Monograph:
Riddalls, C.E., Bennett, S. and Tipi, N. (1999) Modelling the Dynamics of Supply Chains. UNSPECIFIED. ACSE Research Report 741 . Department of Automatic Control and Systems Engineering

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Modelling the Dynamics of Supply Chains
Research Report No. 741

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March 1999

1 Introduction

Since the 1960s many academic and managerial researchers have focused their attention on production-inventory-distribution systems. The application of diverse mathematical techniques from continuous differential equation systems to mathematical programming models have been attempted. Yet none have predominated over Operational Research techniques either in industry or the research literature. This paper aims to enumerate and appraise the various methodologies which have been applied to supply chain analysis over the last forty years. In particular we shall ask of each technique: To what extent does it reveal the dynamics of the process involved? These questions are important since only through knowledge of the dynamics can we gain a full appreciation and understanding of the factors which affect supply chain performance.

In the next section we shall highlight some of the important issues arising in supply chain analysis. Then we take a detailed look at the four main approaches to the analysis of these problems and list the generic merits and limitations of each approach. After that we survey the salient academic research in each of these areas. After these efforts we hope to be able to judge whether the merits of Operational Research techniques justify their status in industry as the standard methodology for the solution of these problems.

2 Supply Chain Issues

A supply chain is a system of business enterprises which link together to satisfy consumer demand. The constituent parts of a supply chain can be contained in the same business unit or be part of different companies. Either way, when we can discern a distinct generic procedure as part of the production/distribution process we call this an echelon in the supply chain. These distinctions are usually prompted by geographical factors but, as we have said, two echelons may exist in a single factory. Supply chains are usually characterised by the forward flow of materials and goods and the backward flow of information. In their most basic form goods flow from one echelon to the next until they reach the consumer. In reality however, supply chains do not exist in isolation, but form part of a network of supply chains satisfying different demands. Also, a linear flow of goods along the chain is rare. Many production processes comprise parallel flows which must coalesce at the right time to form the final product.

In the past, before the existence of supply chain managers, each echelon in the supply chain would operate independently. Managers at each stage made decisions based on the requirements and objectives of their particular activity with only cursory attention to the constraints imposed by neighbouring echelons. As a result, each echelon attempted to optimise its own operations in isolation. A sequence of locally optimised systems doesn't necessarily constitute a global optimum. For example, the logistics of production processes usually favour large batch sizes. Yet supermarkets like to operate very small inventories to minimise costs and retain the flexibility to change product lines. These competing requirements can only be reconciled through consideration of the supply chain as a single entity.

The advent of computer power in the 1970s enabled companies to analyse and streamline their production processes using Materials Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II). Then, in the 1980's, the emergence of intuitively attractive management philosophies like Just-In-Time (JIT) (see [22], [27], [41]) from Japan, a country admired for its manufacturing industry, prompted renewed scrutiny by western companies of their supply chains.

Today supply chain managers have the daunting task of developing an integrated policy with due attention to the following issues:

- Recognising and quantifying demand characteristics such as variation with price, lead time and reliability of service.

- How the logistics of the manufacturing process affect service levels. For example, what are the 'crashing costs' of reducing lead times to increase the reliability of the service.
- How information flows between echelons are handled.
- How demand forecasting is achieved and acted upon.
- Where the decisions are made.
- Where optimum levels of inventory should be placed along the supply chain to ensure critical levels of customer service are maintained at an acceptable cost in tied up stock.
- How disturbances such as machine breakdowns are overcome.

The rigours of international competition and a more discriminating public make these choices more acute. Consumers today are demanding a greater diversity of products than ever before. The capricious nature of such demand implies shorter product lifespans and greater demand variation. Further, the balance of power in many supply chains has shifted towards the retailer. A classic example of this is in food retailing. A handful of supermarkets, which dominate this sector, have pushed inventories further down the chain in order to reduce their own costs. They have also tended to communicate the changing demand characteristics down the chain in order to maintain market share. These trends have great implications for firms trying to maintain service reliability whilst keeping costs down. The international nature of many supply chains further exacerbates many supply side problems.

One of the earliest generic supply chain phenomena to be recognised was *Demand Amplification.* First simulated using a continuous time model [32], this is the process by which small fluctuations in demand at the retailer end of the supply chain are amplified as they proceed down the chain. Typical amplification ratios which have been observed between two echelons are 2:1 [58] and, between four echelons, 20:1 [38]. The Forrester Effect, which has also been called The Law of Industrial Dynamics [16], has traditionally been attributable to a combination of factors. The following chain of events is a typical occurrence: Upswings in demand create a perceived shortage somewhere along the chain. This may simply be inventory falling below a target level. Lacking an overview of the entire supply chain, the company concerned then over orders to protect itself against further fluctuations. This increase in orders triggers further localised protection since it is misinterpreted as real extra orders. Houlihan [38] produced a metaphorical interpretation for demand amplification by observing that the feedback loops inherent in these systems create a 'flywheel effect'. In this way relatively small ripples on level scheduling at the retail end of the supply chain can cause massive variations in demand at the raw materials end. Some factors which exacerbate demand amplification are listed below:

- Lead time delays.
- Unreliable delivery service compensated for by additional inventory investment.
- Uncertainty in the quality of information being passed between echelons.
- Poor demand forecasting. This may be unintentional or caused by tendentious 'forecasts' by ambitious sales departments.
- Reducing product life cycles creating obsolete stock.
- Distinguishing periodic economic and seasonal demand swings from fundamental changes in consumer attitudes.

To counter demand amplification companies typically increase their buffer inventories in an attempt to smooth production rates. Unfortunately, if this is not done in a co-ordinated manner, every company in the chain can end up holding expensive levels of stock against the same contingency. Also, these extra levels of stock serve to cloud further the perception of any genuine demand fluctuations. Later, we will examine some of the techniques companies have used to suppress demand amplification. Some papers discussing general supply chain issues are [38], [40], [42] and [37].

3 Modelling Supply Chain Dynamics

In this section we examine the various ways in which supply chains have been modelled and analysed. There are four main categories of methodology into which most approaches fall. These are: continuous time differential equation models, discrete time difference models, discrete event models and classical operational research methods. An informative review of the models and methods used in the literature can be found in [6].

3.1 Continuous Time Differential Equation Models

Modelling supply chains using differential equations holds great appeal for the control theorist. This is because many of the influential characteristics of the problem can be succinctly expressed in differential equation form. Then a vast array of tools and methodologies from control theory can be invoked to gain insight into the system dynamics. The rationale for this approach is that models of modest complexity, which are therefore amenable to analytical study, can provide an insight into the factors which are common to much larger 'live' systems. Differential equation models also have the advantage of being a conduit into the frequency domain, which offers a framework particularly suited to the study of systems in which oscillations are a salient attribute. There one can investigate which factors determine how various seasonal and other demand fluctuations may be amplified as they are passed along the chain.

Since differential equations produce 'smooth' outputs, they are not suited to the modelling of all supply chains. The system must be considered at an aggregate level, in which individual entities in the system (products) are not considered. Rather, they are aggregated into levels and flow rates. So these methods are unsuited to production processes in which each individual entity has an impact on the fundamental state of the system. For the same reasons differential equation approaches cannot solve lot sizing and job sequencing problems.

We start with the simplest linear deterministic systems. Simon [52] was one of the first to use classical Laplace transform techniques to analyse simple production-inventory systems. In essence, he solved the system equations analytically and investigated how the solution characteristics are determined by the system parameters. In the cited paper he highlighted a fact which persists in influencing research today, namely that pure delays are hard to deal with within this framework. Instead he used exponential delays, which approximate pure delays by smoothing the output signal over time. The extent to which this substitution compromises the true reproduction of the system characteristics must be judged for each individual system.

A controversial figure in this area, who also used exponential delays, was Forrester [32]. In this book he developed a highly detailed nonlinear model of a supply chain using the repeated coupling of simple first order differential equation systems. The nonlinearity of this model was not a bar to progress since very little analysis was carried out. Instead, the model was simply used for simulation purposes only. Simulation models, as the name suggests, are highly accurate models which can be used to replicate the system behaviour given an initial set of conditions. Traditionally their strengths are in the qualitative investigation of 'what if' scenarios. However, their complexity usually discourages attempts at their rigorous validation. By performing an elementary sensitivity analysis on his model, Forrester would have discovered a high degree of parameter sensitivity in the exponential delays. In today's parlance, this lack of robustness was exacerbated by the repeated coupling of similar submodels. Forrester was duly criticised for the lack of theoretical underpinning in these models [4] and later for similar work modelling world populations [33].

Despite these facts, some years later Forrester's work was resuscitated by Denis Towill (see [59], [61], [30]) and his colleagues. By simplifying Forrester,s models, usually into more elementary two or three echelon systems, they facilitated a greater level of analysis whilst still capturing the salient attributes of the system behaviour [12]. Their systems were linear, implying that they were only valid in a subset of the whole state space. This fact makes analysis in the frequency domain fraught with danger (a point we will return to later). These models also assume that all orders between echelons are fully met, i.e. there are no stockouts. Also, there are no capacity constraints. The main limitation of these models emanates from the inherent lack of influence each echelon possesses over the next higher echelon. For example, since all orders placed upon the factory echelon are assumed to be satisfied (after some exponential delay), the internal factory dynamics have no bearing on the system behaviour (see [60]).

However, these models can make a contribution when used in conjunction with other techniques to evaluate the performance of supply chains. Simulation models are used in the paper [43] to illustrate the consequences of re-engineering the supply chain interfaces in a fictitious company. Similar methods are used in [35] as part of an holistic approach to the design of a steel industry supply chain. In the paper [24] Del Vecchio and Towill use expert systems to parameterize a Forrester-type model.

The most important results to come from the work of Towill have been in the investigation of demand amplification. In a series of similar papers (see [63], [57], [58], [12]), the same models are used to highlight the causes of demand amplification and suggest remedies to suppress this phenomenon. The simulation model was used to quantify these improvement by looking at the step response of the system. In [63] and [57] they present a methodology which categorises supply chains on the level of integration between echelons. The following strategies to smooth supply chain dynamics where used in the definition of each category:

- Fine-tuning existing echelon decision rules.
- Reducing system time delays.
- Removing the distributor from the supply chain (originally suggested by Forrester).
- Improving individual echelon design by using 'pipeline' information (exploiting any additional system states).
- Integrating the information flow through the system and dividing orders into true demand and cover orders, used to replenish inventories.
- Creating an inventory of semi-finished goods to replace the more expensive inventories of final products.
- Squeezing low value-added activities.

In all these papers, despite the use of control-theoretic language, the models have been used for simulation purposes only. In contrast, in [60] Towill and Del Vecchio regard the supply chain as a series of amplifiers which are thus amenable to classical frequency domain techniques. An attempt at the application of some heuristic design criteria is made and each individual echelon is tuned in isolation. What this amounts to is the adjustment of the exponential time delays in each echelon. However, when only a subset of the state space is available, the use of frequency domain techniques which relate to the whole state space is of questionable validity.

In [31] Evans and Naim add capacity constraints to these models and simulate the results. As they concede, the authority of their results, which are based on linear techniques must be qualified when applied to these nonlinear systems.

In conclusion, as simulation models, Forrester-type systems have had some influence on supply chain thinking. However, the issue of parameter sensitivity, still applicable to these models, has not been resolved. To our knowledge, no sensitivity analysis has been carried out on these models. An additional failing of this approach is that it provides no opportunity for cost-based analysis, being solely concerned with the dynamics. Lastly, given the limited analytical utility of these models, and their resulting classification as simulation models, the many sophisticated discrete event simulation packages available today may provide a more accurate simulation capability.

We now turn to some other approaches, still using continuous differential equation models. Axsater [5] has produced a detailed review of how control theory has been used in this area.

Porter and Taylor [47] dealt with the set of equations:

$$\begin{aligned}\frac{di}{dt} &= p_a(t) - d(t)\\ \frac{dp_a}{dt} &= \alpha\left(p_d(t) - p_a(t)\right),\end{aligned}$$

where $p_d(t)$ is the desired production rate, $p_a(t)$ is the actual production rate, $d(t)$ is the demand and $i(t)$ is the inventory level. By specifying a constant desired inventory level, these equations can be rearranged and the control inputs chosen to be the desired production rate and its derivative. Simple state feedback techniques are then developed to stabilise the system. Bradshaw and Porter [13] use similar modal control techniques in a slightly more complex environment in which advertising affects demand. This framework fails to take into account the costs of such control strategies. To do this we need to use the theory of optimal control.

The optimal control of such systems is tackled in the papers ([11], [1], [46]) and the book [9]. Using standard optimal control theory over finite time intervals the various costs can be accounted for in the production strategy. A particular innovation by Bensousan and Proth [11] is to take into account capacity constraints. The conditions imposed on the costs structures to ensure the existence of a solution can sometimes be unrealistic. For instance in [46] the production cost function must be twice continuously differentiable, which may not be the case in reality as these costs tend to jump up with the number of production runs, not the number of goods produced. Similarly for holding and backlogging costs. However, these are minor objections compared to the glaring absence of time delays in all these models.

In reality demand is stochastic in nature. Yet the added complexity of stochastic systems may obscure our view of the essential dynamics and hamper the derivation of simple control strategies.

Schneeweiss [51] uses the Weiner-Hopf technique to find a simple control strategy in the presence of stochastic demand. In [10] Bensoussan et al use partial differential equations to model the inventory levels of perishable products. In his book [9] he studies the application of linear quadratic cost stochastic control theory (again ignoring time delays). It could be observed that since the linear optimal control problem incorporating time delays has not been adequately tackled in this field, it is rather premature to jump to stochastic systems.

3.2 Discrete Time Difference Equation Models

These are a close relation of the continuous time differential equation models just examined. Indeed the specific equations used to describe the system sometimes have a continuous time provenance. Hence these methods carry many of the same advantages; for instance, the dynamics involved are clearly revealed and there exists a mature body of applicable theoretical research. Similarly, some of the same limitations apply: The inability to deal with batch and sequencing problems; the difficulty of incorporating transportation costs in the model. Typically a degree of aggregation must again be possible. The progression of individual entities through the system should be deemed less important than the overall flow rate and instantaneous inventory levels.

These observations beg the question: Why use discrete time analysis at all if it is so similar to continuous time methodologies? The answer lies in the hybrid character of these models. Since the dynamics of any supply chain are fundamentally discrete, these models immediately have an innate advantage over continuous time models. They enable the invocation of classical control theory within a discrete framework, which facilitates the inclusion of pure time delays. Hence they blend two of the most important respective properties of continuous time and discrete event models.

By discretizing the continuous time systems found in [47], Porter and Bradshaw [48] again use simple state feedback design to generate piecewise constant controllers in production-inventory systems. Bradshaw and Daintith [14] use similar techniques on larger cascaded systems which are more recognisable as supply chains. One of the disadvantages of these methods is that the control can become unbounded. Constraints on the magnitude of the control signal, which can be interpreted as capacity constraints, are included in [15]. Discrete exponential smoothing is used in [17], along with signal flow graphs, to represent the system. Elementary Z-transform techniques are then used to investigate demand amplification. Similar conclusions to those in the papers by Towill are reached. In his book [28] Elmaghraby analyses simple discrete systems with stochastic demand using Z-transform methods.

The preceding methods all concentrate solely on the dynamics and fail to take the costs of control strategies into account. To do this one turns to optimal control theory. It is theoretically possible to solve the resulting equations using dynamic programming techniques. Yet the curse of dimensionality implies that large problems result in onerous computational burden and so classical Lagrangian techniques have prevailed.

In an often-cited paper by Tzafestas and Kapsiotis, [62] the following inventory balance equations are used to describe chains of suppliers:

$$\begin{aligned} x_1(k+1) &= x_1(k) + u_1(k-\theta_1) - d(k) \\ x_2(k+1) &= x_2(k) + u_2(k-\theta_1) - u_1(k) \\ x_3(k+1) &= x_3(k) + u_3(k-\theta_3) - u_2(k) \\ &\vdots \end{aligned}$$

where $d(k)$ is the demand at time k, $x_i(k+1)$ is the inventory level at echelon i at time $k+1$, and $u_i(k-\theta_i)$ is the order plan of the *ith* level, delayed by an amount θ_i. They assume quadratic inventory and order costs, again both unrealistic suppositions used to simplify the mathematical problem. The optimisation is carried out using classical Lagrangian techniques. Three scenarios are investigated:

1. The manufacturer optimises his own operations and imposes the resulting strategy on the other echelons.
2. The total operational cost of the system is optimised assuming complete co-operation between echelons.
3. Each level optimises locally using individual cost functions in a decentralised manner to produce to produce possibly conflicting strategies.

Each scenario corresponds to a different balance of power in the supply chain network. Singh et al [53] review the existing optimisation techniques with reference to large interconnecting systems. Tamura [56] and Drew [25] concentrate on systems with distributed delays.

3.3 Discrete Event Simulation Systems

Discrete event dynamic systems (DEDS) comprise jobs and resources. Jobs, which, for the majority of applications, are physical entities, travel from resource to resource where their onward progress through the system is determined. For example, in a model of a supply chain, the jobs are raw materials which progress through machines and buffer inventories (both resources) where their attributes are changed and they arrive at the retailer as finished goods.

The emergence of DEDS was engendered by the deficiencies of differential equation approaches to the solution of even simple man made problems. Consider, as an example, the differential equations governing the behaviour of a series of queues at a supermarket. The modelling of phenomena such as queue swapping (when customers jump to shorter queues) and variable service speed (faster when there are more customers) would make these equations incomprehensible. The application of any theoretical tools would then be virtually impossible. Such rules can easily be incorporated into a DEDS model. Further, stochastic factors prove no problem for these models. In fact, the structure of DEDS is congenitally suited to the application Monte Carlo simulation analysis, which can provide definitive answers to many modelling questions. The defining attribute of these models is their ability to capture the discrete nature of events-based processes, whilst retaining a continuous time framework.

A barrier to the wider acceptance of DEDS is the absence of a succinct descriptive language for their formulation. This is a direct result of the lack of a commonly accepted theoretical framework analogous to the rigorous basis provided by calculus. It has mitigated against the wider application of these models and tended to discourage attempts at all but the most rudimentary analytical efforts. Consequently DEDS have been primarily associated with simulation and 'black box' approaches.

However, there have been many attempts at developing a general DEDS paradigm, not least the following:

- Markov chain/Automaton models (eg Petri nets).
- Min-max algebraic models.
- Queuing models.
- Generalised semi-Markov process models.

Markov chain models aim to enumerate the state of the system at discrete times. They tend to be computationally burdensome for real systems. Simple queuing models are very similar to Markov chains. Generalised semi-Markov processes are an attempt to formalise the description of DEDS by defining state trajectories analogous with continuous systems. Algebraic approaches are only applicable to deterministic systems which are not of much use in modelling supply chains. More detail on DEDS theory can be found in [36] and [18].

Most of the relevant DEDS papers are couched in the language of job shop scheduling and inventory management problems [50], [20]. In fact, the same structures arise when modelling supply chains. From a modelling perspective the mathematical similarity of the problems implies that, with a little work, their results can be interpreted to be applicable to supply chain models. In [3] Amin and Altiok use the discrete event language SIMAN to model a multi-product, multi-stage manufacturing system. This can be thought of as a supply chain in microcosm. They investigate policies for job allocation, the supply chain equivalence of which would be the order rates between echelons In an archetypal DEDS simulation paper Southall et al [54] model pull-type supply chains. They heuristically investigate how various system parameters affect system performance. In common with all the cited papers, no rigorous stability or sensitivity analysis is carried out.

3.4 Operational Research Techniques

OR theory comprises a disparate collection mathematical techniques, such as linear programming, queuing theory, Markov chains and dynamic programming. The common theme running through all these tools is their suitability for the solution of man-made problems. Although not strictly modelling techniques, their consideration here is warranted by virtue of their widespread use in industry.

The utility of OR techniques in the solution of batch sizing and job sequencing problems is illustrated in [19]. Here heuristic methods to perform constrained optimisation on a cost function determine optimal strategies. A similar approach is taken by Ishii et al [39] to construct a static model based on inventory levels and lead times. Using simple algebraic methods they determine desirable base stock levels in the presence of changing demand characteristics. Both these papers tackle archetypal OR trade-off problems. In the latter case they are finding a balance between inventory and stock-out costs. One drawback of such methods is their computational burden. Another is the reliance on the estimation of the many parameters and costs comprising the model. Because there is no simulation, usually a more detailed cost structure needs to be known. Sometimes this results in the need to estimate certain factitious dynamic parameters. For instance in [39] one needs to decide upon two linearly varying demand rates to carry out the computation.

In [2] Altiok and Ranjan use Markov chains to approximate the steady state of a production-inventory system. These models are validated by discrete event simulations and a rudimentary analysis is carried out using confidence intervals. Similar methods are used in [23] to investigate the influence of certain system parameters on the model. Pyke and Cohen [49] also use a Markov chain framework and an optimisation algorithm to reconcile the competing desires for large batch sizes and smooth production at the manufacturing stage and small batch sizes at the distribution echelon.

Cost based models are developed in [21] and mathematical programming techniques used to optimise the after tax profits of a production-distribution network. Williams [64] and [65] develops a tree-like representation of a supply chain and uses dynamic programming to calculate optimal inventory levels and batch sizes. In common with most OR techniques, these methods fail to illuminate the dynamics of the system. Consequently there is no theoretical basis for a rigorous and systematic sensitivity analysis.

A series of papers [44], [45], [8] quantify certain trade-offs in inventory systems. By treating lead time as a decision variable, they balance the increased costs of reducing lead times (called crashing costs) against the concomitant decrease in inventory costs, whilst maintaining customer service levels.

4 Conclusions

We have demonstrated the utility of OR techniques through a brief examination of the literature. But do their merits justify their predominance over the other methods reviewed here? The first observation to make is that different methods are suited to different problems. No single technique is likely to prove a panacea in this field.

OR tools have their place at a tactical level in the design of supply chains. They constitute the only analytical approach examined here able to solve batch sizing and job sequencing problems. Yet they fail to throw much light on the dynamic behaviour of the supply chain as a whole. Qualitative phenomena like demand amplification can only be investigated and hence combated by methods based on the dynamics of the system. Further, the implications of strategic design on supply chain performance can only be discovered by using broadbrush simulations based on the dynamics of the system.

The OR optimisation techniques examined provide no insight into how system parameters affect the solution, in contrast to the classical Lagrangian methods referred to earlier. Although it must be conceded that little actual sensitivity analysis has been carried out with any of these methods. In fact, the plausibility of using any optimisation technique in the real world must be questioned since the occurrence of unforeseen disturbances (like machine breakdowns and sick workers) and changing parameter values would render these models ineffectual and of limited utility. Further, the blind acceptance and implementation of their conclusions on a day-to-day basis by managers seems unlikely.

We conclude that, while OR techniques are useful in providing solutions to local tactical problems, the impact of these solutions on the global behaviour of the whole supply chain can only be assessed used dynamic simulation.

5 References

References

[1] Abad, P.L., Two -level algorithm for decentralized control of a serially connected dynamic system, *Int. J. Systems Sci.*, **16**, 5, 619-624, 1985.

[2] Altiok, T., Raghav, R., Multi-stage, pull-type production/inventory systems, *IEE Trans.*, **27**, 190-200, 1995.

[3] Amin, M., Altiok, T., Control policies for multi-product-multi-stage manufaturing systems: an experimental approach, *Int. J. Prod. Res.*, **35**, 1, 201-223, 1997.

[4] Ansoff, H.I., Slevin, D.P., Comments on Professor Forrester's industrial dynamics-after the first decade, *Man. Sci.*, **14**, 9, 600, 1968.

[5] Axsäter, S., Control theory concepts in production and inventory control, *Int. J. Systems Sci.*, **16**, 2, 161-169, 1985.

[6] Beamon, B.M., Supply chain design and analysis: models and methods, *Int. J. Prod. Econ.*, **55**, 281-294, 1998.

[7] Becker, T., Keegan, K., Fourth-wave computer technology will alter supply chain management, *PRTM's Insight*, summer 1998.

[8] Ben-daya, M., Raouf, A., Inventory models involving lead time as a decision variable, *J. Op. Res. Soc.*, **45**, 5, 579-582, 1994.

[9] Bensoussan, A., Hurst, E.G. Näslund, B., Management applications of modern control theory, North-Holland, Oxford, 1974.

[10] Bensoussan, A., Nissen, G., Tapiero, C.S., Optimal inventory and product quality control with deterministic and stochastic deterioration-an application of distributed parameters control systems, *IEEE Trans. Aut. Con.*, 407-412, June 1975.

[11] Bensoussan, A., Proth, J.M., Inventory planning in a deterministic enviroment continuous time model with concave costs, Euro. Inst. Adv. Studies in Man., working paper, April 1982.

[12] Berry, D., Naim, M.M., Towill, D.R., Business process re-engineering an electronic products supply chain, *IEE Proc. Sci Meas. Tech.*, **142**, 5, 395-403, 1995.

[13] Bradshaw, A., Porter, B., Synthesis of control policies for production-inventory tracking system, *Int. J. Systems Sci.*, **6**, 3, 225-232, 1975.

[14] Bradshaw, A., Daintith, D., Synthesis of control policies for cascaded production-inventory systems, *Int. J. Systems Sci.*, **7**, 9, 1053-1070, 1976.

[15] Bradshaw, A., Erol, Y., Control policies for production-inventory systems with bounded input, *Int. J. Systems Sci.,* **11**, 8, 947-959, 1980.

[16] Burbidge, J.L., Automative production control with a simulation capability, Paper presented at IFIP conference, Copenhagen, 1984.

[17] Burns, J.F., Sivazlian, B.D., Dynamic analysis of multi-echelon supply systems, *Comput. & Ind. Engng.*, **2**, 181-193, 1978.

[18] Cao, X.R., A comparison of the dynamics of continuous and discrete event systems, *in* Discrete event dynamic systems, analysing complexity and performance in the modern world, *ed.* Ho, Y.C., IEEE Press, New York, 1992.

[19] Chandra, P., Adynamic distribution model with warehouse and customer replenishment requirements, *J. Op. Res. Soc.*, **44**, 7, 681-692, 1993.

[20] Chung, K.J., Tsai, S.F., An algorithm to determine the EOQ for deteriorating items with shortage and a linear trend in demand, *Int. J. Prod. Econ.*, **51**, 215-221, 1997.

[21] Cohen, M.A., Lee, H.L., Resource deplorment analysis of global manufacturing and distribution networks, *J. Mfg. Op. Mgt.*, **2**, 81-104, 1989.

[22] Cook, R.L., Rogowski, R.A., Applying JIT principles to continuous process manufacturing supply chains, *Prod. Inv. Man. J.*, 12-17, first quarter 1996.

[23] Deleersnyder, J.L., Hodgson, T.M., Muller, H., O'grady, Kanban controlled pull systems: an algebraic approach, P., *Man. Sci.*, **35**, 9, 1079-1091, Sept 1989.

[24] Del Vecchio, A., Towill, D.R., The use of expert systems in the design of multi-echelon production distribution systems, *Int. J. Adv. Manuf. Tech.*, **3**, 3, 141-158, 1988.

[25] Drew, S.A.W., The application of hierachical control methods to a managerial problem, *Int. J. Systems Sci.*, **6**, 4, 371-395, 1975.

[26] Edghill, J.S., The application of aggregate industrial dynamic techniques to manufacturing systems, PhD thesis, University of Wales college of Cardiff, 1990.

[27] Ehrhardt, R., Finished goods management for JIT production: new models for analysis, *Int. J. Comp. Int. Manuf.*, **11**, 3, 217-225, 1998.

[28] Elmaghraby, S.E., The design of production systems, Reinhold, New York, 1966.

[29] Evans, G., Towill, D.R., Naim, M.M., Data Flow, *Manuf. Eng.,* 122-125, June 1994.

[30] Evans, G., Towill, D.R., Naim, M.M., Business process re-engineering the supply chain, *Prod. Plan. & Control,* **6**, 3, 227-237, 1995.

[31] Evans, G., Naim, M.M., The dynamics of capacity constrained supply chains, *Production and Operations Management*, 28-35, 1994.

[32] Forrester, J.W., Industrial dynamics, MIT press, Cambridge Mass., 1961.

[33] Forrester, J.W., World Dynamics, MIT press, Cambridge Mass., 1973.

[34] Gong, L., Kok, T.D., Ding, J., Optimal leadtimes planning in a serial production system, *Man. Sci.*, **40**, 5, 629-632.

[35] Hafeez, K., Griffiths, M., Griffiths, J., Naim, M.M., Systems design of two-echelon steel industry supply chain, *Int. J. Prod. Econ.*, **45**, 121-130, 1996.

[36] Ho, Y.C., Cao, X,R, Perturbation analysis of discrete event dynamic systems, Kluwer Academic Publishers, Boston, 1991.

[37] Horscroft, P., Braithwaite, A., Enhancing supply chain efficiency-the strategic lead time approach, *Int. J. Log. Man.*, **1**, 2, 47-52, 1990.

[38] Houlihan, J.B., International supply chain management, *Int. J. Pys. Dist. Mat. Man.*, **17**, 2, 51-66, 1987.

[39] Ishii, K., Takahashi, K., Muramatsu, R., Integrated production, inventory and distribution systems, *Int. J. Prod. Res.*, **26**, 3, 473-482, 1988.

[40] Jones, T.C., Riley, D.W., Using inventory for competitive advantage through supply chain management, *Int. J. Pys. Dist. Mat. Man.*, **15**, 8, 16-26, 1985.

[41] Kim, G.C., Takeda, E., The JIT Philosophy is the culture in Japan, *Prod. & Inv. Man. J.*, 47-51, first quarter 1996.

[42] Lee, H.L., Billington, C., Managing the supply chain inventory: pitfalls and opportunities, *Sloan Man. Rev.* 65-73, spring 1992.

[43] Lewis, J.C., Naim, M.M., Towill, D.R., Re-engineering the supply chain interface-an integrated approach, *2nd Int. Conf. on Logistics*, Nottingham, 329-335, 1995.

[44] Liao, C.J., Shyu, C.H., Stochastic inventory model with controllable lead time, *Int. J. Systems Sci.*, **22**, 11, 2347-2354, 1991.

[45] Liao, C.J., Shyu, C.H., An analytical determination of lead time with normal demand, *Int. J. Op. & Prod. Man.*, **11**, 9, 72-78, 1991.

[46] Lieber, Z., An extension to Modigliani and Hohn's planning horizons results, *Man. Sci.*, **20**, 3, 319-330, 1973.

[47] Porter, B., Taylor, F., Modal control of production-inventory systems, *Int. J. Systems Sci.*, **3**, 3, 325-331, 1972.

[48] Porter, B., Bradshaw, A., Modal control of production-inventory systems using piecewise-constant control policies, *Int. J. Systems Sci.*, **5**, 8, 733-742, 1974.

[49] Pyke, D.F., Cohen, M.A., Performance charcteristics of stochastic integrated production-distribution systems, *Euro. J. Op. Res.*, **68**, 23-48, 1993.

[50] Raman, N., Input control in job shops, *IEE Trans.* **27**, 201-209, 1995.

[51] Schneeweiss, C.A., Smoothing production by inventory-an application of the Weiner filtering theory, *Man. Sci.*, **17**, 7, 472-483, 1971.

[52] Simon, H.A., On the application of servomechanism theory in the study of production control, *Econometrica*, **20**, 247-268, 1952.

[53] Singh, M.G., Drew, S.A.W., Coales, J.F., Comparisons of practical hierachical control methods for interconnecting dynamical systems, *Automatica*, **11**, 331-350, 1975.

[54] Southall, J.T., Mirbagheri, S., Wyatt, M.D., Investigation using simulation models into manufacturing/distribution chain relationships, *BPICS Control*, 29-34, april/may 1988.

[55] Stevens, G.C., Integrating the supply chain, *Int. J. Pys. Dist. Mat. Man.*, **19**, 8, 3-8, 1989.

[56] Tamura, H., Decentralized optimization for distributed-lag models of discrete systems, *Automatica*, **11**, 593-602, 1975.

[57] Towill, D.R., Supply chain dynamics, *Int. J. Comp. Int. Manuf.*, **4**,4, 197-208, 1991.

[58] Towill, D.R., Supply chain dynamics-the change engineering challenge of the mid 1990s, *Proc. Instn. Mech. Engrs.*, **206**, 233-245, 1992.

[59] Towill, D.R., Industrial dynamics modelling-not so much a subject, more a way of life, *Meas. + Control,* **27**, 226-231, 1994.

[60] Towill, D.R., Del Vecchio, A., The application of filter theory to the study of supply chain dynamics, *Prod. Plan. & Control*, **5**, 1, 82-96, 1994.

[61] Towill, D.R., System dynamics-background, methodology, and applications, *Comp. & Con. Eng. J.*, 261-268, Dec 1993.

[62] Tzafestas, S., Kapsiotis, G., Co-ordinated control of manufacturing/supply chains using multi-level techniques, *Comp. Int. Manuf. Systems*, **7**, 3, 206-212, 1994.

[63] Wikner, J, Towill, D.R., Naim, M.M., Smoothing supply chain dynamics, *Int. J. Prod. Econ.*, **22**, 231-248, 1991.

[64] Williams, J.F., A hybrid algorithm for simultaneous scheduling of production and distribution in multi-echelon structures, *Man. Sci.,* **29**, 1,77-92, 1983.

[65] Williams, J.F., Heuristic techniques for simultaneous scheduling of production and distribution in multi-echelon structures: theory and empirical comparisons, *Man. Sci.,* **27**, 3, 336-352, 1981.