"1961 and all that: The Influence of Jay Forrester and John Burbidge on the Design of Modern Manufacturing Systems"

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Abstract

Modern manufacturing systems are expected to respond rapidly, effectively and efficiently to changes in the marketplace. Simultaneously there is the drive to achieve world class customer service levels coupled with minimum reasonable inventory (MRI). We thus have the classic conflict of interests between marketing, production and materials management. Marketing wants the complete product range available off-the-shelf; production is still all-too-often looking to manufacture in economic batch quantities so as to achieve economies of scale; and materials management is trying to minimise storage and distribution costs which in turn requires that a total systems MRI policy be adopted.

As reviewed in the paper the ground rules for effective manufacturing system design were co-incidentally established in 1961. Jay Forrester showed that medium period demand amplification was a system dynamics phenomenon which could be tackled by reducing and eliminating delays and the proper design of feedback loops. In parallel, via his "rules to avoid bankruptcy" and "laws of manufacturing systems", John Burbidge showed that short period demand amplification was due to multi-phased, multi-period ordering policies.

Some thirty years later the work of both pioneers (which is conveniently summarised in the frequency domain) is still ignored at their peril by manufacturing industry. As an aid to fruitful exploitation of these ideas we describe their application to the analysis and design of a real world automotive spares supply chain and to a multi-product "to-make" ordering model which drives an MRP system to ensure that customer service level targets are met. Input-Output block diagrams were found to be particularly useful diagnostic tools for these projects.

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1. INTRODUCTION

There has been an interesting reaction to a recent paper by Towill [1992] which suggests that many problems still encountered in manufacturing systems operations can be at least partially solved by implementing ideas which were well documented some thirty years ago. This feedback has been triggered not only by the drawing together of the apparently disparate methodologies of Industrial Dynamics (Forrester, 1961) and Material Flow Control (Burbidge, 1961) but by the realisation that they were indeed cognate in two very important respects. Firstly, they cover a wide frequency spectrum of activities; secondly they cover strategic, tactical, and operational aspects of manufacturing system design.

A problem typically encountered in the automotive industry is that JIT shop floor controls seem to be working well, yet the orders placed on the shop-floor via the MRP II system appear to fluctuate excessively compared to perceived demand in the marketplace. Under such circumstances the Production Director may argue with some justification, "Volatility of this magnitude costs me a great deal of money due to unnecessary changes in capacity and work-in-process. I believe this situation is partially due to poor systems design. Can you please substantiate this view, and if true put a ballpark estimate on the effect?" Subsequent investigation requires the formation of a multi-disciplinary Task Force [Parnaby 1993] which may also be subsequently charged with system re-design and implementation once the case for change is proven.

2. "THE FORRESTER EFFECT" AND "THE BURBIDGE EFFECT"

It is customarily the case when the information available to the Task Force is analysed that the problem is seen to be twofold as shown in time series form in Fig.1. Thus there is usually both an unnecessary amplification affecting the medium-term behaviour (the Forrester Effect) and additional unnecessary short-term fluctuations (the Burbidge Effect). No identification technique used to date has reliably separated the two effects: nor is this necessary since the Task Force will be charged with tracking down all significant causes using the manifold tools at their disposal. It is enough at the analysis stage that the Task Force is fully aware of both phenomena and is continuously on the look-out for them.

What Fig.1 does do is to prioritise the most fruitful areas for immediate follow-up. This depends on the local situation and in particular who is the "product champion" responsible for both funding and driving the re-engineering process. Thus in terms of Fig.2 we may well be constrained to act within the individual business but for preference need to urgently create circumstances in which we can re-engineer the business interfaces with customer and/or supplier. In simplest terms the Forrester route may be regarded as dynamic simulation driven strategic re-design, whereas the Burbidge approach is to avoid many potential operating pitfalls by good tactical application of sound industrial engineering principles in order to assure better local control of material flow.

3. MATERIAL FLOW CONTROL

Although the ideas of material flow control date back to at least 1961, two later publications put these ideas even more succintly and it is these which we shall quote in detail. *Firstly, there are the five rules for avoiding bankruptcy (Burbidge, 1983), which state:*

RULE 1:Only make products which you can quickly despatch and invoice to customers.

RULE 2:Only make in one period those components you need for assembly in the next period.

RULE 3: Minimise the material throughput time.

RULE 4:Use the shortest planning period, i.e. the smallest run quantity which can be managed efficiently.

RULE 5:Only take deliveries from suppliers in small batches when needed for processing or assembly.

These were subsequently enriched and supplemented by the six "Laws of Manufacturing Systems" (Burbidge 1984) as follows:

*The Law of Gestalt. *The Law of Material Flow.

*The Law of Prescience. *The Law of Industrial Dynamics.

*The Ordering Cycle Law. *The Law of Connectance.

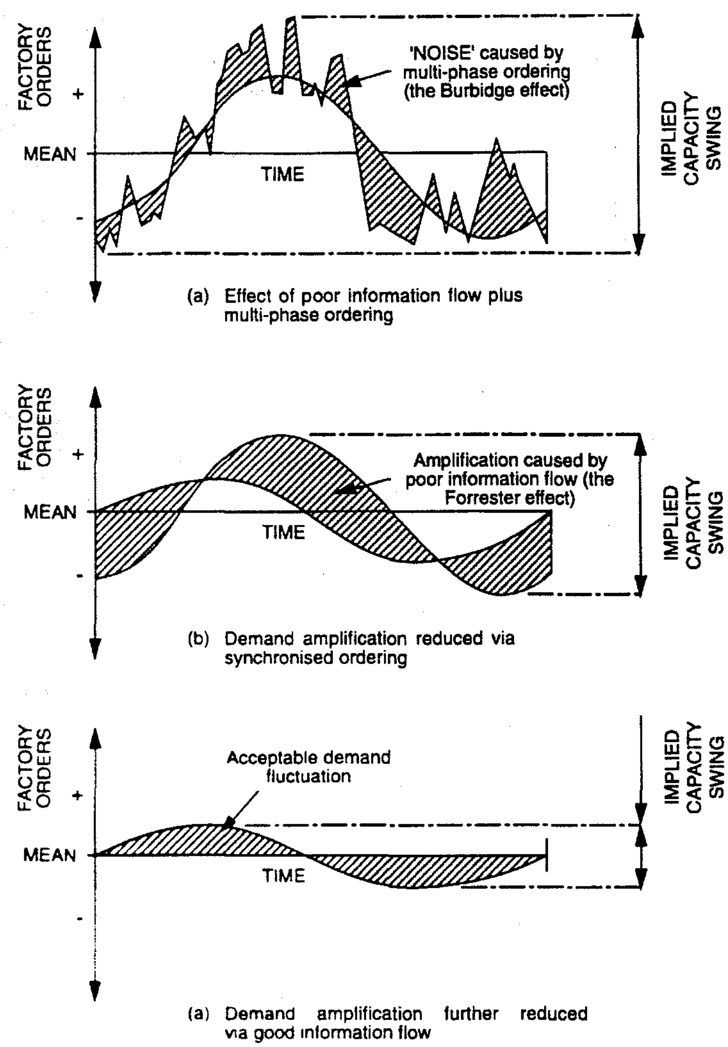


Figure 1. Typical avoidable demand amplification experienced by a manufacturing process

These are briefly defined in TABLE I. Taken together, these Rules and Laws integrate into a prescriptive industrial engineering methodology many of the slogans for improved international competitiveness being advanced by management consultants. These include Ingersoll Engineers, (Small, 1983, "Simplify, Integrate, and Automate"), and the Boston Consultancy Group (Stalk and Hout, 1990, "How Time Based Competition is Re-shaping Global Markets").

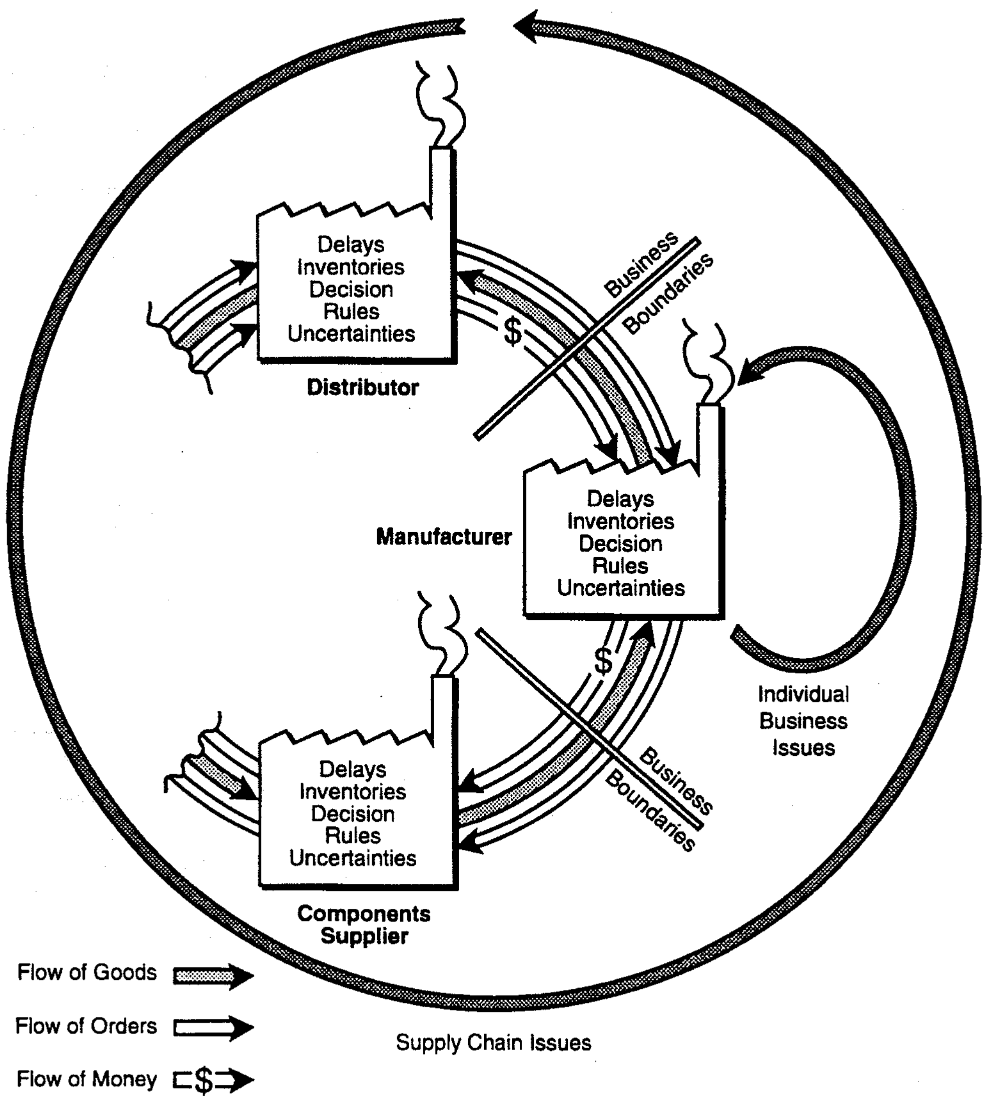


Figure 2. Individual business versus supply chain issues

The reduction or better still, elimination of time delays is well known to system dynamicists as a preferred route to achieving better dynamic behaviour. This is clearly a dual area of concern with material flow control as Burbidge readily acknowledges. So we see many good reasons why in the internal scenario part of Fig.2 management consultants tackle process flow time reduction as the top priority in a new assignment. It not only makes good sense both from the Forrester and Burbidge viewpoints, but much performance improvement can be delivered inside the business boundaries under the direct control of the "problem owner". The Consultant can thus make significant immediate savings and leave until a little later the difficult problem of initiating the cultural change usually needed to improve information flows across boundaries [Towill, 1992].

TABLE I: THE SIX BURBIDGE LAWS OF MANUFACTURING SYSTEMS.

1. THE LAW OF GESTALT
"*The whole is not the sum of its parts*" and by extension "*a set of sub-optimum solutions can never produce a true optimum solution*". An holistic approach requires that all system design stages should be multi-disciplinary and start with corporate planning followed by a total material flow system covering purchasing, manufacture, and distribution.
2. THE LAW OF MATERIAL FLOW
"*The efficiency of a manufacturing system is inversely proportional to the complexity of its material flow system*". So we should design simple material flow systems based on product organisation and then restrict freedom of production planning choice to maintain this simple system.
3. THE LAW OF PRESCIENCE.
"*It is not given to human beings to foretell the future*". Most manufacturing systems ignore this Law by basing production on long term forecasts of future sales. Because of frequent and unavoidable changes in the programme there will be high stock-holding and obsolescent costs. So we should regulate material flow via a series of short term programmes which are then much more likely to cover actual needs.
4. THE LAW OF INDUSTRIAL DYNAMICS.
"*If demand for goods is transmitted along a series of inventories using stock control (i.e. level triggered)ordering, then the amplitude of the demand variation will increase with each transfer*". There is also a Murphy's Corollary; "*If the system design is such that there is any possible way that demand can amplify then this effect will inevitably be triggered during normal operations*".
5. THE ORDERING CYCLE LAW.
"*If the various components made in a factory are ordered and made to different time cycles, they will generate high amplitude and unpredictable variations in both stocks and load as the many contributing component stock cycles drift in and out of phase*". Too many factories still use multi-cycle ordering systems based on EBQ theory.
6. THE LAW OF CONNECTANCE.
"*A given direction of change in the value of any manufacturing system variable will induce, or be induced by a given direction of change in at least one other variable*". A first attempt to codify practical causal relationships has produced hundreds of hypotheses concerning these changes.

The reduction or better still, elimination of time delays is well known to system dynamicists as a preferred route to achieving better dynamic behaviour. This is clearly a dual area of concern with material flow control as Burbidge readily acknowledges. So we see many good reasons why in the internal scenario part of Fig.2 management consultants tackle process flow time reduction as the top priority in a new assignment. It not only makes good sense both from the Forrester and Burbidge viewpoints, but much performance improvement can be delivered inside the business boundaries under the direct control of the "problem owner". The Consultant can thus make significant immediate savings and leave until a little later the difficult problem of initiating the cultural change usually needed to improve information flows across boundaries [Towill, 1992].

4. THE PIVOTAL ROLE OF FEEDBACK

As was seen from Fig.2, no business, and no manufacturing system is an island but is in fact part of a complex production-distribution system known as a Supply Chain. Thus the explanation for demand volatility sought by the Production Director in Section 1 may be found to be caused by internal forces; external forces; or by both acting together or in opposition in whatever way is required to produce the unwanted demand amplification.

If we refer to Fig.1 then there is a good chance that any observed high-frequency amplification can be traced to a "Burbidge" origin, typically due to multi-cycle ordering. This is often unrecognised both in its existence and in its effect until the evidence is produced in the form of vast swings in inventory way beyond that necessary to maintain realistic safety stocks. Indeed it is still our experience that stock control dynamics is very poorly understood and even more badly applied. At least by adopting the "reduce process flow times as top priority" strategy the consultant knows there is a chance that waste will be reduced in proportion to the improvement achieved [Stalk and Hout, 1990].

What is still lost by this parochial approach is the further benefit to be obtained by proper dynamic design. As we would expect, this is where Forrester [1961] comes to the fore with his statement on the pivotal role of feedback within system modelling and simulation as typified by;

"Systems of information feedback control are fundamental to all life and human endeavour; a feedback control system exists whenever the environment causes a decision which in turn affects the original environment. In business, orders and inventory levels lead to manufacturing decisions which satisfy orders and correct inventories. Feedback theory explains how decisions, delays and predictions can produce either good control or dramatically unstable operation. It relates sales promotion to production swings, purchasing and pricing policies to inventory fluctuations and typical life cycles to the need for research. Typical manufacturing and distribution practices can generate the types of business disturbances which are often blamed on conditions outside the company. Thus random, meaningless sales fluctuations can be converted into annual, seasonal production cycles by the action of feedback. Advertising and price discount policies of an industry can similarly create two and three year "rogue" sales cycles".

So we would expect to find many potential traps for the unwary in manufacturing system design, particularly in the supply chain scenario where for reasons which will become apparent later the Law of Industrial Dynamics seeks centre stage with the Laws of Gestalt and Material Flow.

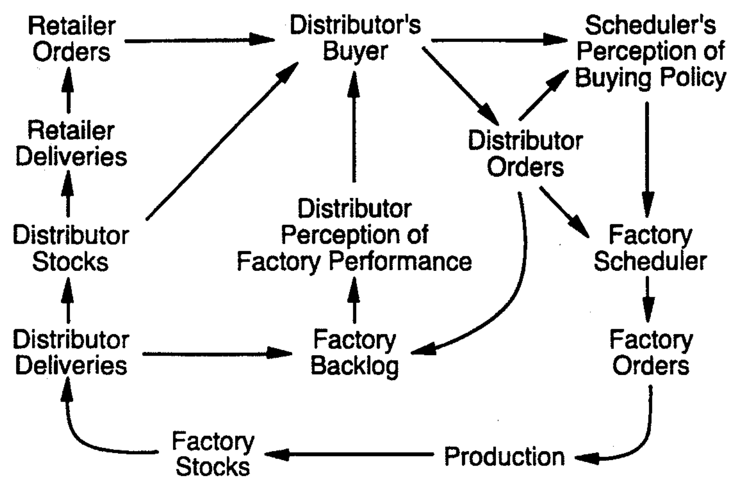
5. THE SUPPLY CHAIN CHAIN SCENARIO

Each stage within a supply chain is known as an echelon, and embraces the following characteristics;

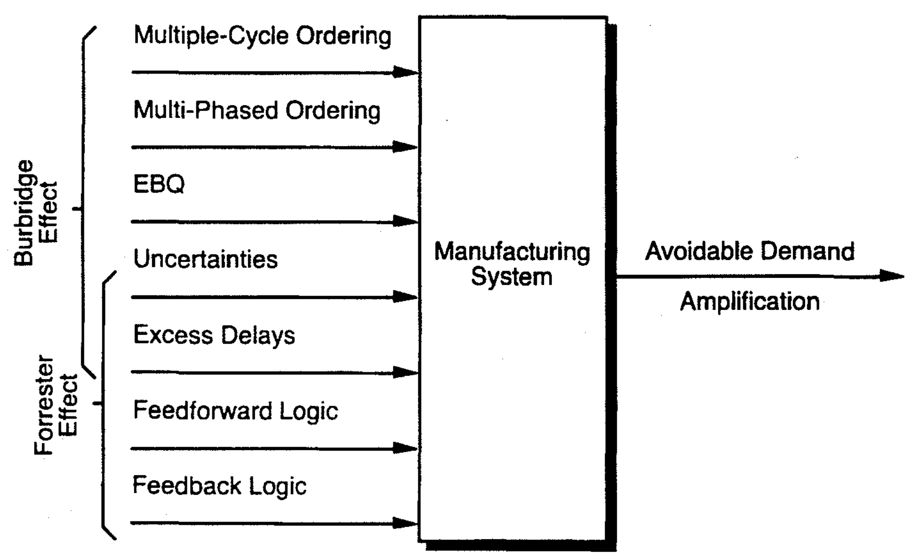
* perceived demand for products which may be firm orders or just forecasts.
* a "production" or "added value" process (at least as perceived by the particular echelon concerned).
* performance data (which may be stale and/or distorted)
* disturbances due to breakdowns, faulty parts etc.
* transmission lags for information, material, and cash flows.
* points in the chain where information is brought together for management decision making.
* formal or informal algorithms for issuing instructions both internally and externally.

Crucially, there is uncertainty associated with perceived demand, with the quality of information available, and with the value of transmission lags. It is therefore not surprising to find that many supply chains exhibit the dynamic behavior already met in Fig.1 with medium period amplification present. This phenomenon is almost certainly due to "The Forrester Effect" and Fig. 3 shows an example of a causal loop diagram which explains how this can happen due to the interaction between the decision makers in successive echelons in an automotive supply chain [Towill, 1988].
Also shown is an Input-Output Diagram which summarises the sources of amplification noted by the Task Force conducting the study. Note that at the analysis stage the synthesis techniques to be used later are not pre-selected but depend on what is discovered during the investigation [Weill and Veit, 1989].

An obvious possibility for improving supply chain performance in this scenario is to combine the manufacturing and distribution functions. This procedure, which had already been proposed in general terms by Jay Forrester was implemented to good effect in this particular supply chain. However, an even more spectacular example is due to Toyota [Towill 1992]. That company found that the distribution process was taking longer than needed for car manufacture. Not only does this build up excessive total system stocks, but the Distributor masks the true market demand. So Toyota promptly bought out the Distributor and solved two problems for the price of one.



(a) Caual loop description of interaction between distributor and manufacturer situated within an automotive products supply chain



(b) Input-output diagram of influences on avoidable demand amplification

Figure 3. Sources of demand amplification in an automotive products supply chain

6. SUPPLY STRATEGY AS A SYSTEM DYNAMICS PROBLEM

Burbidge in his 1961 paper also demonstrated graphically that supply strategy may be succintly described via system dynamics. As shown in Fig.4, by using a frequency domain representation of demand it is possible to schematically demonstrate the industrial meaning of such strategies as Deliver from Stock i.e. "make what think we can sell", to the other extreme of Keep the

Factory Busy at all Costs i.e. "Sell what we make". The first policy is strongly evident, for example, in the components industries, whilst the second is common in capital intensive industries such as rolling of steel products.

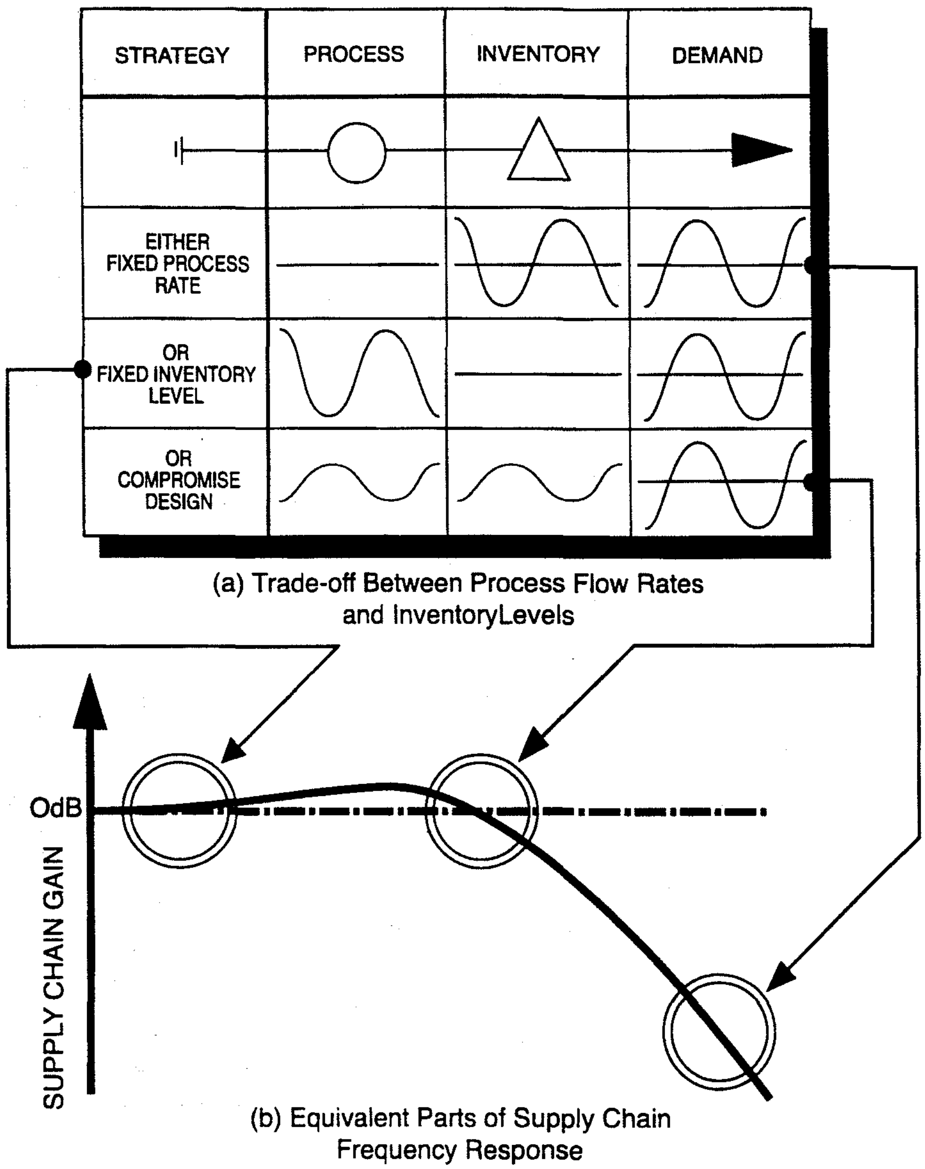


Figure 4. Relating process flow rates and inventory levels to the filter characteristics of a supply chain (Towill and Del Vecchio, 1994)

An advantage of Fig.4 is that it enables both individual manufacturing systems, and quite complicated supply chains to be studied using filter theory, since this allows us to design individual echelons which are well damped, or if this is not possible, to avoid unnecessary amplification by ranging the resonant frequencies over a limited part of the spectrum [Towill and del Vecchio, 1994]. Whilst the approach is limited to linear and quasi-linear systems, there is much evidence to suggest that this is what the system user actually prefers, i.e. simple robust controls [Monniot et al, 1987]. Unavoidable non-linearities are then allowed for on an individual basis. For example if capacity limitation is a problem then the best "linear" design under this circumstance is readily established using the root-square locus technique, or better still, the Bode plot equivalent [Towill, 1981].

Where the dynamics approach has a uniquely important contribution to make is in the optimum design of systems which meet agreed customer service levels. An example is the design of an adaptive ordering system which will achieve, say, 97.5% "off-the-shelf" deliveries to the customer across a 400 product range with minimum reasonable inventory (MRI) to achieve this goal [Cheema, 1994]. The way in which this links in with the existing industrial MRP system is shown in Fig.5. The purpose of this dynamic "to-make" ordering model is to drive the MRP system so as to achieve target customer service levels despite inevitable variability in manufacturing lead times. Hence we incorporate an adaptive feedback loop based on current shop floor performance of individual orders thus updating the pipeline control scheme advocated by Lyneis [1980].

It should be noted that the concept of MRI as a target for system design is gaining ground [Grunwald and Fortuin, 1992]. This, by definition is a dynamic concept which can only be evaluated satisfactorily by simulation. It was introduced as a backlash to JIT pundits talking as though zero inventory is achievable simultaneously with attaining end-customer satisfaction under all operating circumstances. It cannot, as with all dynamic problems there is a trade-off to be evaluated and a judgement to be made from amongst many competing alternatives.

7. SYSTEM DESIGN LESSONS FROM 1961

The Japanese *appear* to find little use for simulation in the design of manufacturing systems. Whether this is true or not in practice is difficult to establish with any degree of certainty. What we do know is that manual simulation is frequently adequate to establish the principles of good system design provided we keep things simple. There is a Corollary to Ashby's Law of Requisite Variety which says that complex controls are only needed for complex systems. The absence of computer based design techniques should therefore not be construed as meaning there is a lack of insight into effective systems synthesis.

Is it not the case that the work of Jay Forrester and Jack Burbidge is urging us to "keep it simple" in the manufacturing systems scenario? Let us consider the evidence; both strenuously urge the reduction of all process flow times, and Burbidge has given us a host of tools to achieve this goal including Group Technology and Material Flow Concepts. Yet thirty years on we still have management consultants anxious to implement lead time reduction programmes for manufacturing industry and offering many persuasive reasons for wanting our patronage.

Burbidge pointed out that stock control systems triggered by pre-determined re-order levels are already centuries old. They treat each component individually and generate extremely variable multi-cycle, multi-phase flow leading to highly fluctuating inventories and stop-go plant utilisation. These systems are based on the belief that increasing the stock will increase service. Perhaps because to our ancestors winter stocks of food meant survival, we may be programmed at birth to associate high stocks with peace of mind. Instead we need to see JIT operations in the Japanese style as a manifestation of lead time reduction coupled with simple localised production control systems, i.e. design simplicity in.

Jay Forrester showed that feedback systems had to be designed with extreme care. But this is no recipe to make them *unnecessarily* complex. Keeping delays of material flow, information flow, and cash flow to a minimum will help enormously. Also we need to ensure that information is not "stale" or "noisy", and the system has good filtering properties. Also esoteric games should not take place in which decision-makers try and double-guess what is really happening further downstream in the supply chain to the detriment of all echelons conducting business therein.

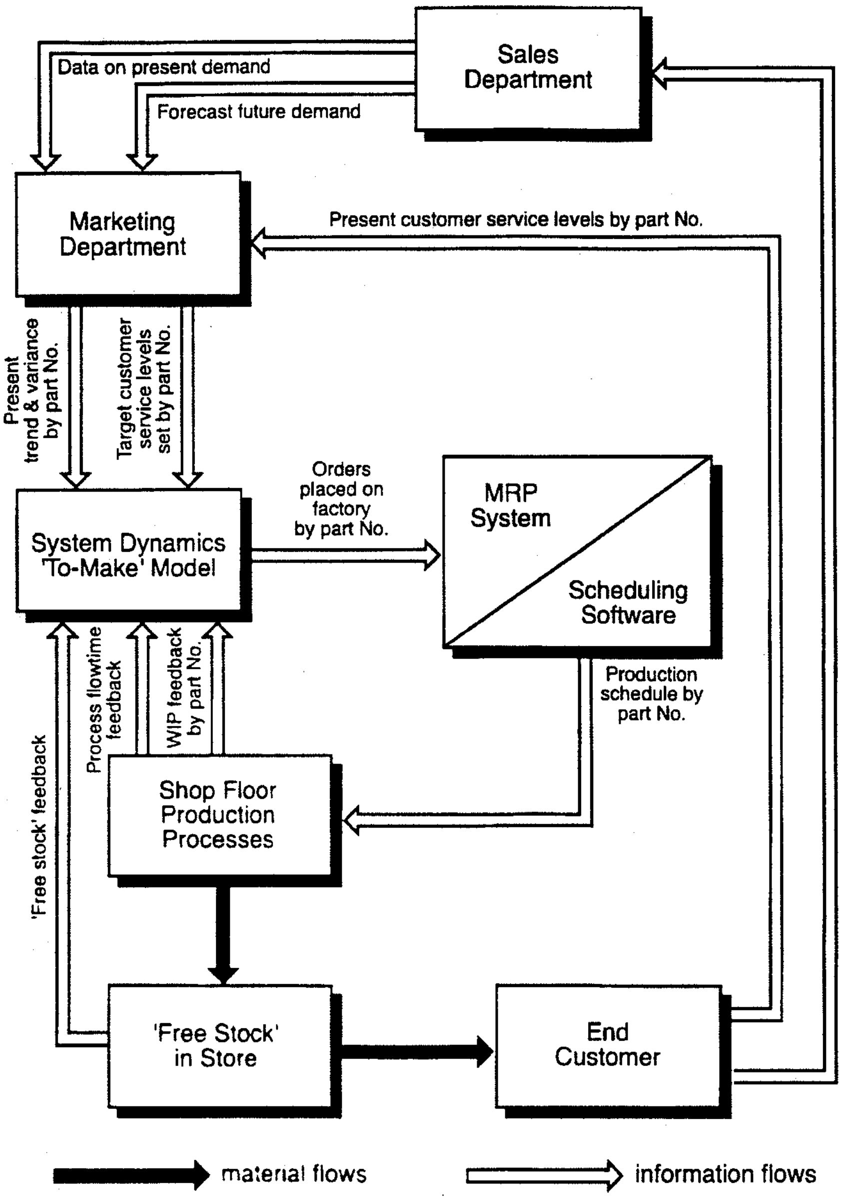


Figure 5. Block diagram representation of a multi-product factory incorporating a 'to-make' system dynamics model to ensure achieving target customer service levels

8. CONCLUSIONS

So the purpose of "1961 and all that" to show that in at least two respects we have long had available complimentary tools for manufacturing systems design has been achieved. These tools have been well demonstrated in industrial practice by the Japanese via a process of evolution, and by well organised Western companies. With a thirty year knowledge lead time we really have no excuses left!

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