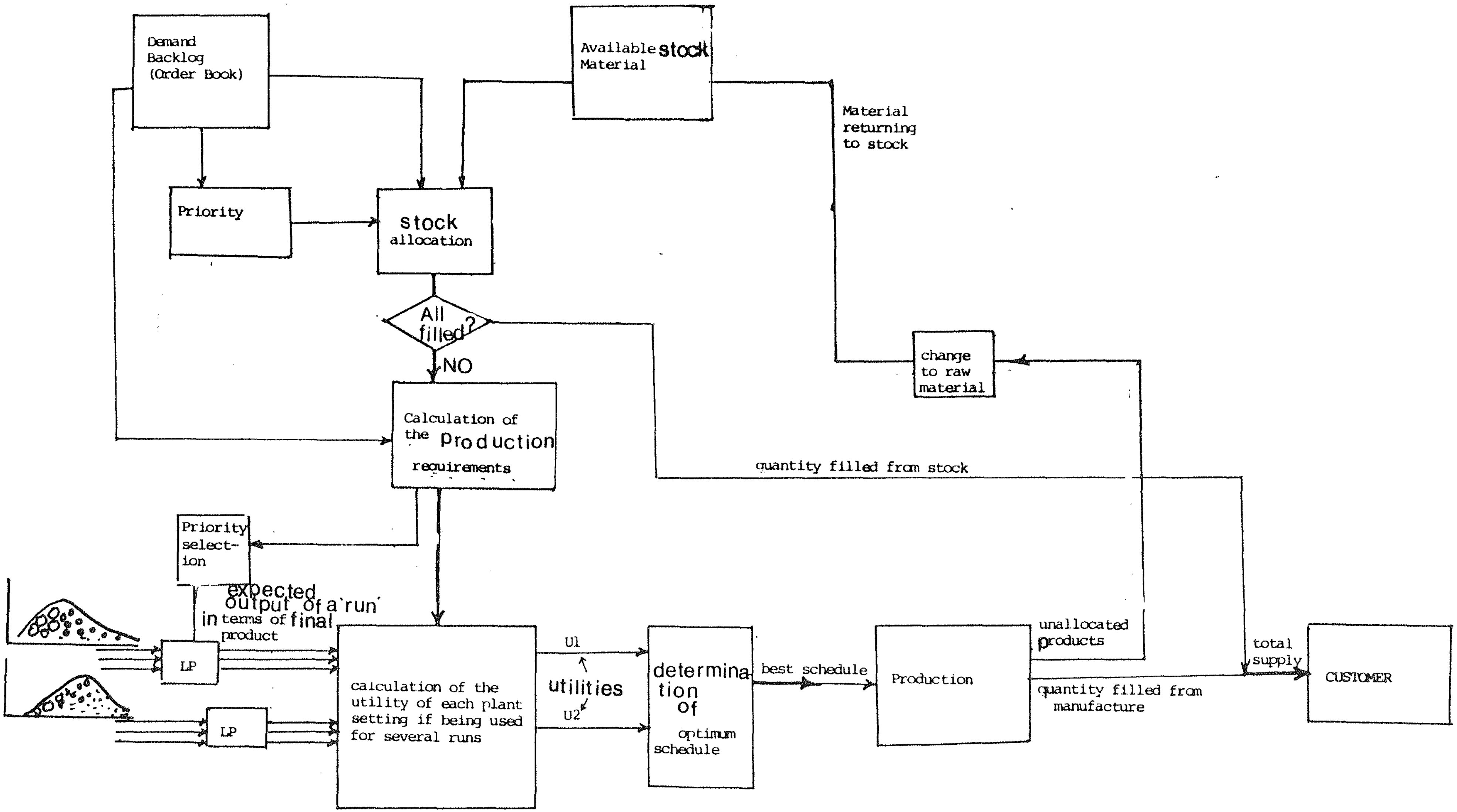


Table 6.1 Simulation Events

EVENTS	FUNCTION
1	Generate customer orders - either at a predetermined interval or via a stochastic process.
2	Update the level of order backlog.
3	Check the available stock material against the backlog of orders and fill the orders if the items are available.
4	Reduce the level of backlog (and consider the balance as production requirements).
5	Generate a schedule for meeting the production requirements and determine the expected production.
6	Fill the orders that are not met in '3' from the expected production at '5'.
7	Reduce the level of backlog again, and consider it as the ending level of backlog.
8	Repeat from '1' through '7'.

can best maintain the stability of the company operation over a longer period of time.

A dynamic 'company model' of the type known as the "Industrial Dynamics" model, originally introduced by Jay. W Forrester and his colleagues at Massachusetts Institute of Technology (44), would be such an appropriate tool.

In a paper contained in the Appendix (V), the author has shown that the models which have been developed in this thesis to simulate the individual operations of the metal powder making industry could effectively contribute to the development of an "Industrial Dynamics" model for the metal powder making company.

b) CONCLUSIONS

The study has been carried out to satisfy the requirements of management of several powder making companies who approached the University and asked for some tools and techniques that can assist them in organizing and controlling production in their respective companies. The question that was put forward by them is whether they can be helped in determining:

i) Whether a particular customer requirement will be "in stock" at the time it is required as a result of production of complementory fractions for other customers in the same class of quality.

ii) If not, when can a production be fitted in?

iii) What production settings? (Those which produce coarse, medium or fine) - is desirable for this specific requirement.

iv) What other fractions will be generated by the sieving operation necessary to give the customer the fraction he wants?

v) What quantities of these fractions will be in stock as a result of this when these powders have been produced, etc.

They also wish and indeed endeavour to keep powder stock as low as possible because of their high cost.

Until now, the manager has had to do many tedius calculations and computations to answer these questions and as a result he was not always sure of the consequences of the final decision. On occasions he did not involve himself with making these decisions because it was too tedius and time consuming. In this circumstance the operations are left either uncontrolled, or left under the control of the Forman, who is not always aware of the policy of the manager. The consequences of inconsistent decisions were often costly. These are exemplified in a high level of stock of the 'wrong' or undesirable fractions, and a low level of stock of products in more demand.

Reviewing the technology of the process and the product specifications in those companies (who use the atomization method of powder manufacturing), revealed that a mathematical abstraction of powder making operations in quite possible, and programs can be produced which allow the various decision making tasks of the managers to be given to computers which are capable of considering many economic and technical factors, and can produce and evaluate many possible alternatives at a speed and accuracy far beyond the capability of human decision makers. Various questions which were listed previously are now possible to be answered more effectively than otherwise was possible through guessing or rough estimation of the manager. In addition to this the manager is now equipped with a mechanism which will allow him more control over the operations of his powder making plant as well as more readiness in taking quick actions against the market variation. He is provided with a mechanism for quick and rapid product definition considering the market, plus the companies policy (or willingness).

The manager now has complete control over the stock situation and can make decisions which lead to release a significant amount of capital, which would otherwise be tied-up in idle or unknown stock materials.

The research has concentrated on the short term tactical problems of metal powder manufacture and is believed to have contributed to, and have provided a springboard for, the future research work on the managerial problems of production control in this sector of the industry.

Future research work should be concerned with the problems of higher levels of control, namely, the problems of design and development of 'policies' which should maintain the stability of the powder manufacturing industry over a longer period of time. These researches would basically make use of the simulation method of analysis to test and evaluate the effects of alternative managerial policies upon the company performance.

Any simulation model which was developed for this purpose, and which replicated the operations of powder manufacture, would include some check points and activities which are not easily duplicable through the use of logic computer commands, and have to be input as subroutines.

Such subroutines are, of course, the ones which have been already developed and explained in this thesis.

CHAPTER SEVEN

FUTURE WORK DEALING WITH THE POLICY FORMULATING TASK OF THE MANAGER

The work presented in the previous chapters illustrates the approach to the 'low level' control and decision making problems of the management in the metal powder making industry. Within a wide spectrum of managerial control problems met in this industry, the manufacturing organizational problems including the control of the manufacturing operations and the control over the use of the stock materials was sought as the most immediate concern for the research. These areas involve complex decision problems whose effective treatment is vital to the short term success of the operation of a metal powder making company.

The approach taken in this project provided a management strategy for the solution to the organizational problems of the industry and facilitated a greater control of the management over the production and stocking operations of the industry. It has facilitated the effective short term matching of the plant resources and the requirements of the companys' order book through the provision of mathematical models that allow optimum allocation of stock materials and optimum scheduling of the plant settings for the manufacture of orders which could not be filled from the stock. These models also enable the manager to plan an optimum production output for his plant.

The proposed approach, however, is static in the sense that the solutions it provides to the problems are valid only at one point in time. Given information on stock materials, on the requirements, and the plant available capacity, it determines an organization of production which is the best answer to that situation. The assumption made in taking this approach was that the manager will review the situation more frequently and at each instant of time he makes use of the models presented in this thesis to reach the optimum decisions. The term used by engineers for this type of control is 'point to point' control.

The future work should extend the present work to deal with the 'higher level' decision problems of management in this industry. It should also extend the control problem area to deal with the dynamics of the operation of a metal powder making company.

The higher level decision problems of management are related to policy formulating. Policy formulation is a most important reaction in the operation of business activity. A policy is usually considered as a guide to action, or a basis for future business decisions. Once a policy is established with regard to a particular field of activity, recurring problems may be solved upon the basis of a previously established policy without the necessity of going into the matter fully each time a question arises, ie. use of precedents. The manager then being relieved of the repetitive or operating decisions is free to devote himself more to the major strategy decisions. (The strategic decision area is concerned with establishing the relationship between the company (firm) and it's environment).

In designing the policies, however, there is the difficulty that a policy which is established to well guide the decisions or the activities of one section of the company may not be effective when considered in terms of the overall effect upon the operation of other sections of the company and/or on the overall operation of the company. In addition to this, an established policy which may well apply to the regular situations of the present time may not cover, or may not be applicable to, the new situations which arise in the future. If this problem (ie unsuitability of the previously established policy to cover new situations) arises, the future decisions or actions will then be misguided by the existing policy and this may well result in the instability of the operations of the company (firm).

Assisting the manager in exploring improved policies for his company should therefore be the objective of future work. The ultimate goal is to provide management with the tools to assess the nature of the responses of the company to the various dynamic influences of the external environment.

Simulation is an especially powerful technique that assists in the testing and designing of managerial policies. Simulation as used in business would simply mean setting up on a digital computer the conditions that describe the company operations. On the basis of the descriptions and assumptions about the company, the computer would then generate information concerning finance, manpower, product movement and so on, to be used as a basis for judging performance. With simulation models one can determine the effects of dozens of alternate policies without tampering with the actual system. The manager, through the analysis of the simulation results, will make the judgment on the plausibility of the policies.

Of the existing simulation models or studies used for the testing and designing of managerial policies in the business and industry, perhaps the work of Jay W. Forrester, Professor of Industrial Management at Massachusetts Institute of Technology (MIT), is the best known.

Forrester and his colleagues at MIT developed a computer-based simulation methodology that assists managers in assessing how their policies will affect the performance of companies over a period of time. The method uses the simulation techniques to reveal how the system behaves when it operates a particular policy. The comparison of simulated system behaviour at two occasions which use different management policies would reveal the effectiveness of the policies. A policy which leads to more stable company operation is of course more plausible.

Figures 7 1 and 7 2 illustrate two examples of a company's responses to variation in customer order rates. Figure 7 1 is the simulated system performance when operating with a 'fast' decision policy for adjusting the inventory and Figure 7 2 is the system performance when it works with a 'delayed' or slow decision rule for adjusting the inventory. It can be concluded through the comparison of the two companys' responses (shown in Figures 7 1 & 7 2) that, under the 'fast' decision rule (Figure 7 1) the system would be able to adjust and stabilize after a disturbance caused by an increase in the customer order rate. The 'delayed' decision rule, however, had a dramatic effect on the behaviour of the system as shown in Figure 7 2 Under the 'fast' rule, the system was able to dampen oscillations caused by the change in the

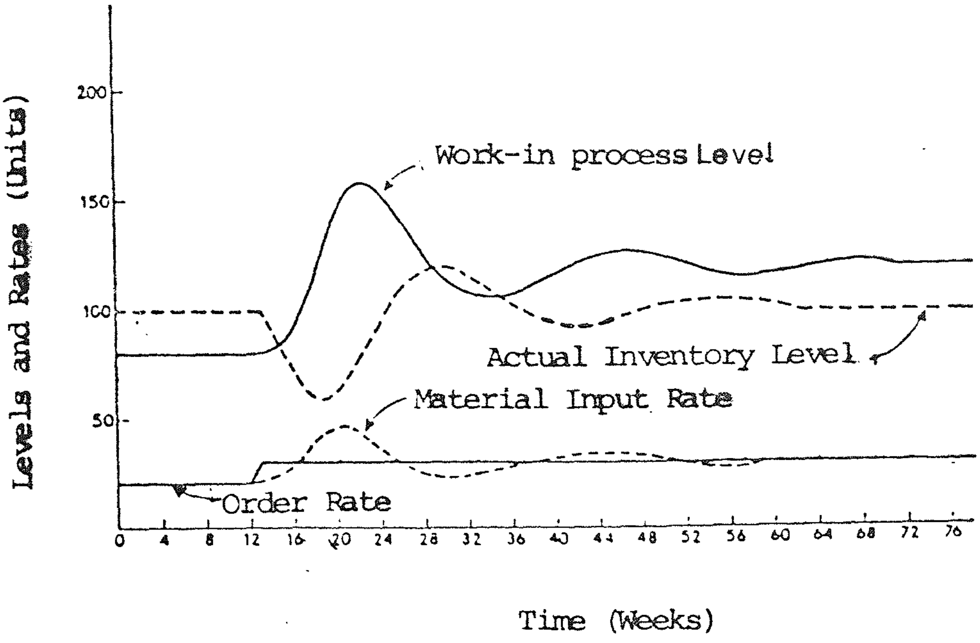


Fig. **7.1** System Responses to Change in Order Rate (When the system operates with a policy which adjusts the inventory fast). (40)

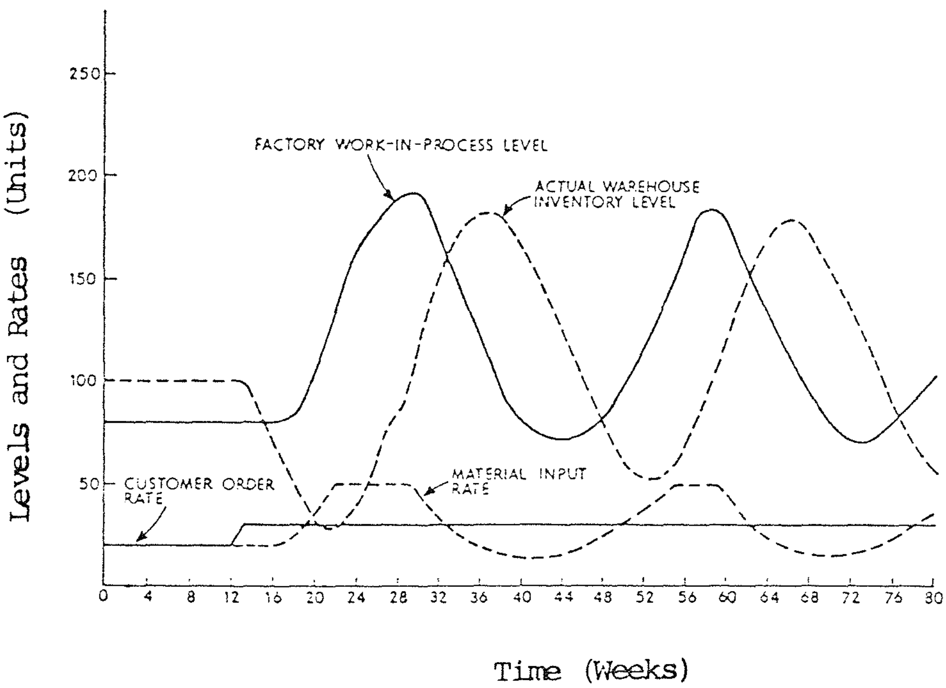


Fig. **7.2** System Responses to a Change in Order Rate (When the system operates with a policy which adjusts the inventory slowly).

customer order rate. Under the 'delayed' rule, however, the system aplifies and perpetuates the oscillations caused by the disturbance. As a result the 'fast' rule is a better policy.

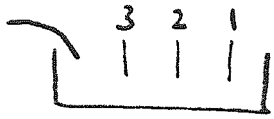
The above form of analysis and simulation is named by Forrester as "Industrial Dynamics" or "System Dynamics".

It is believed that there is a logical relationship between the O.R. methods used in the work reported in this thesis and Industrial Dynamics. This is explored at some depth in a paper contained in the Appendix (V).

APPENDIX I The Technical Information on Two Different Atomized Powder Making Companies

a- Technical information on the processes in Company No. 1

1). Time cycle from the point of disintegration in the water jet to bagging off - 8 hours.



2). Sequence of magnet - Position 1 at fine end of tank.

Position 2 middle of tank.

Position 3 at coarse end of tank.

Normal sequence is to take 1 lift from position 1, followed by 2 lifts from position 2, followed by 2 lifts from position 3. Any variation in this sequence is normalised within one hour.

3). Influence of variables at the point of disintegration i.e., in the blowing tank are as follows :-

Assume we have 3 sets of conditions which correspond to 3 different pressures, the minimum pressure is 15 p.s.i. below which the amount of oversize material becomes unacceptably high and the maximum pressure is 30 p.s.i. above which the amount of fine oxides produced becomes unacceptable and also in general shape deteriorates rapidly.

The following ranges could be anticipated on the 4 grades mentioned between these extremes of jet pressure.

S.660	15 p.s.i.	25%
	20 p.s.i.	20%
	30 p.s.i.	16%
S.460	15 p.s.i.	10%
	20 p.s.i.	15%
	30 p.s.i.	20%
S.230	15 p.s.i.	5%
	20 p.s.i.	7%
	30 p.s.i.	10%
S.110	15 p.s.i.	3%
	20 p.s.i.	5%
	30 p.s.i.	7%

b- Technical information on the processes in Company No. 2

1. <u>OUR PROCESS</u>

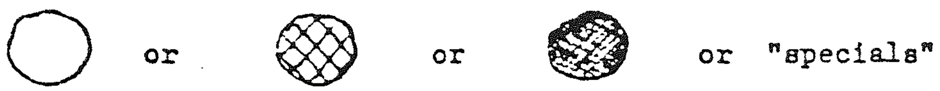
1.1 Our problem is concerned with the production of aluminium powder on a continuously operating plant.

1.2 This plant has two operations:

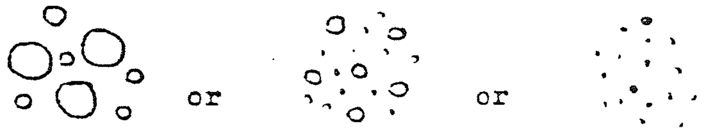
1.21 Production of the basic powders.
1.22 Classifying these basic powders into desired fractions by sieving.

2. <u>PRODUCTION OF BASIC POWDERS</u>

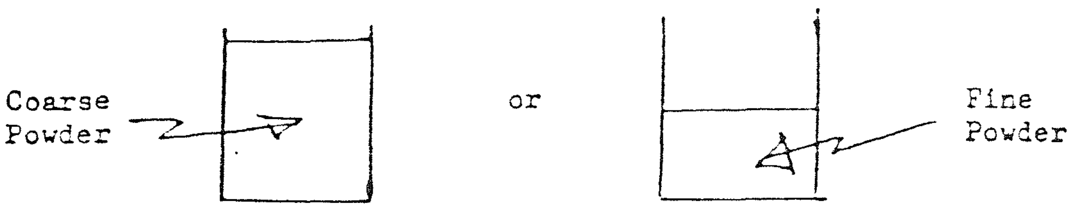
2.1 We produce more than one chemical quality of base powder. There are three standard qualities but some customers require tighter specifications of these standard qualities. Thus



2.2 The plant can be adjusted to produce fine powder, coarse powder or intermediate grades of particle size. Thus



2.3 The rate of production of basic powders is conditioned by the plant setting indicated in 2.2 above. Slower rates of production yield finer powders and vice versa. Thus



in a given period

2.4 There are other factors which affect the use of the capacity available for the production of basic powders. These are

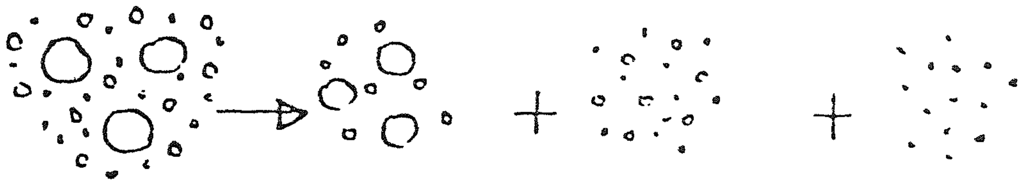
2.41 Total customer demand for the products. Continuous operation (24 hrs/7 days per week) can only be maintained if the sales demand is there.

2.42 Downtime for maintenance, breakdowns, raw material supply holdup, &c. Experience on this has produced average rates of production used in planning but any one factor can temporarily interrupt the programme.

Cont./2...

3. CLASSIFYING OF THE POWDERS BY SIEVING

3.1 Basic powders are subsequently sieved before sending to customers in order to provide them with the specific fractions which they require and which vary over a wide range. This operation generates other fractions which are not required by a specific customer for which we are at the time preparing a required fraction. These other fractions are sooner or later sold to other customers. Thus



Base Powder	Fraction A To stock	Fraction B To immediate customer	Fraction C To stock

3.2 The fraction required by a specific customer's order will represent only a defined proportion of the base powder used for preparing this fraction. This proportion must be borne in mind when determining the amount of base powder to be produced for our plant to yield this fraction in the amount required by the customer.

3.3 We endeavour to keep powder stocks as low as possible because of their high cost. Therefore we attempt to integrate customer requirements to produce the powders required when they are required with as much balancing of fractions as possible.

4. CUSTOMER INFORMATION

The essential information from the customer's order is

4.1 The chemical quality.

4.2 Particle size range, the fraction he wants.

4.3 The quantity he wants.

4.4 When it is required by him.

4.5 The price he will pay.

5. WE HAVE TO DETERMINE

5.1 Whether a particular customer requirement will be "in stock" at the time it is required as a result of production of complementary fractions for other customers in the same chemical quality.

5.2 If not, when can production be fitted in?

5.3 What production setting - fast or slow (producing coarser or finer base powder) - is desirable for this specific requirement?

5.4 What other fractions will be generated by the sieving operation, necessary to give the customer the fraction he wants?

5.5 What quantities of these fractions will be in stock as a result of this when these powders have been produced?

APPEND II

Process Control Study in Metal Powder Making Industry

To find a correlation between process parameters and powder parameters the atomization process has been studied so far in great detail through experimental, visual (photographic) and theoretical (analytical) investigations.

In experimental investigations this process has been studied through observation of the properties of the powder after being quenched. Visual (photographic) investigations included the observation and the analysis of the fillers taken from the atomizing zone of the process from which the fluid dynamics of the process and the mechanisms of the particle formation were explained. Finally, the analytical investigations which often have been carried out to either give a better insight into the mechanisms of the process or to verify the results obtained in experimental investigations, included the mathematical modelling of the process, utilizing the fluid dynamics and heat transfer principles.

The following are some of the results achieved from these studies. They show the influence of process parameters upon the particle size and particle shape of metal powder. These are quoted from the book of 'J K Beddow' but are introduced in other references which have been given in the bibliography of this project.

INFLUENCE ON PARTICLE SIZE

The important factors are listed below with examples from the literature:

1. Increase of atomizing pressure generally reduces the mean powder particle size. (See Fig. 46 for gas (jet) atomization and Fig. 47 for water atomization.)
2. Increase in flow rate of gas, decreases particle size (see Fig. 48) but this was not found to be the case for water atomization.[24]
3. A high atomizing fluid velocity reduces the particle size of the powder produced. In the case of gas atomization, supersonic gas velocities were said to produce finer powder than subsonic velocities and at a lower gas consumption.[24] In wat

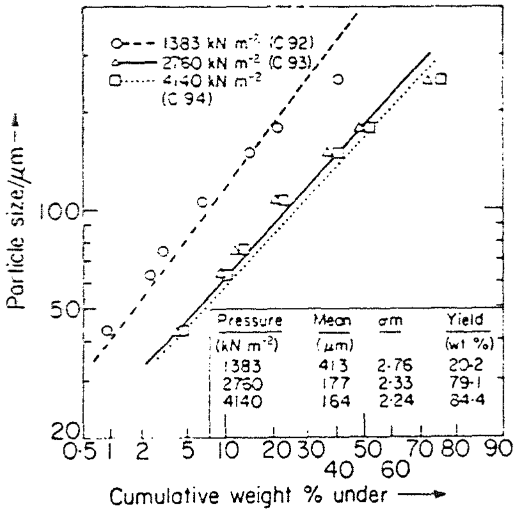


Fig. 46. Effect of jet pressure on cumulative size distribution of −40 mesh powder.[45]

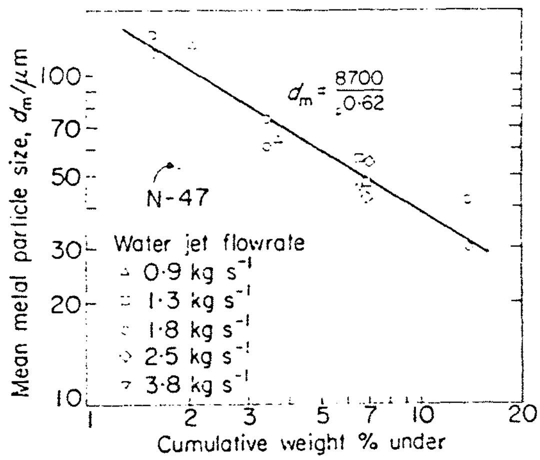


Fig. 47. Effect of water jet pressure P (kN m^{-2} × 10^{-3}) on particle size; 4620 steel 2-jet, 60°.[24]

atomization, the major variable for reducing the particle size of powder was said to be water velocity (see Figs 49 and 50).

4. In general, the shorter the metal stream (before impact with the atomizing fluid) the finer the powder produced. One reason for this is that in this situation, the difference in gas/metal stream velocities will be a maximum.

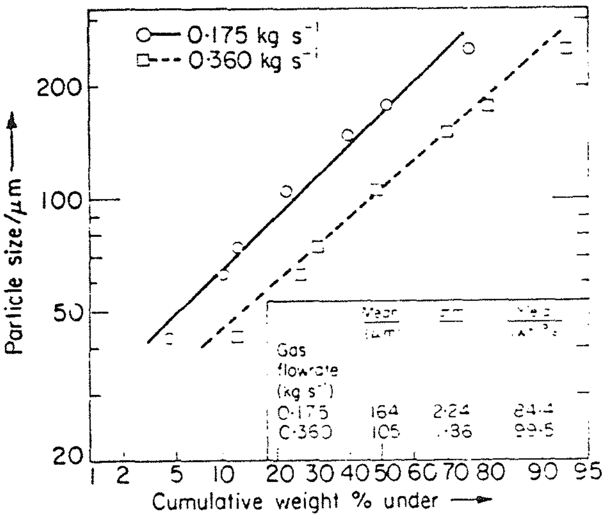


Fig. 48. Effect of gas flowrate on cumulative size distribution of −40 mesh powder.[45]

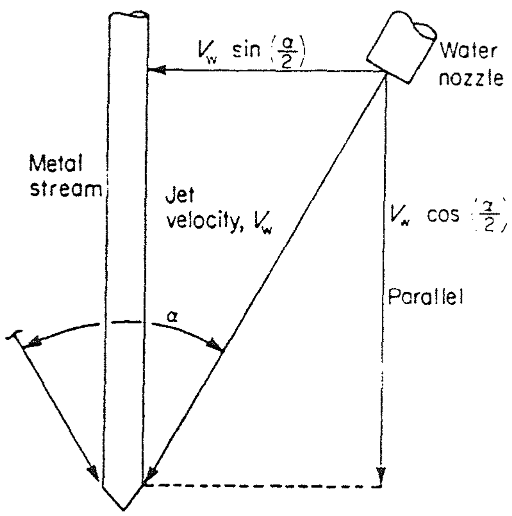


Fig. 49. Components of water jet velocity.

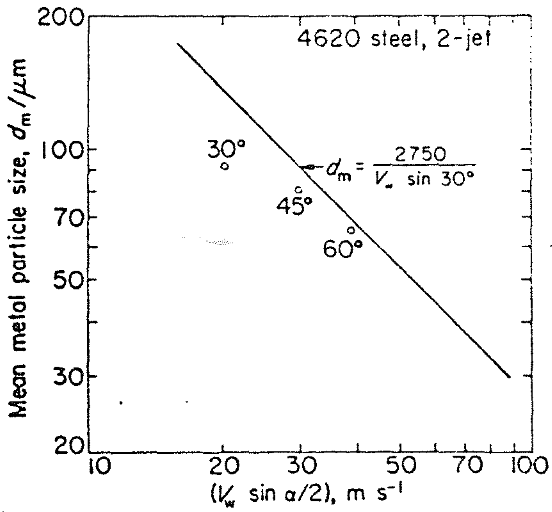


Fig. 50. Effect of normal water velocity component on particle size.[24]

5. Probably for much the same reason as in 4 above, decreasing the jet distance reduces the powder particle size, as shown in Fig. 51.
6. Studies of water atomization have shown that the choice of jet apex angle is specific to each system and that an optimum range of angles can be experimentally determined.[9,104] In the case of gas atomization, it has been shown that if the angle is too small, the coalescence stage of particle formation predominates. The reason for this is shown in Fig. 52 which shows that a small angle causes all of the product to concentrate near the axis. A larger angle promotes a greater spread of product with less coalescence.[10]

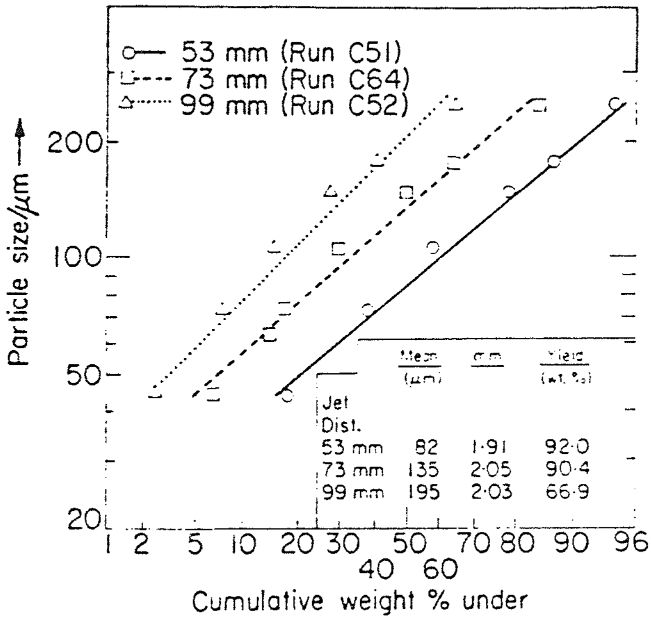


Fig. 51. Effect of jet distance on cumulative size distribution of −40 mesh powder.[45]

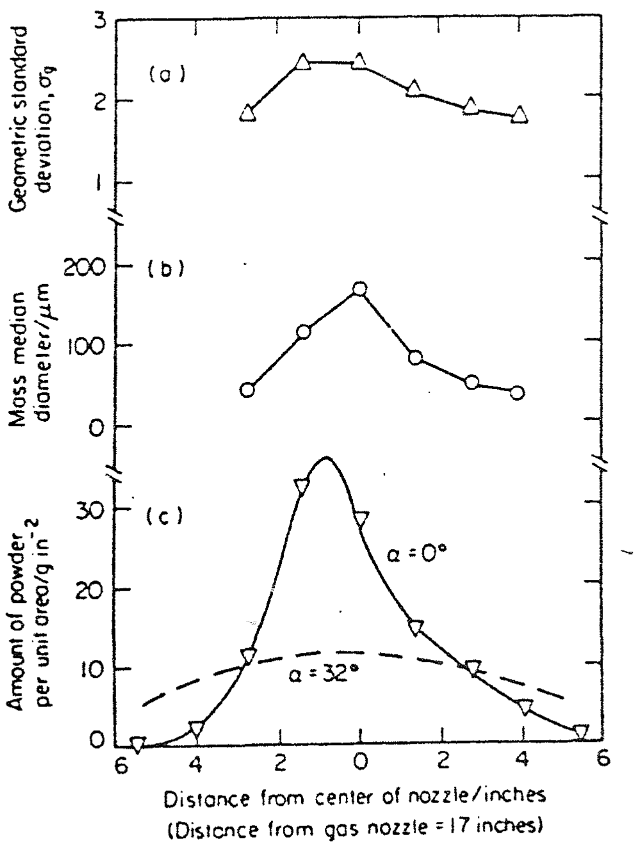


Fig. 52. Effect of patternation on [illegible]

INFLUENCE ON PARTICLE SHAPE

The comparison of shape has been dealt with in the literature from two major aspects: comparing spherical shapes with ellipsoidal shapes and smooth shapes with rough shapes.

A fairly detailed outline of a simple method of assessing shape in terms of L/D ratio is explained in the literature.[45] As a method of shape determination this method leaves much to be desired and more will be said of this later in Chapter 6. However, Ref. 45 is the first full-scale study of particle shape in metal powder atomization and so as a pioneering study the details may be overlooked.

1. Low jet velocity in water atomization is considered to promote spheroidization.[9] It was observed above that with low jet velocities large particle sizes predominate. As shown in Fig. 53, the smaller sizes tend to be much less regular (i.e. less rounded and spherical) than the larger sizes.[24]
2. The larger the apex angle, the more rounded the metal particles produced by water atomization.[9] One must assume that in this condition, the flight path of the solidifying droplets would be increased and they would therefore tend to be more rounded when finally solidified.
3. The longer the flight path, the more rounded, and smoother the surface of particles produced during atomization. This follows directly from the longer time for solidification.
4. In general, gas atomization produced more rounded shapes than water atomization. In Ref. 45 a theoretical model was developed for predicting the shape (L/D) of atomized metal particles. The model accounted for the following variables:

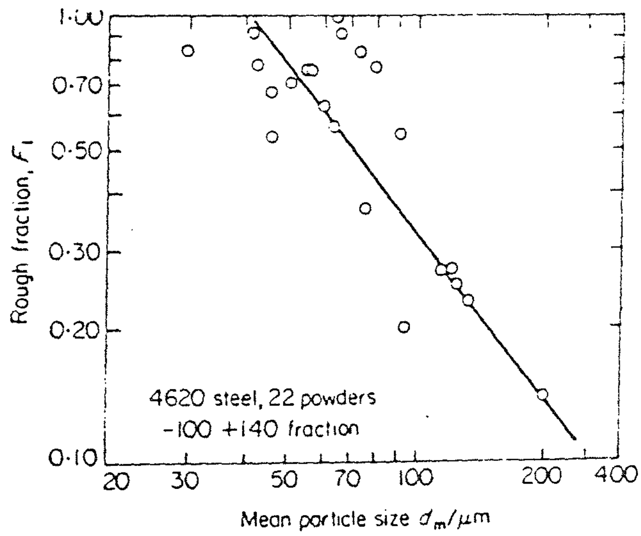


Fig. 53. Size vs shape for water-atomized powder.[24]

Metal properties: cold density
liquid density
liquid metal viscosity
surface tension

Gas properties:	density
	viscosity
	pressure
	jet velocity

Three graphs from the program of the model are shown in Fig. 54, in the case of cast iron.

5. As is shown in Fig. 55, increasing the jet distance increases the aspect ratio (L/D) of the powder particles.

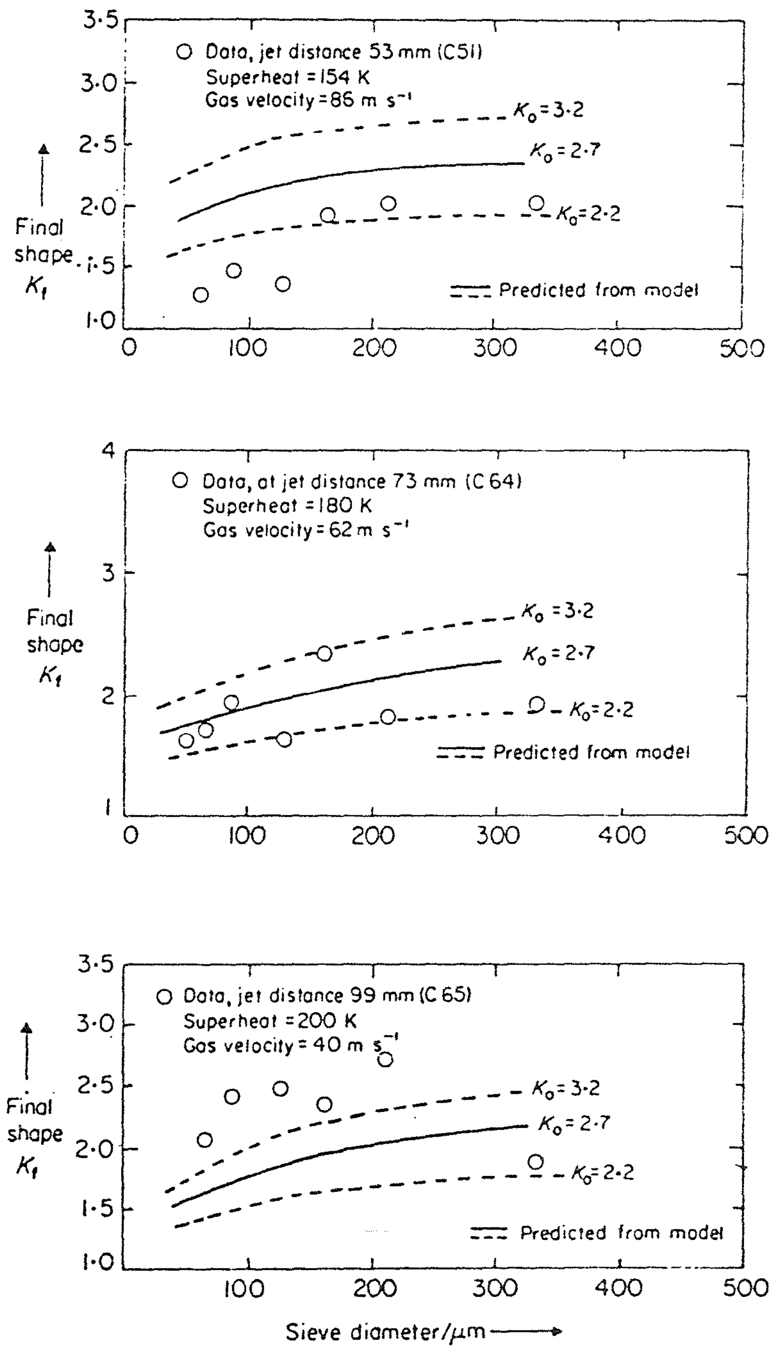


Fig. 54. Comparison of shape/size properties of cast iron powder.[45]

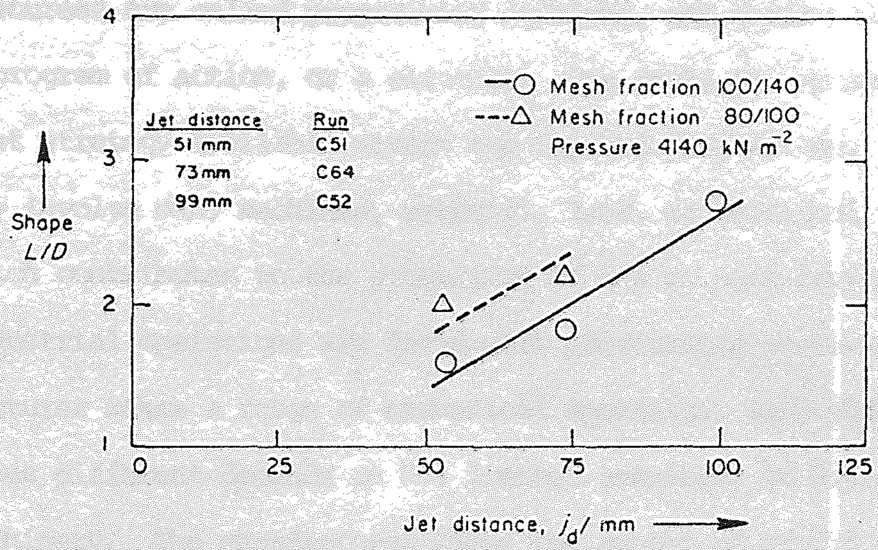


Fig. 55. Effect of jet distance on particle shape.[45]

10. R. L. Sands and C. R. Shakespeare, *Powder Metallurgy*, CRC Press, 1966, p. 29.

24. R. J. Grandzol, *Water Atomization of 4620 Steel and other Metals*, Ph.D. Thesis, Drexel University, 1973. Also, R. J. Grandzol and J. A. Tallmadge, *Int. J. Powder Metall. Powder Technol.* 11, 103 (1975).

45. P. Rao, *Shape and other properties of gas atomised metal powders*, Thesis, Drexel University, Philadelphia (1973).

APPENDIX III Linear Programming

a) Linear Programming Method

The problems which deal with the optimum allocation of limited resourses are called programming problems, and their solution involves a program of action, or a strategy. One seeks the optimum program or best strategy available within the imposed limitations. Such a program may involve men, machines, material, land, or financial assets, all of which contributes to the production of one or more items. Almost all industrial operations are faced with programming problems. A manufacturer makes a range of mechanical apparatus, each model of which makes different demands on his limited resources of man power and machinery. The manufacturer knows the amount of profit he makes on each model. His problem is to schedule the production of various models so as to make maximum profit. The examples of such optimisation problems can be seen in the steel industry, in food production etc.

Linear programming techniques have successfully been applied to these problems (45). The method and the full examples of the application of this technique can be found in many operational research text books. The most authorative sources are (46), (47), (48). Here a short brief is given of this technique to illustrate how the allocation problem of powder making operation can be modeled by linear programming.

Formulation of Linear Programming

In the technical literature, the system of equations that describe a business problem is referred to as the mathematical model of the business problem. Linear programming model is a system of linear equations which are the mathematical expressions of the technological and economic restriction on the company's freedom of action. For example; a delivery firm has to buy a fleet of vehicles, up to eight in number, and has two types in mind. Vans which can carry 0.5 ton each and lorries which can carry 1.5 ton each. A total minimum carrying capacity of 6 tons is needed. Vans cost £1,500 each and lorries £3,000 each, and the capital outlay must not exceed £18,000. This problem can be represented as follows:-

X = number of Vans $\geqslant 0$

Y = number of Lorries $\geqslant 0$

$X + Y\ 0$ = total number of Vans and Lorries hired < 8 (maximum of 8 vehicles)

$0.5\ X + 1.5\ Y \geqslant 6$ = minimum carrying capacity

$1.5\ X + 3.0Y \leqslant 18$ = maximum capital outlay

This problem however should be solved with respect to some objectives of the delivery firm. The firm may seek a solution which maximises his expected profit.

If, for example, it is estimated that profit from each van is about £1,500 per annum and from each lorry is £2,500 per annum, the mathematical formula which expresses the objective of the delivery firm is

Maximize $P = 1.5\ X + 2.5\ Y$

P, and the point which maximises P is X = 4, Y = 4, being one of the four vertices of the unshaded polygon.

For continous variable problems it is known that an optimum solution will be at one of the vartices (or as close as one wishes to get for the strict inequality case). However, where discrete variables are involved - as typified by my example dealing with integer numbers of vehicles - one can at best say that an optimum solution will be near to, or at, a vertex. If our vehicle problem were such that vans cost £1,800 and lorries cost £4,000, the 'optimum' solution is $X = 4\frac{2}{7}$, $Y = 2\frac{4}{7}$ which is of course impractical. The best (integer pair) solution, in fact, turns out to be X = 3, Y = 3 in this case.

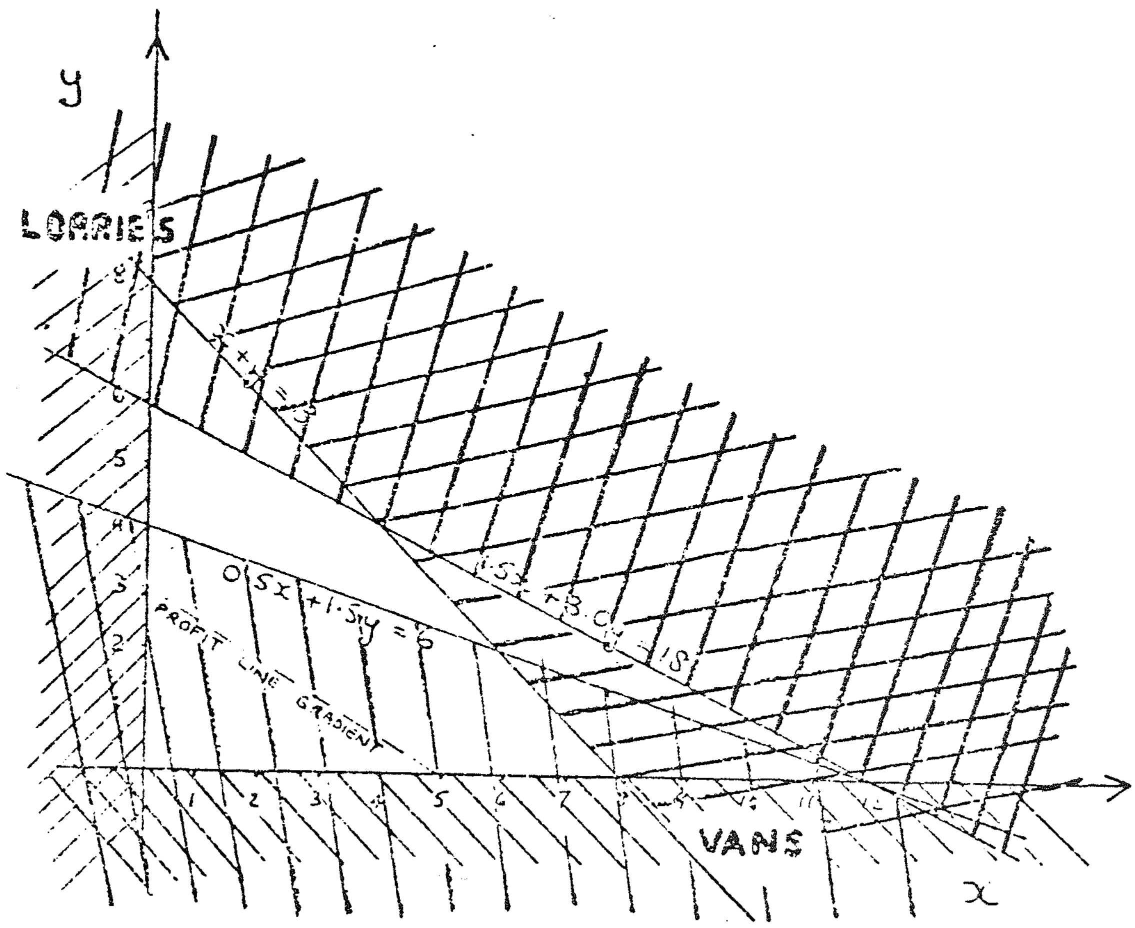


Fig 1
Graph of 2 variable linear programming problem

thus the complete mathematical model which defines this problem can be represented as:-

$X + Y \leqslant 8$

$.5 X + 1.5 Y \geqslant 6$

$1.5 X + 3.0 Y \leqslant 18$

Maximize $P = 1.5 X + 2.5 Y$

This system of linear inequalities now represent the linear programming model of the problems of the delivery firm.

These type of problems can best be solved by linear programming. Since in this particular case the problem is of two dimensional, it can be graphically solved as shown below but the basic method for solving this problem (being of any dimension) is the method called 'Simplex Method' which was first developed by George B Dantzig (46). This method has been used for formulating and solving stock allocation problems but first the graphical solution of the above example is presented for illustrating the method of solution by linear programming.

Graphical Method of Linear Programming

By shading out each region which does not satisfy a constraint we are left with a quadrillateral where the possible solutions lie on the boundary or inside the unshaded region.

The optimum solution must lie on the line $P = 1.5 X + 2.5 Y$, for some

The Simplex Algorithm

The simplex algorithm solves the problem:

$$\text{Maximise } Z = \sum_{j=i}^{n} C_j X_j$$

$$\text{subject to} \sum_{j=i} A_{ij} X_j < B_i \quad (B_i > 0) \qquad (i = i \ldots . M)$$

$$\text{and} \quad X_j > 0 \qquad (j = i \ldots . n)$$

To use the simplex algorithm for minimisation, we negate the objective function and maximise. Thus to minimise (X-Y), we maximise (-X+Y). It is important to note that the numbers B_i must be positive. For example, we might have:-

$$\begin{aligned} &\text{Maximise } Z = 2X + 3Y \\ &\text{subject to} \quad 2X + Y < 7 \\ &\qquad\qquad X + Y < 4 \\ &\qquad\qquad 2X + 4Y < 11 \\ &\qquad\qquad X, Y > 0 \end{aligned}$$

The first step is to convert the inequalities into equalities by the introduction of slak variables. For example, the constraint:-

$$2X + Y < 7$$

is equivalent to the two constraints:-

$$2X + Y + U = 7$$

and $\quad U > 0$

Thus the problem above may be written:-

$$\text{Maximise } Z = 2X + 3Y \qquad (1)$$

$$\text{subject to} \quad 2X + Y + U + 0 + 0 = 7 \qquad (2)$$

$$X + Y + 0 + V + 0 = 4 \qquad (3)$$

$$2X + 4Y + 0 + 0 + W = 11 \qquad (4)$$

$$X,Y,U,V,W \gg 0$$

The above set of equations is called a basic set of equations because the coefficients of the constraints contain a permutation of the unit matrix. In this case the coefficients of U,V, and W form a unit matrix, and U,V, and W are said to be the basic variables in the equations, while X and Y are non-basic variables. Also, the objective function (to be maximised) does not contain the basic variables. The equations are said to be feasible because the right-hand sides are positive. Now a basic feasible set of equations has one simple and obvious solution (among the infinity of possible solutions). This is obtained by setting the non-basic variables to zero. The solutions for the basic variables are then given by the right-hand-sides. This type of solution is called a basic solution and there is a theoram which tells us that the optimum of any linear function will occur at a basic solution. Thus our initial basic solution is :-

$X = Y = 0$

$U = 7$

$V = 4$

$W = 11$

$Z = 0$

The Simplex Algorithm takes linear combinations of the equations to form an equivalent set of basic equations with different basic variables, so that the new basic solution will increase the value of the objective Z. The first step in the algorithm is to select the variable with the greatest positive coefficient in the objective function, in this case the variable Y. This is the Pivot variable. We then devide the positive coefficients of this variable into the corresponding right-hand-sides of the constraints, obtaining in our case 7 for the equation (2), 4 for equation (3), and 2.75 for equation (4). We then select as the Pivot equation the equation with the least of these values, in our case equation (4). The coefficient of the Pivot variable in the Pivot equation is called the Pivot element. We now add or subtract multiples of the Pivot equation to the other equations (including the objective) to eliminate the Pivot variable from the other equations. Finally, we divide the Pivot equation by the Pivot element. Thus in our case we carry out the operations:-

$\text{Eq } 2 \leftarrow \text{Eq } 2 - 0.25 * \text{Eq } 4$

$\text{Eq } 3 \leftarrow \text{Eq } 3 - 0.25 * \text{Eq } 4$

$$\text{Eq } 1 \leftarrow \text{Eq } 1 - 0.75 * \text{Eq } 4$$

$$\text{Eq } 4 \leftarrow 0.25 * \text{Eq } 4$$

and we have the following set of equations:-

$$\begin{array}{llll} 1.5X & +U & -0.25W = 4.25 & \\ 0.5X & +V & -0.25W = 1.25 & (5) \\ 0.5X + Y & & +0.25W = 2.75 & \\ 0.5X & & -0.75W = -8.25 + Z & \end{array}$$

We see that this is a basic feasible set of equations, with the variables Y, Y, V basic, and X, W non-basic. Our new basic solution is therefore:-

$$X = W = 0$$

$$Y = 2.75$$

$$U = 4.25$$

$$V = 1.25$$

$$Z = 8.25$$

We repeat this process of transforming to the new basis until all the coefficients in the objective function are negative. Thus at the next stage we select variable X and equation (5) and find the new set of basic feasible equations, with X, Y, U basic:-

$$U - 3V + 0.5W = 0.5$$

$$-2V - 0.5W = 2.5$$

$$Y \quad -V \quad +0.5W = 1.5$$

$$-V \quad -0.5W = -9.5 + Z$$

Since all the objective coefficients are now negative, this basic solution is the optimum solution. So we have our optimum solution:-

$V = W = 0$

$U = 0.5$

$X = 2.5$

$Y = 1.5$

$Z = 9.5$

PROCEDURE SUMMARY FOR THE ALGEBRAIC APPROACH (Maximization case)

STEP 1. Formulate the problem

a) Make a precise statement of the objective function and translate the technical specifications of the problem into inequalities.

b) Convert the inequalities into equalities by the addition of non-negative slack variables. Attach a per unit profit of zero to each slack variable or imaginary product.

STEP 2. Design initial program

Design initial program so that only the imaginary products are being produced, that is only the slack variables are included in the solution. Represent the initial program by arranging the equations of step 1, such that the products being produced (i.e., basic variables) are on the left-hand sides.

STEP 3. Revise the current program

a) Identify the incoming variable. In-so-far as the initial program consists of only the imaginary products (slack variables), its profit contribution is zero. Thus, to improve the initial program, the variable with the largest positive co-efficient is chosen as the incoming variable. For programs other than the initial program, the incoming variable is identified by step 4b.

b) Determine the maximum quantity of the incoming variable. From the equations representing the current program, determine the limiting or key equations that will indicate the maximum quantity of the chosen incoming variable that can be introduced into the solution without violating the non-negativity constraints.

c) Obtain equations that represent the new program. Solve for the incoming variable from the limiting equation, and substitute it in the remaining equations of the current program. The new equations represent the revised program.

d) Obtain the associated objective function. Substitute the limiting equation (from step 3b), in the objective function associated with the preceeding program. The result is the objective function associated with the revised program.

STEP 4 <u>Test for optimality</u>

a) If there is no positive co-efficient term in the modified objective function, the problem is solved.

b) Otherwise, the program should be revised by bringing in the largest positive co-efficient variable included in the modified objective function.

STEP 5

Repeat steps 3b, 3c, 3d and 4 until an optimal program has been designed. An optimal solution has been found when all co-efficients in the modified objective function (step 4a) are negative.

A schematic diagram of this procedure is shown in Figure 2.9 below.

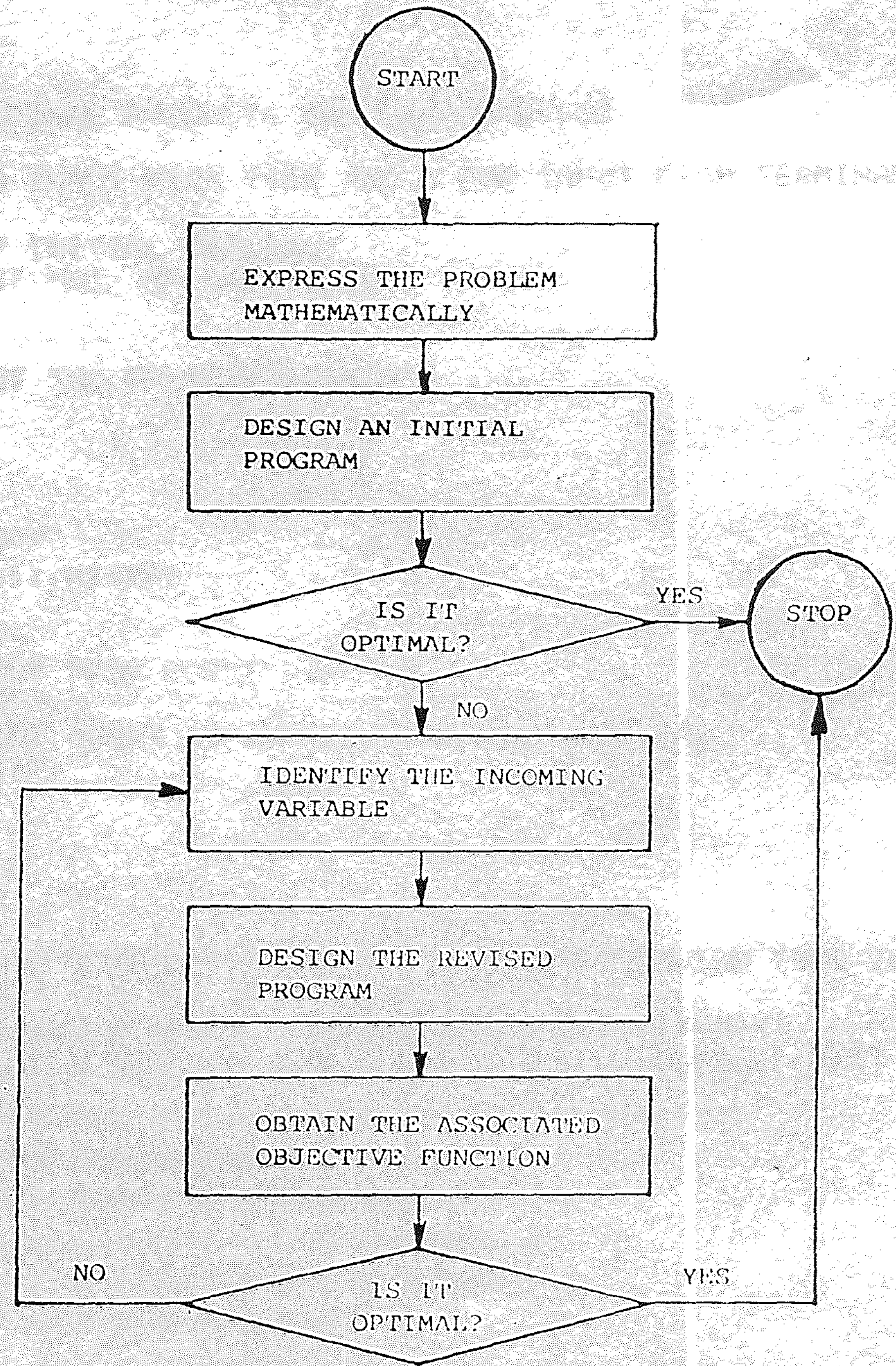


Fig. 2. A Schematic of the Algebraic Method (Max. Case)

b – The Computer Program used for **Stock** allocation and for the selection of the Cloth Gauges.

```
10 DIM A(13,41), L(40) ,B(12),A4$(6)
20 MAT A=ZER
30 MAT L=ZER
31 NP=8
32 INPUT" HOW MANY FINAL PRODUCTS YOU CAN MAKE";Z2
34 NP=Z2
35 INPUT"TYPE 1 FOR INPUT FROM TAPE AND 0 FOR INPUT FROM TERMINAL";Z
36 OPEN 1,Z,0
40 PRINT"REM SET UP INITIAL TABLEAU
50 IF Z=0 THEN PRINT "NO. OF VARIABLES";
60 INPUT£1,M
62 PRINT" "
70 IF Z=0 THEN PRINT "NO.OF CONSTRAINTS";
80 INPUT£1,N
82 PRINT""
90 P=M+N
100 Q=P+1
110 R=N+1
112 DIM E(N*M),G(N*1),H(1*M)
114 F=0
120 FOR J=1 TO N
130 IF Z=0 THEN PRINT "FOR CONSTRAINT";J
140 FOR K=1 TO M
150 IF Z=0 THEN PRINT "WHAT IS COEFF.OFVARIABLE NO.";K;
152 F=F+1:INPUT£1,E(F)
154 PRINT" "
160 A(J,K)=E(F)
170 NEXT K
172 IF Z=1 THEN 179
173 PRINT:PRINT
174 INPUT"TYPE COLUMN NUMBER IF CHANGE REQUIRED OTHERWISE TYPE ZERO";K
175 IF K=0 THEN 179
176 PRINT:INPUT"NEW VALUE";E((J-1)*M+K):A(J,K)=E((J-1)*M+K)
177 FOR K=1 TO M:PRINT"COEFF.OF VARIABLE"K";"J;E((J-1)*M+K):NEXT K
178 GOTO 173
179 F1=0
180 B$=" ":FOR I=1 TO6:B$=B$+B$:PRINT
181 IF Z=0 THEN PRINT "WHAT IS THE R.H.S.";
182 Q=M+N+1
184 F1=F1+1:INPUT£1,G(F1)
186 PRINT" "
190 A(J,Q)=G(F1)
192 PRINT" "
196 NEXT J
198 FOR J=1 TO N:PRINT"J=";J;"R.H.S.=";A(J,Q):NEXT
```

```
202 IF Z=1 THEN 209
203 PRINT:PRINT
204 INPUT"TYPE CONSTR.NUMBER IF CHANGE REQUIRED OTHERWISE TYPE ZERO";J
205 IF J=0 THEN 209
206 PRINT:INPUT"NEW VALUE";G(J):A(J,Q)=G(J)
207 FOR J=1 TO N:PRINT"J=";J;"R.H.S.=";A(J,Q):NEXT
208 GOTO 203
209 F2=0
210 PRINT "FOR THE OBJECTIVE"
220 FOR K=1 TO M
230 IF Z=0 THEN   PRINT "WHAT IS COEFFICIENT NO.";K;
231 R=N+1
232 F2=F2+1:INPUT£1,H(F2)
234 PRINT" "
240 A(R,K)=H(F2)
250 NEXT K
252 IF Z=1 THEN 261
253 PRINT:PRINT
254 INPUT"TYPE COLUMN NUM IF CHANGE REQ OTHERWISE TYPE ZERO";K
255 IF K=0 THEN 261
256 PRINT:INPUT"NEW VALUE";H(K):A(R,K)=H(K)
257 FOR K=1 TO M:PRINT"COEFFICIENT NO."K";"R;A(R,K):NEXT K
258 GOTO 253
261 PRINT:PRINT"TABLEAU COMPLETE":CLOSE1
262 FOR J1=1 TOR:FOR K1=1 TO M:PRINT,A(J1,K1);:NEXT K1
263 Q=M+N+1:J2=J1:PRINT,A(J2,Q)
264 PRINT""
265 NEXT J1
268 IF Z=1 THENPRINT"DO YOU WISH TO CHANGE);F$
270 GET F$:IF F$="" THEN 270
271 IF F$="N"THEN 280
272 IF F$="Y" THEN INPUT"1 FOR COEFF,2 FOR R.H.S.,3FOR OBJ,VE,4 NO CHANGE "
273 IF C9=1 THEN GOSUB 5000
274 IF C9=2 THEN GOTO  5100
278 IF C9=3 THEN GOTO  5200
279 IF C9=4 THEN268
280 FOR J1=1 TOR:FOR K1=1 TO M:PRINT,A(J1,K1);:NEXT K1
281 Q=M+N+1:J2=J1:PRINT,A(J2,Q)
282 PRINT""
283 NEXT J1
284 OPEN4,4,0
285 FOR J1=1TO R
286 Q=M+N+1:J2=J1:PRINT£4,A(J2,Q)
287 PRINT" "
288 NEXT J1
289 CLOSE4
290 INPUT"TYPE 1 IF YOU WISH TO SAVE THE INPUT OTHERWISE TYPE 0";T1
292 IF T1=0 THEN 310
302 OPEN 1,1,1:PRINT£1,M:PRINT£1,N
303 FOR J=1 TO N:FOR K=1 TO M:E(K)=A(J,K):PRINT£1,E(K):NEXT K
304 J1=J:Q=M+N+1:G(J1)=A(J1,Q):PRINT£1,G(J1)
305 NEXT J
306 FOR K=1 TO M:J=N+1:H(K)=A(J,K):PRINT£1,H(K):NEXT K
307 CLOSE1
310 FOR J=1 TO R
311 FOR K=M+1 TO P
312 A(J,K)=0
314 NEXT K
```

```
314 NEXT K
316 NEXT J
318 FOR J=1 TO N
320 K=J+M
330 A(J,K)=1
340 NEXT J
350 A(R,Q)=0
360 FOR K=1 TO M
370 L(K)=0
380 NEXT K
390 FOR K=M+1 TO P
400 L(K)=K-M
410 NEXT K
420 REM FIND MAXIMUM OBJECTIVE COEFFICIENT
430 X=A(R,1)
440 S=1
450 FOR K=2 TO P
460 IF A(R,K)<X THEN 490
470 X=A(R,K)
480 S=K
490 NEXT K
500 IF X>0 THEN 670
510 REM IF MAX.COEF.NOT POSITIVE PRINT ANSWER
520 PRINT
530 PRINT "OPTIMUM POINT"
531 S7=0
532 S6=0
534 OPEN4,4,0
540 FOR K=1 TO M
550 IF L(K)=0 THEN 600
560 J=L(K)
570 F=A(J,Q)
580 PRINT "X(";K;")=";F
582 PRINT£4,"X(";K;")=";F
590 GO TO 605
600 PRINT "X(";K;")=";0
602 PRINT£4,"X(";K;")=";0
605 NEXT K
606 PRINT£4,""
607 PRINT£4,""
611 GETG$:IFG$=""THEN 612
612 PRINT"REM NO.OF YOUR FINAL PRODUCT IS=";NP
613 FOR R1=1 TO NP
614 PRINT"TYPE THE NO. OF VARIABLES WHICH GO INTO PRODUCT",R1;
615 INPUT K1,K2,K3
616 P(R1)=A(L(K1),Q)+A(L(K2),Q)+A(L(K3),Q):PRINT"P(";R1;")=";P(R1)
617 PRINT£4,"P(";R1;")=";P(R1)
618 NEXT R1
619 PRINT:PRINT"STRIKE ANY KEY"
620 GET S$:IF S$=""THEN 620
636 F=-A(R,Q)
638 PRINT£4,""
639 PRINT
640 PRINT "VALUE OF OBJECTIVE IS";F
642 PRINT£4,"VALUE OF OBJECTIVE IS";F
650 STOP
660 REM FIND PIVOT ROW
670 FOR J=1 TO N
680 IF A(J,S)<=0 THEN 710
690 B(J)=A(J,Q)/A(J,S)
700 GOTO 720
```

```
 710 B(J)=1E+18
 720 NEXT J
 730 Y=B(1)
 740 T=1
 750 FOR J=2 TO N
 760 IF B(J)>Y THEN 790
 770 Y=B(J)
 780 T=J
 790 NEXT J
 800 IF Y<1E+17 THEN 840
 810 PRINT "UNBOUNDED SOLUTION"
 820 STOP
 830 REM CHANGE BASIS
 840 FOR J=1 TO R
 850 IF J=T THEN 900
 860 FOR K=1 TO Q
 870 IF K=S THEN 890
 880 A(J,K)=A(J,K)-A(J,S)*A(T,K)/A(T,S)
 890 NEXT K
 900 NEXT J

READY.

 900 NEXT J
 910 FOR K=1 TO Q
 920 IF K=S THEN 940
 930 A(T,K)=A(T,K)/A(T,S)
 940 NEXT K
 950 FOR J=1 TO R
 960 A(J,S)=0
 970 NEXT J
 980 A(T,S)=1
 990 FOR J=1 TO P
1000 IFL(J)<>T THEN 1020
1010 L(J)=0
1020 NEXT J
1030 L(S)=T
1040 GOTO 430
1050 END
1050 END
5000 PRINT"GIVE CONST.NUM,VAR.NUM";
5005 INPUT J3,K3
5010 PRINT:INPUT"NEW VALUE";D(J3,K3)
5020 A(J3,K3)=D(J3,K3)
5030 FOR J=1 TO N:FOR K=1 TO M:PRINT"COEFF.OF VAR"K";"J;A(J,K):NEXT K
5040 NEXTJ
5050 GOTO 272
5100 PRINT"FOR CHANGE OF R.H.S.     GIVE CONST.NUM ";
5110 INPUT J3
5115 Q=M+N+1:PRINT:INPUT"NEW VALUE";D(J3,Q)
5130 A(J3,Q)=D(J3,Q)
5135 FOR J=1 TO N:K=Q:PRINT"J=";J;"R.H.S.=";A(J,Q):NEXT
5140 GOTO 272
5200 PRINT"FOR CHANGE OF COEFF.OF.OBJECTIVE,GIVE VARIABLE.NUM ";
5210 INPUT K3
5215 R=N+1
5220 PRINT:INPUT"NEW VALUE";D(R,K3)
5230 A(R,K3)=D(R,K3)
5235 FOR K=1 TO M:PRINT"COEFF NO."K";"R;A(R,K):NEXTK
5240 GOTO 272
EADY.
```

APPENDIX IV Dynamic Programming

a) Dynamic Programming Method

Dynamic programming is a technique for solving a special class of optimisation problems called multi-stage decision process. The title "Dynamic Programming" stems from the work of Richard Bellman published largely in Bellman (49), (50). Dynamic programming is rather a computational technique for reducing the dimensionality of a problem by embodying the solution in a special set of relationships called 'recurrence relations'. Indeed the whole method might well have been named recursive optimisation. Generally the achievment of dynamic programming is to reduce a difficult problem in N variables into a series of optimisation problems in one variable which are comparatively easy to solve. The possibility of applying the dynamic programming method depends on a successful formulation of the problem in terms of a multi-stage decision process. The structure of a multi-stage process can be seen in Fig. 1 below. It is characterized in terms of stage and states.

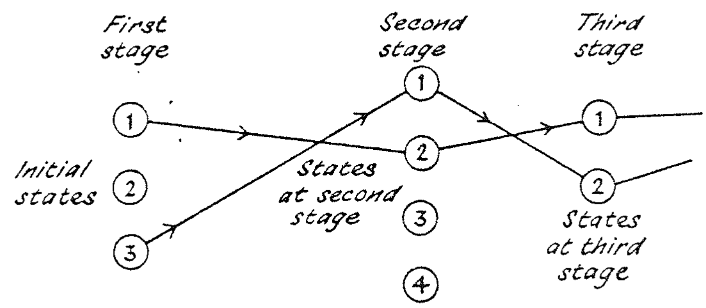


Fig. 1 Flow diagram of a multi-stage decision process

At each stage there are several states corresponding to the alternative decisions which could be made at the stage and these will often be a range of possible values for a control variable. At each stage therefore one decision would be made and then the process moves from this stage to another stage to enter the possible states at that stage and again make a decision. Two possible sequence of decisions through the three stages are marked in the diagram, one leading from state 3 to state 1 to state 2 and the other leading from stage 1 to state 2 to state 1 in the respective stages.

The full description of the terms stages state and the mathematical formulation of the dynamic programming can best be illustrated through an example in which a single resource is allocated among several number of independent activities. This example is (52) shown in the following pages.

Allocation of one Resource

A factory can produce goods of types A, B and C in various quantities. Each product needs a raw material of which only four tons are available. Allocation of a certain quantity of the raw material to a certain product results in a corresponding return, as detailed in Table 1 The possible allocations are restricted to the levels shown in the table. Determine the allocation which maximizes the total return.

The dynamic programming formulation of the problem is as follows. A *stage* corresponds to the allocation of raw material to the production of a particular type of product. There are three products and hence three stages. When n types of product remain to be considered we are at stage n. The order in which products are considered can be chosen arbitrarily, and once it is chosen the product to be considered at stage n is referred to as product n. Products A, B, C will be considered at stages 3, 2, 1 respectively.

Table 1 RETURNS RESULTING FROM VARIOUS ALLOCATIONS

Allocation of raw material (tons)	*Type of product*		
	A	B	C
0	0	0	0
1	10	6	8
2	17	17	11
3	19	—	—

A state (n, i) corresponds to a situation where i tons of raw material remain to be allocated and n products remain to be considered. Action k corresponds to the allocation of k tons of raw material to the current product. The return resulting from the allocation of k tons of raw material to the current product is $r(n, k)$. The optimal value of a state is the total return generated when the system starts in that state and an optimal plan is followed, and is denoted by $f(n, i)$. This specification is summarised in Table 2

Table 2 ALLOCATION OF ONE RESOURCE: PROBLEM SPECIFICATION

Stage	Allocation of raw material to a product. n = no. of products remaining	n
State	i tons of raw material remain to be allocated and n products remain to be considered	(n, i)
Action	Allocate k tons of raw material to current product	k
Return	Return from allocation of k tons of raw material to product n	$r(n, k)$
Optimal value of a state	Total return when state (n, i) is the starting state and an optimal plan is followed	$f(n, i)$

The recurrence relation is

$$f(n, i) = \underset{k \in K}{\mathrm{Max}}\,[r(n, k)+f(n-1, j)] \qquad (1)$$

where k is the set of feasible allocations associated with state (n, i)

The transition equation is

$$j = i-k \qquad (2)$$

which expresses the fact that allocation of k tons at the current stage leaves $i-k$ tons available at the next stage. The recurrence relation and transition equation can be combined into the recurrence relation 2

$$f(n, i) = \underset{k \in K}{\mathrm{Min}}\,[r(n, k)+f(n-1, i-k)] \qquad (3)$$

The return function $r(n, k)$ is given by Table 1 The stage space is $0 \leqslant n \leqslant 3$. The state space is given by $0 \leqslant i \leqslant 4$ and the action space by

$$\left.\begin{aligned} 0 &\leqslant k_1 \leqslant 2 \\ 0 &\leqslant k_2 \leqslant 2 \\ 0 &\leqslant k_3 \leqslant 3 \\ k &\leqslant i \end{aligned}\right\} \qquad (4)$$

The first three inequalities in 2 reflect limitations on allocation implied by Table 1 The last constraint follows from the fact that no more than the remaining quantity of raw material can be allocated.

If raw material left over has no value (which we assume to be the case) the terminal values are $f(0, i) = 0$ for all i. The returns are additive and depend only on the current stage and action so that the validity conditions are satisfied.

Calculation

The calculations are shown in Table At stage 1 the trial values under action k are given simply by $r(1, k)$ and follow directly from Table 1 The largest possible allocation is optimal at each state and the optimal values are

$$f(1, 0) = 0,\ f(1, 1) = 8,\ f(1, 2) = f(1, 3) = f(1, 4) = 11 \qquad (5)$$

To illustrate the calculation at stage 2 consider state (2, 1). One ton of raw material is available. We can either allocate nothing to product B or allocate the one ton. In the former case there is no income at stage 2 and the system moves to state (1, 1), that is the one ton of raw material remains available at stage 1. The optimal value of state (1, 1) has already been determined (equation and Table) and is $f(1, 1) = 8$. Thus for action $k = 0$ the trial value of state (2, 1) is

$$r(2, 0)+f(1, 1) = 0+8 = 8 \qquad (6)$$

If the one ton is allocated to product B there will be an immediate return $r(2, 1) = 6$ units, and the system will move to state (1, 0), corresponding to zero raw material at stage 1. The trial value of state (2, 1) under action $k = 1$ is therefore

$$r(2, 1)+f(1, 0) = 6+0 = 6 \qquad (7)$$

The set of feasible actions is now exhausted. Comparison of the trial values shows that action $k = 0$ is optimal and hence $f(2, 1) = 8$. This calculation and result are shown in Table 3, rows 15 and 16. Similar optimisation over the remaining states at stages 2 and 3 completes Table 3. At stage 3 it is only necessary to consider state (3, 4) since the initial quantity available is known to be 4 tons. The optimal allocation is determined by following through the optimal process in Table . The optimal process is shown in Table 4 The solution is to allocate 1 ton to product A, 2 tons to product B and 1 ton to product C. The total return is then 35 units.

Table 3 . ALLOCATION OF ONE RESOURCE: CALCULATIONS

Stage	*State*	*Action*	*Trial Value*
0	*i*		*0*
1	0	*0*	*0*
1	1	0	0
1	1	*1*	*8*
1	2	0	0
1	2	1	8
1	2	*2*	*11*
1	3	0	0
1	3	1	8
1	3	*2*	*11*
1	4	0	0
1	4	1	8
1	4	*2*	*11*
2	0	*0*	*0*
2	1	*0*	0+8 = *8*
2	1	1	6+0 = 6
2	2	0	0+11 = *11*
2	2	1	6+ 8 = 14
2	2	*2*	17+ 0 = *17*
2	3	0	0+11 = 11
2	3	1	6+11 = 17
2	3	*2*	17+ 8 = *25*
2	4	0	0+11 = 11
2	4	1	6+11 = 17
2	4	*2*	17+11 = *28*
3	4	0	0+28 = 28
3	4	*1*	10+25 = *35*
3	4	2	17+17 = 34
3	4	3	19+ 8 = 27

Table . ALLOCATION OF ONE RESOURCE: OPTIMAL PROCESS

Stage	*State*	*Action*	*Value*
3	4	1	35
2	3	2	25
1	1	1	8

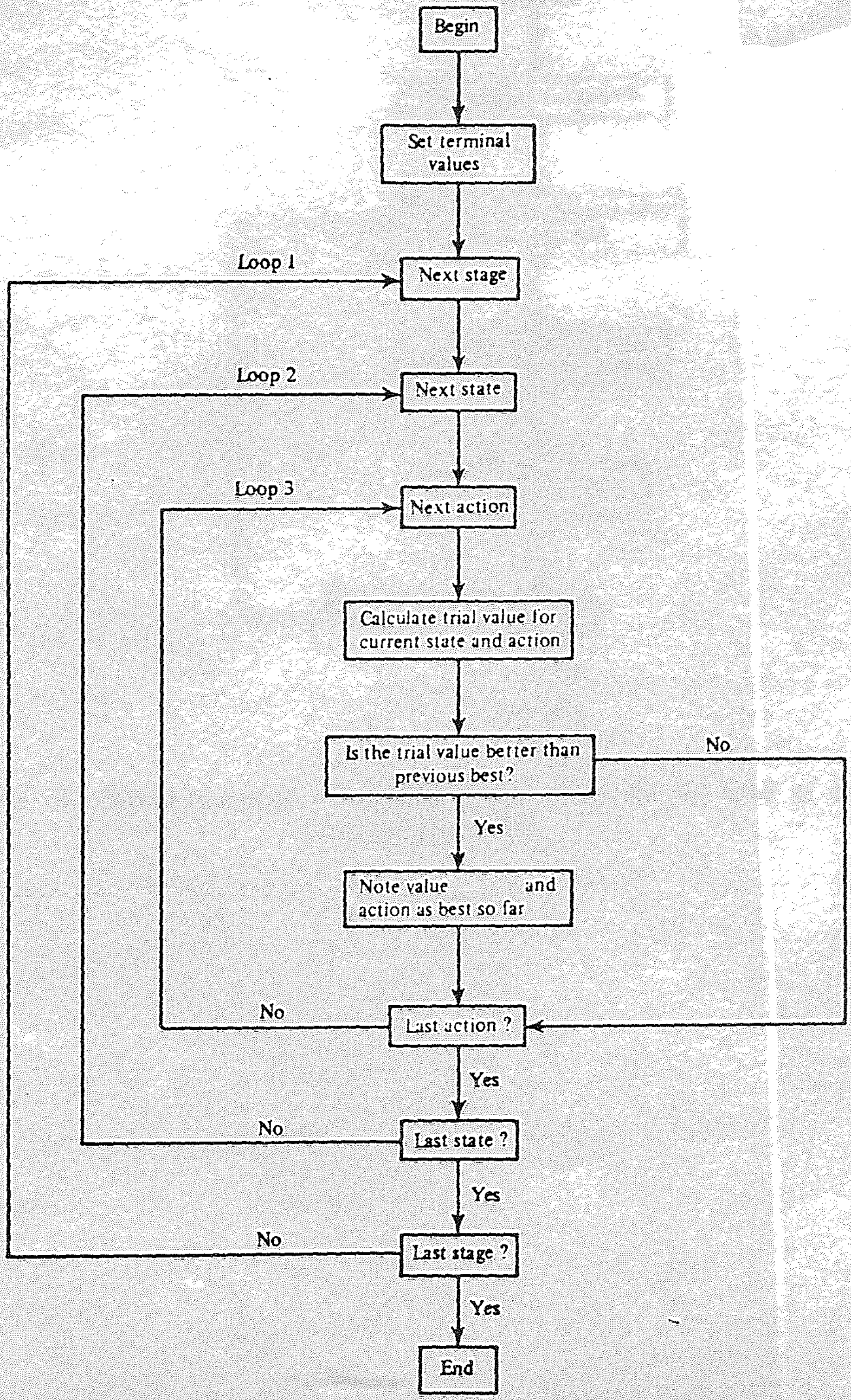


Figure 2 Flow chart for the value iteration algorithm

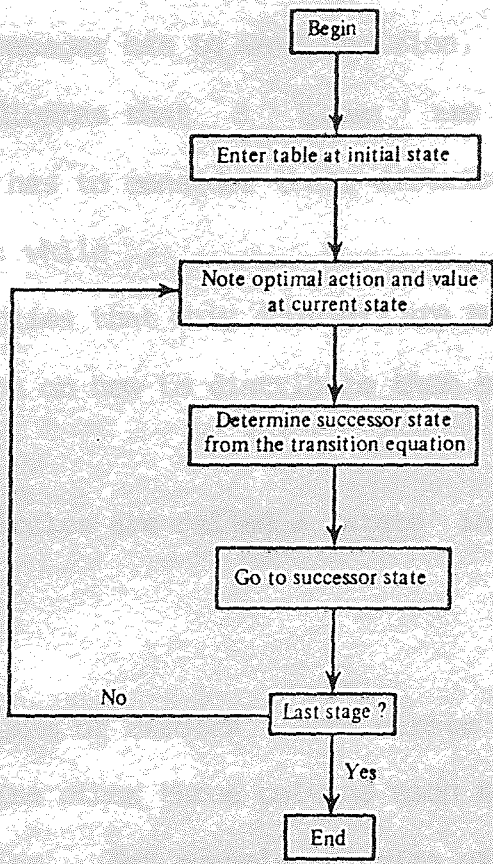


Figure 3 *Determination of the optimal process from the full table of optimal actions and values* b-The symbols which define the various elements of the scheduling problem in network model.

(i) Each circle in the model describes the state upon which the manager has to make decision. For example, circle (6.3) indicates that 6 ' blows ' are possible and the manager has to consider their distributions between 3 plant settings, while circle (4.2) implies that only 4 blows are possible and he can make decision on how to distribute them to 2 plant settings .

Each of these circles are called a '<u>state</u>' in Dynamic Programming.

(ii) There are 4 columns of circles. The circle (0,0) the start of decisions .The other three columns each represent a '<u>stage</u>' of decision making. For example, circles of column 1,(?,1) are the various allocation decisions when only one plant setting rate is decided to be used. Circles of up to column 2 show that manager decide to consider the use of two plant settings

(iii) The arrows between two circles show a sequence of possible decisions, for example, the arrow between two circles(shown in Fig 1 would imply that the following decisions are possible:-

With 6 blows possible;

(6-4)=2 blows can be allocated to plant setting No.3

and 4 blows remaine to be distributed between the two remaining plant settings.

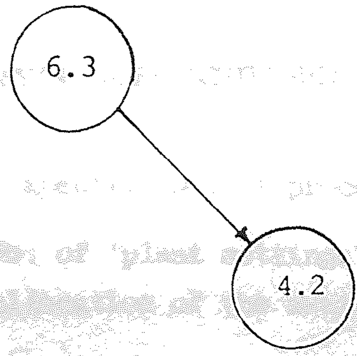


Fig 1 a sequence of possible decisions

(iv) Each decision taken is an 'action' and the value on this arrow shows the 'return' that can be achieved from the action to allocate (6 - 4) = 2 blows to plant setting No 3.

(v) In the same manner a sequence of arrows indicates a route or a 'schedule'.

For example, Fig. 2 (below) shows a 'route' which indicates with 6 blows possible

1 blow is allocated to plant setting No. 1

3 blows are allocated to plnt setting No.2

2 blows are allocated to plant setting No.3

The Total 'return' from this schedule is 92 + 144 + 44 = £280

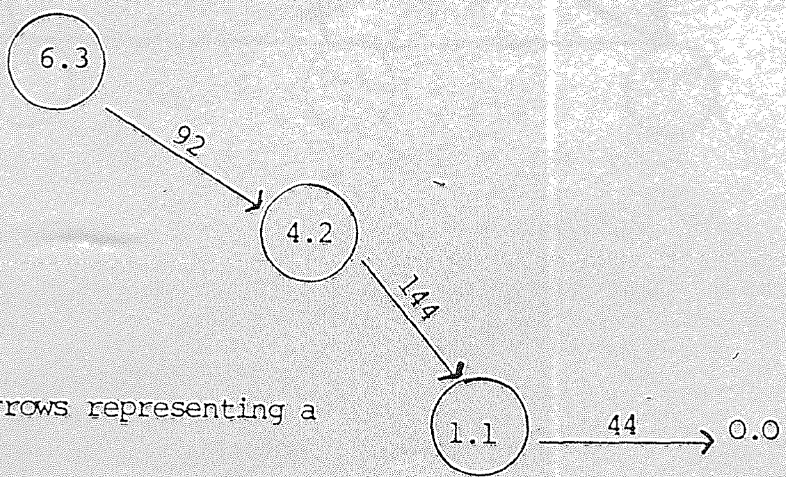
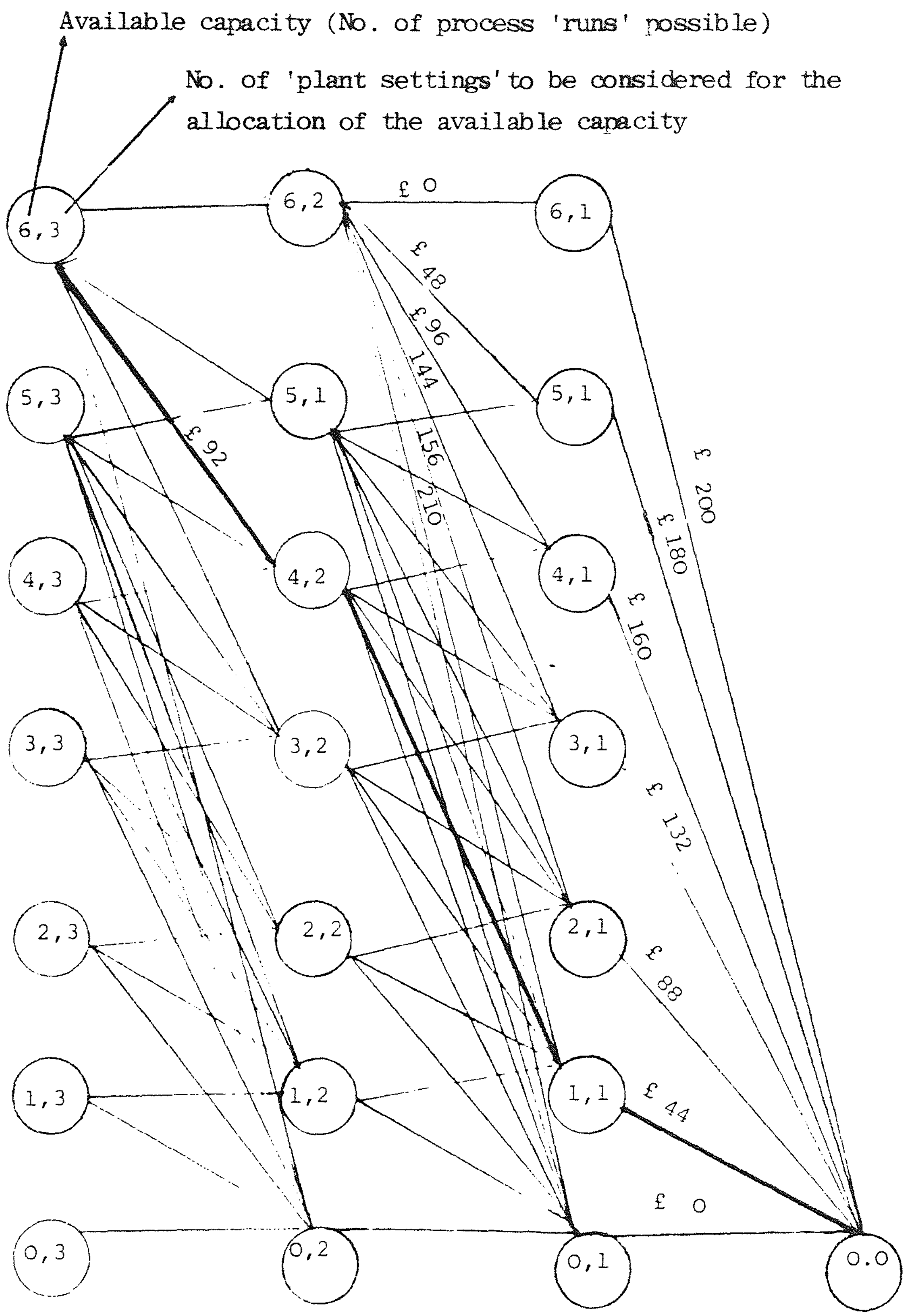


Fig. 2 A set of arrows representing a schedule.

Fig (3) COMPANY'S SALES ACHIEVABLE NETWORK



c . - FINDING FORMULA FOR UTILITY FUNCTION

To find the utility function it is assumed that:

X_i = quantity produced for $product_i$

I_i = inventory level of $product_i$ before making decision on Production

D_i = Demand for $product_i$ for $period_t$

$DF = D_i - I_i$ = Requirements on production plant

It is also assumed that:

the demand is satisfied in a Linear fashion during production $interval_t$ and the manufacturer may not insist on satisfying all customers demand on time but accept back orders at a finite penalty cost ν per unit

The possible inventory curve when the quantity of x produced is shown at Fig 1

IF $x < DF$ it is allowed for shortage $(DF - X)$

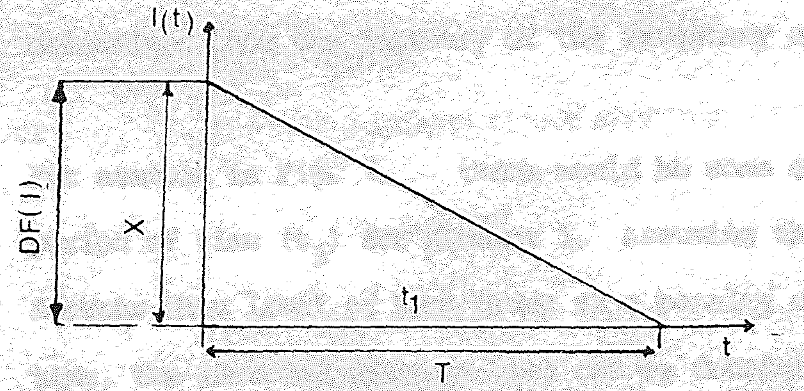
The shortage charge is assumed proportional to the the area under the negative part of the area made with the axis and inventory curve.

IF $x > DF$ Excess materials coming into inventory

It is assumed that excess inventory is unuseable during the production interval, and it would be taken from the inventory at the end of the period. Thus we incur :

a) interest cost

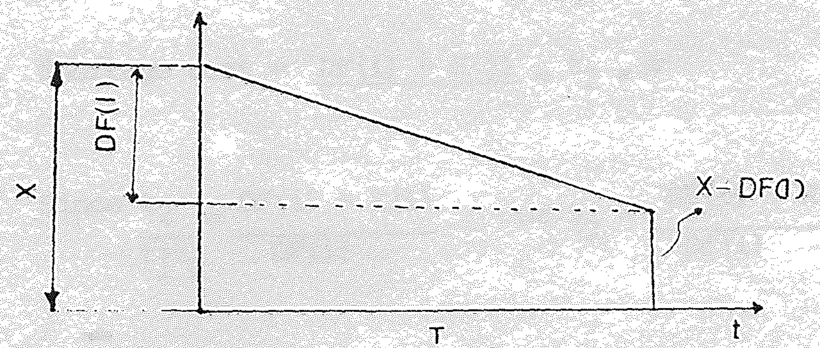
b) waste of money which is not returnable



a – Production equals to demand

No shortage cost
No excess cost

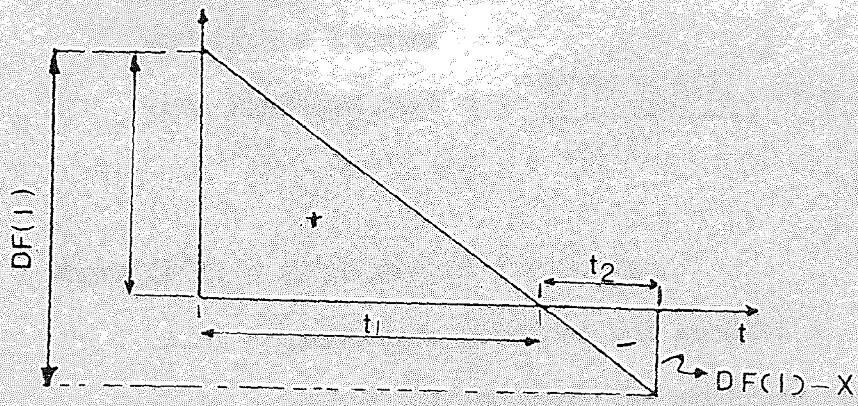
There is a sales revenue



b – X>DF

Production exceeds the requirement

Cost, excess cost, inventory cost



c – X<DF

Production is less than requirements

shortage cost (penalty)

Fig 1. Inventory Curve

Since there was no stock of the required products the production quantities would be considered as the available inventory immediately after being produced. The various costs incurred can easily be determined from the geometry of the inventory curve in each situation.

For example in Fig. 1 there would be some shortages for a limited period of time (t_2) for product i. Assuming that the manufacturer accepts this level of back order at a penalty charge of £v per unit of time, the incurred shortage cost can be determined (53) as follows:

$$\text{Shortage cost} = \underline{DF(i) - X(i)} * t_2 * v$$

$$\text{Since } \frac{t_2}{t_1 + t_2} = \frac{DF(i) - X(i)}{DF(i)} \qquad \text{or } t_2 = \frac{DF(i) - X(i)}{DF(i)} T$$

and if T = 1 period

$$\text{then shortage cost} = \frac{DF(i) - X(i)\ ^{2}}{2DF(i)} * v$$

Where DF(i) = requirements for product i

X(i) = quantities produced for product i

t_2 = period during which the shortage occurs

The costs and revenues which would result from using different 'blow rate' would obviously be different because the quantities of various products by each 'blow rate' differ from the other and with a specific blow rate being used there would be different costs and revenues associated with the products themselves.

THESE NOTATIONS ARE USED

A	excess cost. Cost of holding excess inventory =
BJ(I)	quantity of product I contained in one blow with size distribution J
C	Cost to the production plant of one blowing with size distribution
CP	Cost of purchasing the shortage quantity from outside supplier
DP(I)	Demand for product (I)
DF(I)	Demand for product after filling some proportion of total demand with available inventory - part of demand unfilled.
E(J)	Cost of manufacturing one tonne of product (I)
EX(I)	Excess tonne producted for product (I)
F(I)	Cost of purchasing one tonne product (I) from outside supplier
H(I)	Cost of holding one tonne of product I in inventory up to next decision period
I	Product number
J	Size distribution
KJ	No. of blows done with size distribution J
M(J)	Shortage (quality) for product I = $\begin{matrix} DF(I)-X & \text{if } X<DF(I) \\ 0 & \text{if } X>DF(I) \end{matrix}$
NP	Number of products
SO	Sum of all excesses from all products = $\sum_{J=I}^{NP} EX(I)$
P(J)	Shortage cost for shortage quantity M(I) = $M(I)_* V(I)$
R(I)	Price at which each tonne of product I can be sold
S(I)	Potential sales for product I
SA	Sum of all excess cost = $\sum_{I-1}^{NP} A(I)$
SD	Total V demand on production plant = $\sum_{I=1}^{NP} DF(I)$

SM — Total shortage occurred for all products $= \sum_{I-1}^{NP} M(I)$

SN — Total purchase cost for all products $= \sum_{I=1}^{NP} CP(I)$

SO — Total excess for all products $= \sum_{I=1}^{NP} EX(I)$

SP — Total penalty charged for all products $= \sum_{I=1}^{NP} P(I)$

SS — Total potential market (or sales) for all products $= \sum_{I=1}^{NP} S(I)$

U(I) — Utility of one product with respect for each blow, each size distribution

SU — Total utility for all product with respect to side distribution $= \sum_{I=1}^{NP} U(I)$

Y(I) — Sales of those quantities demanded for product (I)

= sales achievable

SY — $= \sum_{I=1}^{NP} Y(I)$

V(I) — penalty or shortage charge for one tonne shortage for Product (I)

SX — Total quantities produced for all products $= \sum_{I=1}^{NP} X(I)$

the compound of the schedule's utility against each product is as follows:

$X * R(I)$ = Revenue if X are sold

$(X-DF(I)*R(I)*G$ = Those portions of X which are not sold was reduced from revenue

$\frac{X*X}{2*DF(I)} * E_{(I)} *H(I)*W$ interest charge upon the money tied up in work in process inventory

$\frac{(DF(I)-X)^2}{2*DF(I)} * V(I)$ penalty charged on the shortage quantity over the production interval

$(X-DF(I)*E(I)$ money not used effectively. Loss of money (resource)

$\frac{X-DF(I)}{2} *E(I)*H(I)$ interest charged upon the money tied up in those shot which is in the system but are excess for this period (i.e. production interval)

$U^J_{(I)}$ = Utility of Plant setting No j for Product i

$$U^J_{(I)} = X * R(I) - (X - DF(I)) * R(I) * Q \quad \text{quantity not being sold}$$
$$- \frac{X * X}{2*DF(I)} * E(I)*h(I)*S$$
$$- \frac{(DF(I)-X) * (DF(I)-X)}{2*DF(I)} * V(I)*W$$
$$- (X-DF(I)) * E(I)*Q$$
$$- \frac{(X-DF(I))}{2} * E(I)*H(I)*Q$$

and the utility of a schedule for all products would be:

$$U = \sum_{Kj=1}^{KB} \sum_{I=1}^{NP} U(I)$$

This information is now fed into the dynamic programme to find a schedule which gives the maximum utility.

d - The Computer Program used for finding an optimum Schedule of Plant Settings.

```
5 OPEN4,4,1
7 G=0
8 DIM ZD(JT,KB),ZE(JT,KB),ZF(JT,KB),ZH(JT,KB)
10 INPUT"ENTER NO.OF PRODUCT INCLUDING REFERENCE PRODUCT";NP
12 DIM U(NP),P(NP),A(NP),S(NP),O(NP),M(NP),EX(NP),Y(NP),X(NP),N(NP)
15 PRINT£4,"NO.OF PRODUCT..NP=";NP-1
20 INPUT"ENTER NO.OF JET";JT
25 PRINT£4,"NO.OF JET SIZE DISTRIBUTION EXAMIND....JT=";JT
26 INPUT"ENTER MAX BLOW YOU WISH";KB
27 PRINT£4,"MAX BLOW POSSIBLE FOR YOU...KB=";KB
28 DIM DP(NP),IP(NP),DF(NP),Z(JT)
29 DIM ST(JT,KB+1),FT(JT,KB+1),ZA(JT,KB+1),ZB(JT,KB+1),ZC(JT,KB+1)
38 PRINT£4,"DEMAND FOR THE PRODUCTS"
45 FOR I=2 TO NP
50 INPUT"ENTER THE VALUES FOR THE PRODUCT AND INVENTORY";DP(I),IP(I)
60 DF(I)=DP(I)-IP(I)
70 NEXT
75 FOR I=2 TO NP:PRINT£4,DP(I);:NEXT
76 PRINT£4," ":PRINT£4," "
77 PRINT£4,"VALUES FOR THE INVENTORY"
78 FOR I=2 TO NP:PRINT£4,IP(I);:NEXT:PRINT£4," ":IF G=1 THEN 145
79 PRINT"ENTER VALUES FOR Z"
80 PRINT£4,"JET COST..."
81 FOR J=1 TO JT:INPUTZ(J):NEXT
83 FOR J=1 TO JT:PRINT£4,Z(J):NEXT:PRINT£4," "
86 PRINT£4,"HOLDING COSTS......"
88 DIM B(JT,NP),H(NP),V(NP),R(NP),E(NP),L(NP),F(NP),F1(JT,KB)
89 PRINT"ENTER VALUES FOR H"
90 FOR I=2 TO NP:INPUT H(I):PRINT£4,H(I);:NEXT:PRINT£4," "
91 PRINT£4,"PRODUCTION COST OF PRODUCT...."
92 PRINT"ENTER VALUE FOR E"
93 FOR I=2 TO NP:INPUT E(I):PRINT£4,E(I);:L(I)=H(I)*E(I):NEXT:PRINT£4
94 PRINT"ENTER VALUES FOR R"
95 PRINT£4,"SALES PRICE..."
96 FOR I=2 TO NP:INPUT R(I):PRINT£4,R(I);:NEXT:PRINT£4," "
97 PRINT"ENTER VALUES FOR F"
98 PRINT£4,"PURCHASE PRICE..."
99 FOR I=2 TO NP:INPUT F(I):PRINT£4,F(I);:NEXT:PRINT£4," "
100 PRINT"ENTER VALUES FOR V"
101 PRINT£4,"PENALTY COSTS.."
102 FOR I=2 TO NP:INPUT V(I):PRINT£4,V(I);:NEXT:PRINT£4," "
103 PRINT£4," ":PRINT£4," PRODUCTION RATE"
104 PRINT"ENTER DATA....."
106 FOR J=1 TO JT
107 PRINT"FOR JET";J
108 PRINT"ENTER PRODUCTION RATE FOR REF PRODUCT AND MAIN PRODUCTS"
109 FOR I=1 TO NP
110 INPUT B(J,I)
120 NEXT I
125 FOR I=2 TO NP:PRINT£4,B(J,I);:NEXT
126 PRINT£4," "
130 NEXT J
132 DIM KJ(JT,NP),C(JT)
133 INPUT"TYPE 0 IF YOU WISH FOR SENSITIVITY OTHERWISE TYPE 1";K
134 FOR J1=1 TO JT
135 FOR T=1 TO KB
136 IF K=0 THEN G=1:GOTO 141
137 IF K=1 THEN 145
```

```
141 INPUT"ENTER FINAL DEMAND FPR REF PRODUCT";T:PRINT£4," "
145 PRINT£4," ":PRINT£4,"   NO. OF BLOW"
161 J=J1
162 I=1
170 KJ(J,I)= (T)/B(J,I)
175 PRINT£4,KJ(J,I)
185 PRINT£4," ":PRINT£4," "
192 I1=1
198 C=KJ(J1,I1)*Z(J1)
201 SN=0
202 SD=0
203 SX=0
204 SY=0
205 SO=0
206 SM=0
207 SA=0
208 SP=0
209 SS=0
210 SU=0
211 PRINT£4,"WHEN JET SIZD=";J1;"AND PRODREF=";I1;"AND NO.OF  BLOW =";KJ(
212 PRINT£4,".DF";".X";".M";".P";".CP(I)";".EX";".A";".P+A";".S";".Y";".U
213 PRINT£4," "
214 FOR I=2 TO NP
215 X=KJ(J1,I1)*B(J1,I)
217 PRINT£4,;DF(I);
218 PRINT£4,X;
229 IF X<DF(I) THEN Q=0:W=1:GOTO 232
230 Q=1:W=0
232 M1=(X-DF(I))*R(I)*Q
233 M2=(1/(2*DF(I)))*X*X*E(I)*H(I)*W
234 M3=(1/(2*DF(I)))*(DF(I)-X)*(DF(I)-X)*V(I)*W
235 M5=(X-DF(I))*E(I)*Q
236 M6=(1/2)*(X-DF(I))*E(I)*H(I)*Q
238 U(I)=X*R(I)-M1-M2-M3-M5-M6:SU=SU+U(I)
241 M(I)=(X-DF(I))*W
242 EX(I)=Q*(X-DF(I))
243 S(I)=DF(I)*R(I)
244 P(I)=(-1)*(1/(2*DF(I)))*V(I)*M(I)*M(I)*W
245 A(I)=((X-DF(I))*E(I)*Q+(1/2)*(X-DF(I))*E(I)*H(I)*Q)*(-1)
246 SP=SP+P(I)
247 SA=SA+A(I)
248 SS=SS+S(I)
249 SM=SM+M(I)
250 SO=SO+EX(I)
251 Y(I)=X*R(I)*W+S(I)*Q
252 SY=SY+Y(I)
253 SX=SX+X
254 SD=SD+DF(I)
255 N(I)=M(I)*F(I)
256 SN=SN+N(I)
258 PRINT£4,M(I);P(I);N(I);EX(I);A(I);A(I)+P(I);S(I);Y(I);U(I);"I=";I:NE
261 PRINT£4," "
262 PRINT£4," "
263 PRINT£4,".SU";"...C";"..SU-C";"....SY";"...SY-C;";".SD";".SX";"..KJ(J1
264 PRINT£4," "
265 PRINT£4,SU;C;SU-C;SY;SY-C;SD;SX;KJ(J1,I1)
266 PRINT£4," "
267 PRINT£4,".SM";".SP";".SN";".SO";".SA";".SP+SA";".SS";".SY";".SY-C"
269 PRINT£4,SM;SP;SN;SO;SA;SP+SA;SS;SY;SY-C
272 ST(J1,T)=SU
275 ZB(J1,T)=SY
280 ZC(J1,T)=SX
300 NEXT T
304 NEXTJ1
311 INPUT"ENTER1 FOR SU,2FOR SY,3FOR SX,7FOR OUT OF LOOP";C9
312 IF C9>7 THEN PRINT"REENTER":GOTO 311
```

```
313 IF C9=7 THEN 476
324 FOR J2=1 TO JT
325 FOR J3=1 TO KB

326 ZA(J2,J3)=0
327 IF C9=1 THEN ZA(J2,J3)=ST(J2,J3):GOTO350
328 IF C9=2 THEN ZA(J2,J3)=ZB(J2,J3):GOTO350
329 IF C9=3 THEN ZA(J2,J3)=ZC(J2,J3)
350 NEXT J3
351 NEXT J2
375 FOR I=1 TO JT
376 FOR J=1 TO KB+1
377 FT(I,J)=0
379 NEXT J
380 NEXT I
381 FOR I=1 TO JT
382 FOR J=1 TO KB+1
383 PRINT£4,ZA(I,J-1);:PRINT£4," ";:NEXT:PRINT£4," "
384 NEXT
385 INPUT"(MAT) OR (LIST)";X$
386 IF X$="MAT"THEN M3=1:GOTO 390
387 IF X$="LIST"THEN M3=2:GOTO 390
388 PRINT"REDO!!!":GOTO 385
390 FOR I=1 TO JT
395 IF M3=1 THEN PRINT£4,"FOR I=";I
400 FOR J=0 TO KB+1
405 IS=0
410 FOR K=0 TO J
420 TV=ZA(I,K)+FT(I-1,J-K)
430 PRINT"I=";I;"J=";J;"K=";K;"TV=";TV;ZA(I,K);FT(I-1,J-K)
432 IF M3=1 THEN PRINT£4,TV;:GOTO 440
435 IF Z1=1 THEN PRINT£4,"I=";I;"J=";J;"K=";K;"TV=";TV;ZA(I,K);FT(I-1,
440 IF IS<TV THEN IS=TV
450 NEXT K
455 IF M3=1 THEN PRINT£4,
460 FT(I,J)=IS
462 NEXT J
463 IF M3=1 THEN PRINT£4,:PRINT£4,:PRINT£4,:PRINT£4,
465 NEXT I
470 GOTO 311
476 IF K=1 THEN 133
499 IF K=1 THEN 133
500 END
READY.
```

APPENDIX V

THE RELATIONSHIP BETWEEN OPERATIONAL RESEARCH TECHNIQUES AND " INDUSTRIAL DYNAMICS" AS APPLIED TO THE MANAGERIAL PROBLEMS OF DECISION MAKING IN THE METAL POWDER MAKING INDUSTRY.

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This paper discusses the problems that would be encountered when the Industrial Dynamics approach is used to aid in the design of improved managerial policies for a metal powder making company. It seems that the very basic requirements of the industrial dynamics model building (i.e. the formation of feedback loops) is difficult to be met in the case of modelling the operations of a metal powder making company, and it demonstrates that the use of Operational Research Techniques would greatly assist, in tackling this problem by allowing for the required decisions to be made quickly and the data to be circulated throughout the system which otherwise would not be possible. The Industrial Dynamics Technics was proposed by Jay. W. Forrester at about two decades ago (1) as a method of systems analysis for management. This methodology aims to study the performance of business corporations or entire industries by using simulation techniques to show how they respond to various conditions (2). Industrial Dynamics explains the systems' behavior in terms of the structure and policies within a system and suggests changes in the structure and policies so as to improve the system performance (1) & (3).

The structure of a system as represented in an industrial dynamic model is comprised of a set of interacting feedback loops.

The feed back loop is the structural setting within which all decisions are made. It is a closed path as shown in Fig (1). A decision is based on the observed state of the system. The decision produces action which alters the state of the system and the new state give rise to new information as the input to further decision*.

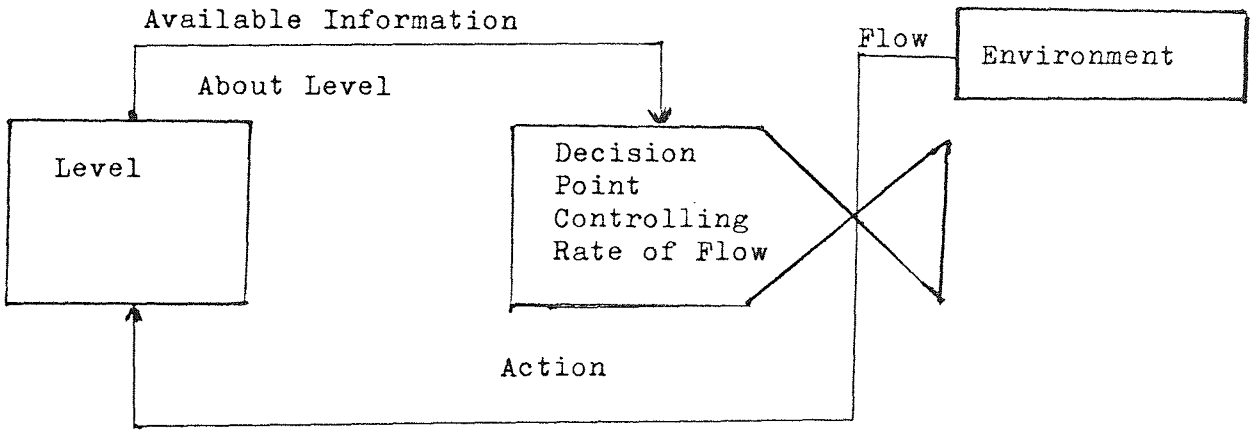

Fig (1) simple feedback loop

In this Figure (Fig 1) the'level' represents the accumulation of various entities in the system such as inventories of goods, unfilled orders, number of employees, etc. Decision point contains decision rule or "controlling policy" which control the rate of flow of system entities such as money, order, etc. Available in formation about level is received by decision point whereby it is used as a basis for decision that causes action to be taken - This action, in turn, alters the level of the system variable.

A decision is made within a feedback loop aims to achieve a certain set of goals which is the subset of total systems' goal. Fig (2) illustrates the rate of decision making in a 'goal-striving' system (2). Decision rule (contained in the decision point or decision center) recognises a goal towards which the decision point strives, compares the goal with

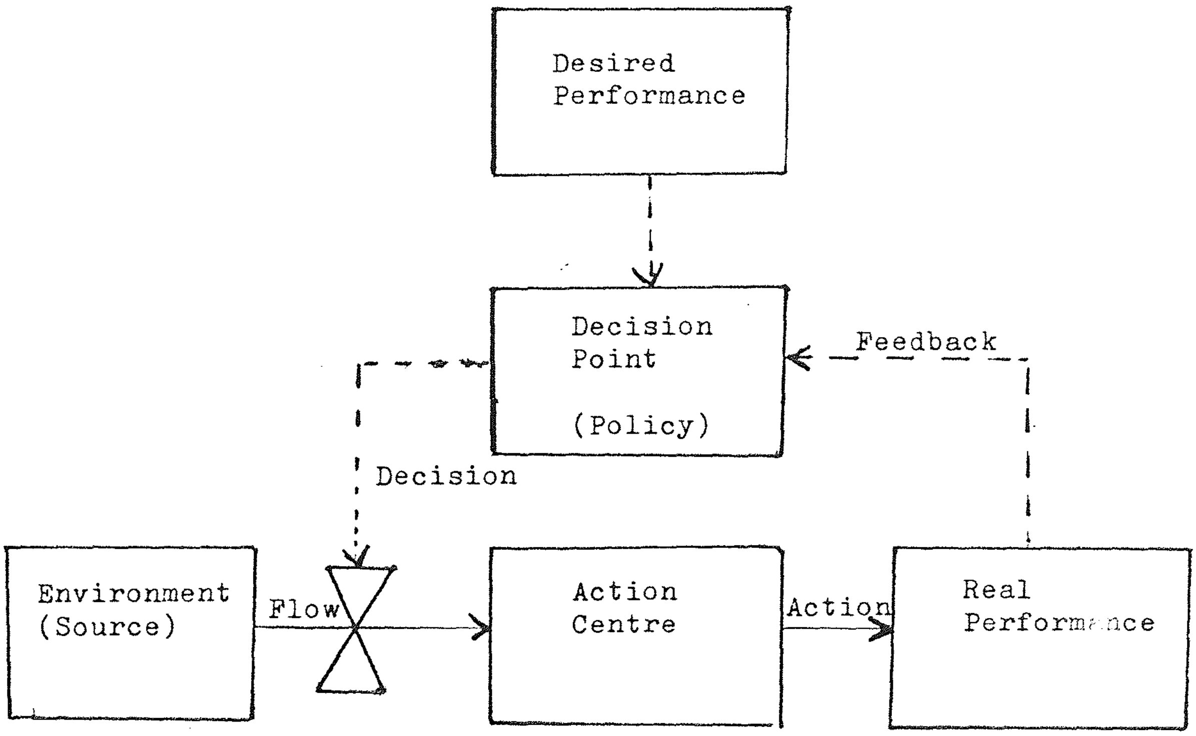

Fig 2 a goal striving feature in a feed back loop

the apparent system conditions to detect any discrepancy and uses the discrepancy to regulate action so as to achieve the goal.

In this loop there is a continuous feed back path of decision-result-measurement-evaluation-decision.

The industrial-dynamics model of an organisation might include numerous subsystems of the type shown in Fig 2.

An Industrial Dynamics Simulation Model of factory operation for a metal powder making company may have the feature as shown in Fig 3. As can be seen in this Figure there are a number of goal striving (not necessarily goal-achieving) sub-systems within the total factory system.
One such goal striving system involves a loop which contains the 'desired level of inventory', the 'actual level of inventory of finished goods', and the 'decision centre which controls the flow of input material'.

The decision centre recognising the desired inventory level as a goal and receiving information on the actual level of finished goods would be able to output a decision which results in an action to be taken to adjust the level of actual inventory.

The feedback loops, explained in the above mode however, is difficult to construct as such due to the following reasons:

a) There is often is a lack of precise knowledge as to

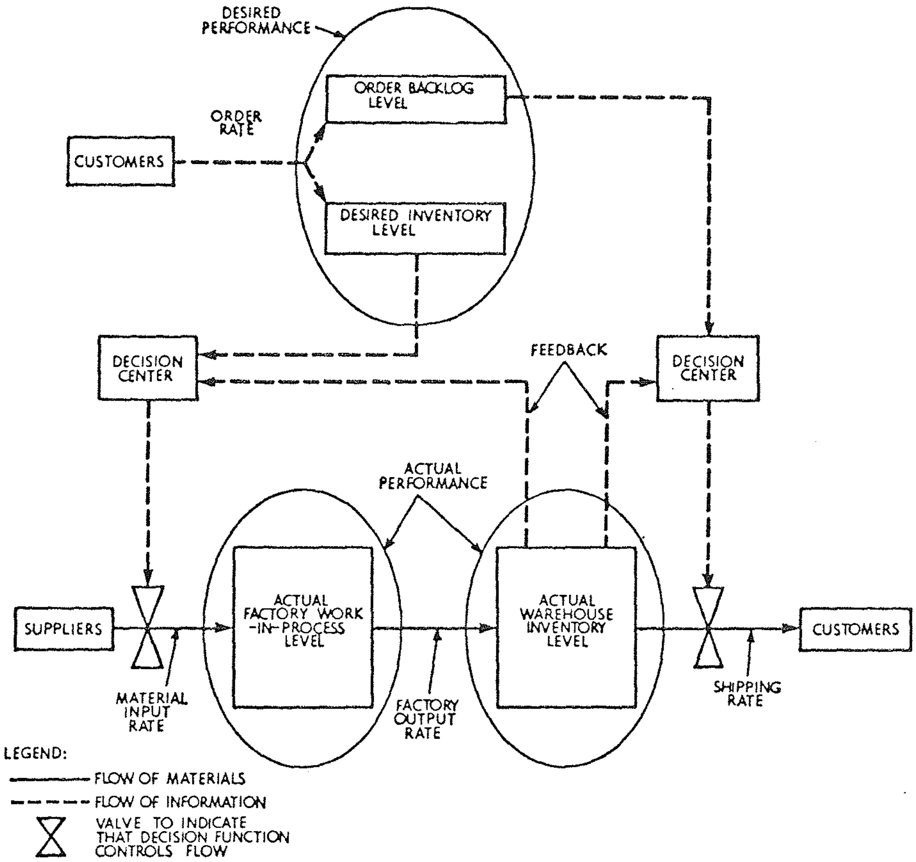

Fig 3 Simple Model of a Factory System

the actual level of inventory of finished products. To obtain this information it is required to quantify the stock material which is a mass of particulate material to convert it into the final product equivalence. The stock material which comprises of large number of particles of various size is not measurable easily (The 'amount' of particles of individual size classes could be know only statistically. In addition to this there is a large number of routes into which these particles could be blended to form the final products and the blending schedule is normally decided only when the exact specification of the customer-requested- products is 'decided.' The latter is often subject to variation due to both the customer request or the companys plan to make more use- - of stock materials.

(b) The decision concerning the quantities to order to replenish the inventory is also difficult to be made for the reason that first; the information on actual level of inventory is not readily available (as explained in a), and second, the production rate-decision making involves comparison between the outputs of the process when different plant settings are utilized and the consideration of the combinations of the various process 'runs' which result in an economic production run.

The above decisions are difficult to be made by the human decision maker and is also difficult to put under the control of a specific fixed policy because the parameters of the policy which should control this decision is difficult to determine precisely.

It is shown in Fig 4 that the use of Operational Research techniques such as Linear Programming and Dynamic - Programming will solve the above two problems - respectively. The author has developed such programs for solving these operational decision problems of the metal powder making industry, and he beleives that these programs could conceivably be incorporated as "sub-assemblies" into an Industrial dynamics "gestalt" model.

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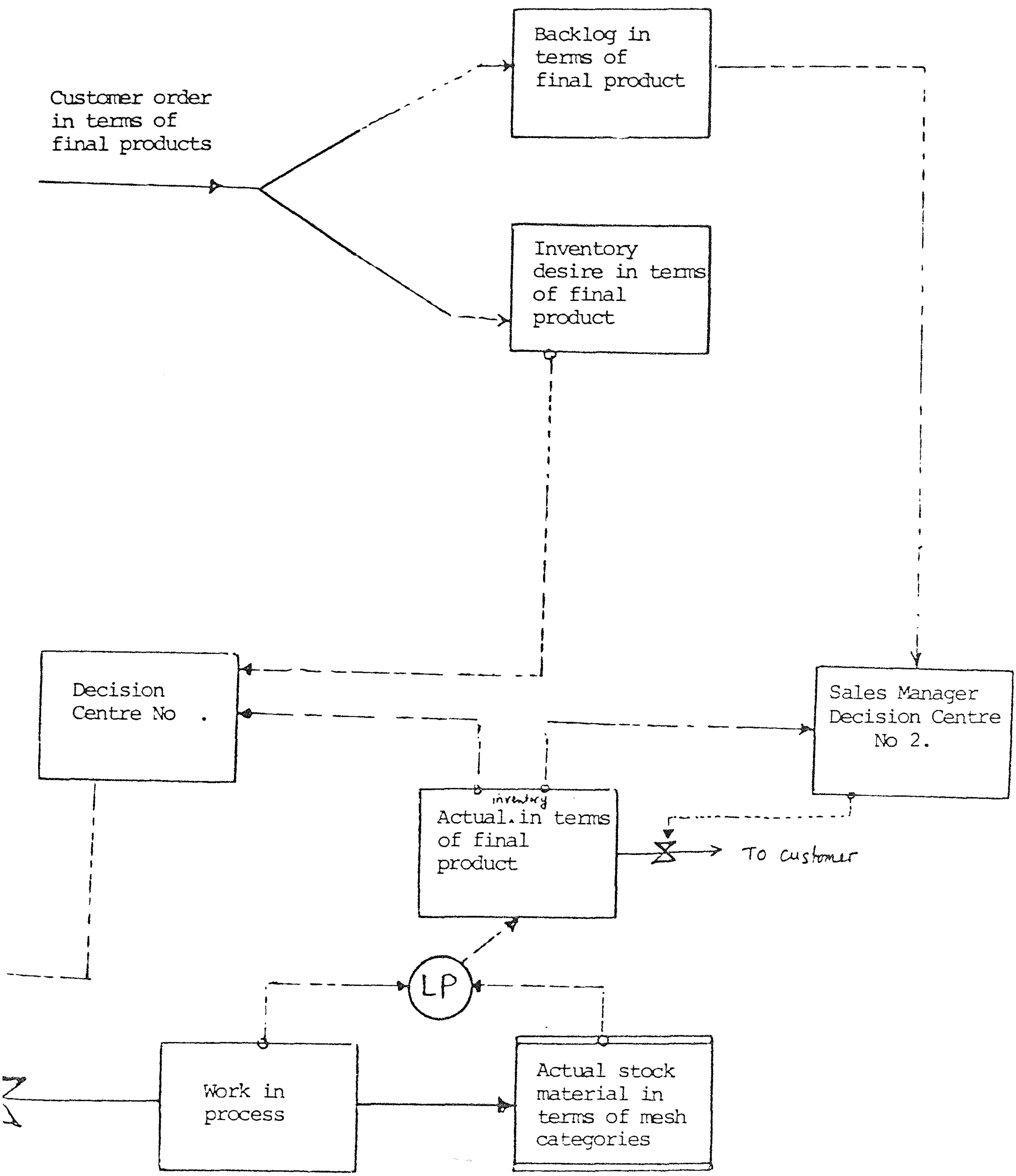

Fig 4 Simulation Model of Powder Making Factory

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