Supply Chain Optimization under Uncertainty

Supply chain design for optimum performance

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Foreword

This work discusses the planning and optimisation of the infrastructural configuration, i.e. the design, as well as the optimisation of operational performance of supply chains that are subject to conditions of **operational uncertainty**, i.e. fuzziness (<, ≤, >, ≥) and stochastic uncertainty that typically exist in a supply chain operational environment. The 'planning' aspect refers to an occasional need to accommodate multiple performance objectives in the assessment and management of supply chains, and this aspect is more commonly referred to as 'multi-objectivity, which means the existence of multiple maxima, multiple minima or a combination of both maxima and minima objectives in a supply chain environment.

This is an extension of prior thought on the subject where, previously, only one or two conditions of operational uncertainty were considered in a supply chain environment, and sometimes also the planning requirement, i.e. multi-objectivity, was involved. The discussions in this study then effectively represent an extension of previous thought on the subject in that by considering not only relevant cases of operational uncertainty, i.e. fuzziness and/or stochastic uncertainty, but also by considering those prevailing planning instances of multi-objectivity (i.e. maxima or minima or a combination of both maxima and minima) in a supply chain operational environment. Such capability would be tantamount to being able to deliver **'realistic'** and planned supply chain solutions since all prevailing conditions of operational uncertainty would have been accommodated. A typical supply chain is a production and distribution network consisting of multiple production centres, distribution facilities and sales outlets. The objective of this work is to introduce and define a methodology for the optimisation of supply chains under prevailing combinational conditions of uncertainty and planning, which would be tantamount to the means of finding the best operating solution for supply chains, Such methodology is formulated by identifying single (e.g. fuzzy optimisation), dual (e.g. fuzzy-multi-objective optimisation) and ternary (e.g. stochastic-fuzzy-multi-objective optimisation) instances of supply chain under uncertainty and planning techniques from previous research works, analysing them and then extracting the sequence of optimisation steps utilised. Such extracted optimisation techniques are then logically collated, according to established procedure, to create a methodology for the planning and optimisation of supply chains, under conditions of uncertainty.

This method is applied to the planning and optimisation of a NPK fertiliser production and distribution facility, which is subject to fuzzy market demand uncertainty and which also has a multi-objective operational planning requirement, to maximise the production and distribution of an entire range of NPK fertiliser in accordance with market demand, as well as to simultaneously minimise the generation and discharge of hazardous Hydrogen Fluoride (HF) gaseous effluent from the NPK fertiliser Nitrophosphate production unit. There are over 15 different blends of NPK (nitrogen, phosphorous, potassium) fertiliser available, with each blend being suited to a particular agricultural crop-type, e.g. maize, wheat, lucerne etc., and therefore the market demand uncertainty is directly translated into production uncertainty with uncertain raw material allocation in terms of the various sources of N, P and K, i.e. ammonium nitrate (NH_4NO_3), nitrophosphate ($(NH_4)_2SO_4$, $(NH_4)H_2PO_4$, NH_4NO_3, $CaSO_4.2H_2O$), superphosphate (40%$Ca(H_2PO_4)_2$ + 60%$CaSO_4.2H_2O$) and potassium chloride (KCl). Optimum production/distribution results revealed an achievement of 99.3% of maximum possible production and distribution capability, and also in accordance with market demand in conjunction with an effluent discharge, which was 94.1% of the minimum possible.

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Chapter 1

INTRODUCTION

1.1 Purpose

The primary intention of this work is to provide guidelines to the various custodians of supply chain management, be they operational or management in obligation, so that optimal designs as well as optimal performances may be achieved for those operationally ***uncertain*** supply chains that they are responsible for. For the sake of clarity, it must be borne in mind that optimal supply chain design normally implies lowest possible supply chain infrastructure cost whereas optimal supply chain performance normally equates to highest possible supply chain throughput or profitability. A supply chain infrastructure is typically defined as being comprised of an integrated network of permissibly interconnected supply chain units, i.e. production or manufacturing plants with associated inventory management capability, distribution centres or warehouses and retail sales outlets. Moreover, supply chain uncertainty is defined as the relevant combination of fuzzy uncertainty or imprecision, e.g. product demand is in the region of 2,500 t/mth, and/or stochastic, or probabilistic, uncertainty that exists in a supply chain environment whereas supply chain planning refers to the number and type of operational objectives to be achieved.

Therefore, the primary purpose of this work is to: *define and derive a planning, i.e. multi-objective, and optimisation methodology for a supply chain network that is operating under conditions of uncertainty, i.e. fuzzy and stochastic uncertainty, and that can be successfully applied to any Supply Chain Network*

1.2 Key Definitions

Supply Chain Management

Interest in **supply chain management** has steadily increased since the 1980s when firms saw the benefits of collaborative relationships within and beyond their own organisation. Firms are finding that they can no longer compete effectively in isolation of their suppliers or other entities in the supply chain. Interest in the concept of supply chain management has steadily increased since the 1980s when companies saw the benefits of collaborative relationships within and beyond their own organisation. A number of definitions have been proposed concerning the concept of "the supply chain" and its management. The term, supply chain management, does not replace supplier partnerships nor is it a description of the logistics function. Industry groups are now working together to improve the integrative processes of supply chain management and accelerate the benefits available through successful implementation. The competitive importance of linking a firm's supply chain strategy to its overall business strategy and some practical guidelines are offered for successful supply chain management.

Definitions of the term, ‘supply chain’, abound and since a number of definitions of supply chain management have been proposed in the literature and in practice, this work defines the concept of supply chain management and discusses its historical evolution. The term does not replace supplier partnerships, nor is it a description of the logistics function. The competitive importance of linking a firm's supply chain strategy to its overall business strategy and some practical guidelines are offered for successful supply chain management. Various definitions of a supply chain have been offered in the past several years as the concept has gained popularity.

The *APICS Dictionary* describes the supply chain as:

1. The processes from the initial raw materials to the ultimate consumption of the finished product linking across supplier-user companies; and
2. The functions within and without a company that enable the value chain to make products and provide services to the customer.

Another source defines supply chain as, the network of entities through which material flows. Those entities may include suppliers, carriers, manufacturing sites, distribution centres, retailers, and customers. The Supply Chain Council (1997) uses the definition: "The supply chain - a term increasingly used by logistics professionals - encompasses every effort involved in producing and delivering a final product, from the supplier's supplier to the customer's customer. Four basic processes - plan, source, make, deliver - broadly define these efforts, which include managing supply and demand, sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, and delivery to the customer." Occasionally, a supply chain is defined as "all of those activities associated with moving goods from the raw-materials stage through to the end user. This includes sourcing and procurement, production scheduling, order processing, inventory management, transportation, warehousing, and customer service. Importantly, it also embodies the information systems so necessary to monitor all of those activities."

Further to the definition of a supply chain, the concept of supply chain management has also been defined as, “An integrating philosophy to manage the total flow of a distribution channel from supplier to ultimate customer". It has also been stated that integrated supply chain management’ is all about “migrating from the external customer and then managing the processes that are needed to provide that customer with value in a horizontal way". It is believed that it is supply chains, and not firms, that compete and that the strongest competitors will be those that can provide management and leadership to the fully integrated supply chain solution, including external customers as well as prime suppliers, their suppliers, and their suppliers' suppliers".

From these definitions, a summary definition of the supply chain management may be stated as;

All the activities involved in delivering a product from raw material through to the customer including sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, delivery to the customer, and the information systems necessary to monitor all of these activities.

Supply chain management therefore coordinates and integrates all of these activities into a seamless process. It links all of the partners in the chain, including departments within an organisation, and all the external partners, including suppliers, carriers, third-party companies, and information systems providers. Managers in companies across the supply chain take an interest in the success of other companies. They work together to make the whole supply chain competitive. They have the facts about the market, they know a lot about competition, and they coordinate their activities with those of their trading partners. Supply chain management encompasses the processes necessary to create, source, to make, and to deliver demand. It uses technology to gather information on market demands and exchange information between organizations. A key point in supply chain management is that the entire process must be viewed as one system. Any inefficiencies incurred across the supply chain (suppliers, manufacturing plants, warehouses, customers, etc.) must be assessed to determine the true capabilities of the process within the supply chain.

Logistics management

Logistics management is the management of the flow of goods between the point of origin and the point of consumption in order to meet some requirements, for example, of customers or corporations. The resources managed in logistics can include physical items, such as food, materials, animals, equipment and liquids, as well as abstract items, such as time, information, particles, and energy. The logistics of physical items usually involves the integration of information flow, material handling, production, packaging, inventory, transportation, warehousing, and often security. The complexity of logistics can be modeled, analysed, visualised, and optimised by dedicated simulation software. The minimisation of the use of resources is a common motivation in logistics for import and export.

1.3 History of Supply Chains

The history of the supply chain initiative can be traced to early beginnings in the textile industry with the quick response program and later to efficient consumer response in the grocery industry. More recently a variety of companies across many industries have begun looking at the entire supply chain process. This section will discuss those early beginnings of the supply chain, the fundamental rationale for them and some of the more recent success stories.

Quick response, for general merchandise retailers and their suppliers

As a result of intense competition in the textile and apparel industry world-wide, leaders in the US apparel industry formed the Crafted With Pride in the USA Council in 1984 (Kurt Salmon Associates, Inc., 1993). In 1985, Kurt Salmon Associates were commissioned to conduct a supply chain analysis. The results of the study showed the delivery time for the apparel supply chain, from raw material to consumer, was 66 weeks long, 40 weeks of which were spent in warehouses or in transit. The long supply chain resulted in major losses to the industry due to financing the inventory and lack of the right product in the right place at the right time.

The result of this study was the development of the quick response (QR) strategy. QR is a partnership where retailers and suppliers work together to respond more quickly to consumer needs by sharing information. Significant changes as a result of the study were the industry adoption of the UPC code used by the grocery industry and a set of standards for electronic data interchange (EDI) between companies. Retailers began installing point of sale (POS) scanning systems to transfer sales information rapidly to distributors and manufacturers. "QR maximizes the profitability of inventory by placing the company's dollars where and when they are needed based on point of sale data plus sales history" (Mullin, 1994). QR incorporates marketing information on promotion, discounts, and forecasts into the manufacturing and distribution plan.

Efficient consumer response, the grocery business initiative

In 1992, a group of grocery industry leaders created a joint industry task force called the efficient consumer response (ECR) working group. The group was charged with examining the grocery supply chain to identify opportunities to make the supply chain more competitive (Kurt Salmon Associates Inc., 1993). Kurt Salmon Associates were engaged by the group to examine the grocery supplier/ distributor/consumer value-chain and determine what improvements in cost and service could be accomplished through changes in technology and business practices.

The results of the study indicated little change in technology was required to improve performance, other than further development of EDI and POS systems. However, the study identified a set of best practices which, if implemented, could substantially improve overall performance of the supply chain. As Kurt Salmon and Associates (1993) had found: "By expediting the quick and accurate flow of information up the supply chain, ECR enables distributors and suppliers to anticipate future demand far more accurately than the current system allows". Through implementation of best practices they projected an overall reduction in supply chain inventory of 37 per cent, and overall cost reductions in the industry in the range of $24 to $30 billion.

The successful adoption of ECR for a manufacturer depends on their ability to maintain manufacturing flexibility, which would enable them to match supply with demand. Key to this flexibility is a process that tightly integrates demand management, production scheduling, and inventory deployment to allow the company to better utilize information, production resources, and inventory (Weeks and Crawford, 1994).

A further development of ECR was the concept of continuous replenishment (CRP). CRP is a move away from pushing product from inventory holding areas to pulling products onto grocery shelves based on consumer demand (ECR Performance Measures Operating Committee, 1994). Point of purchase transactions are forwarded by computer to the manufacturer allowing them to keep the retailer replenished and balanced just-in-time. CRP has been introduced by a number of manufacturers (Garry, 1994). Procter & Gamble and Campbell soup are delivering as much as 30 to 40 per cent of their volume by CRP. Ralston, General Mills and Pillsbury distribute about 10 per cent by CRP. Estimates of improvements in performance with CRP include increasing inventory turns from 10 up to 50, reducing days of supply from 30 to 5 and increasing net margin from 5 per cent to 7 per cent.

1.4 Early supply chain initiatives

Apart from the apparel and grocery industry initiatives, other early manufacturing efforts to improve supply chain performance have been documented. Some of these include: Hewlett-Packard, Whirlpool, Wal-Mart, West Co., Becton Dickinson, Baxter, and Georgia-Pacific Corp. A brief outline of their various supply chain initiatives is described:

Hewlett-Packard

The computer components manufacturer systematically linked its distribution activities with its manufacturing activities in the computer terminal business in the early 1990s (Hammell and Kopczak, 1993). The implementation included changes in both the physical distribution of the product, and a new distribution requirements planning (DRP) system. The DRP system nets customer orders with forecasts and serves as the beginning pull in the supply chain.

Whirlpool

This appliance manufacturer commenced its supply chain performance improvement initiatives with a team of executives in 1992 chartering the vision - "Winning companies in the future will be those that come closest to achieving an inter-enterprise pull system. They will be linked in a short cycle response mode to the customer" (Davis, 1995). Whirlpool had created a new vice-president of logistics position who had established cross-functional teams for key product areas that had entered into single source agreements with certain suppliers. Such agreements were built around product reliability and were therefore utilised in product design. EDI (Electronic Data Interchange) was utilised to communicate with suppliers on a regular basis, and which was integral to the supply chain management program. As a result of all this, product availability was increased to the 90-95 per cent range, inventories levels were reduced by 15 - 20 per cent and product lead times were reduced as well.

Wal-Mart

This company commenced its supply chain initiative by working directly with certain key manufacturers (Johnson and Davis, 1995). The manufacturers were responsible for managing Wal-Mart's warehouse inventory levels and, as a result, Wal-Mart demanded and achieved a near 100 per cent order fulfilment rate on those products. KMart and other large retailers had implemented similar VMI (Vendor Management Inventory) programs.

West Co., Becton Dickinson, and Baxter

Within the medical products industry, three firms engaged in mutual supply chain relationships in the early 1990s (Battagia, 1994). Working together, at all management levels, all three companies had achieved significant improvements in quality and service, whilst, simultaneously, reducing their cycle times and costs.

Georgia-Pacific Corp.

A leader in the manufacturing and distribution of building products in North America, Georgia-Pacific began implementing supply chain management practices within the decentralised operations of their company (Blackwell, 1994). Previously, traffic managers in each division had controlled inbound and outbound shipments for each division. Shipping priorities were fragmented and internal and external customers were not satisfied. A new centralised Transportation and Logistics Division was created to coordinate and streamline the distribution process. The new division looked at needs and priorities across the business units and had realised savings to the company in terms of reduced freight costs and other logistics improvements.

Many other examples of companies successfully implementing their respective supply chain strategies are available (Blaser and Westbrook, 1995; Cook and Rogowski, 1996; Semich, 1994). The high level of interest in this topic clearly indicates that supply chain management had become a key strategic issue amongst a diverse group of companies, which resulted in steps being continually taken to improve customer delivery whilst, simultaneously, reducing overall costs.

1.5 Growth of interest in supply chains in the 20th century

Why had the effective management of supply chains become such a key issue during the 1990s? In part, the answer lies in the fact that very few of these supply chain companies continued to operate as vertically integrated entities. Companies had become far more specialised, which resulted in the search for suppliers who could provide certain quality materials at low cost, rather than them providing them themselves. It had become critical for such companies to manage the entire network of supply, themselves, in order for them to achieve optimum performance. They had realised that whenever a company dealt with another company, as part of the supply chain, both party's stood to benefit from the other party's success.

A second reason for increased supply chain interest partially stemmed from increased national and international competition. Multiple sources had become available from which customer demand could be satisfied and also alternative distribution channels had become available, from which customer accessibility could be maximised, and also at the lowest possible cost. Prior to this, companies had solved the distribution problem through the provision and maintenance of inventory levels at different locations throughout the entire supply chain. However, this had not been very economical since the dynamic nature of the marketplace had necessitated the maintenance of reasonable inventory levels, which was both risky and unprofitable. Further, the changing buying habits of customers taken together with the changing nature of products contribute greatly to this unprofitable situation. Such situation is further aggravated by the fact that changes in market demand contributes significantly to dynamically high inventory levels, which has a negative impact on product cost.

A third reason for the shift in emphasis to the supply chain is on account of the realization by most supply chain companies that by maximizing the performance of one department or function may lead to a less than optimal performance for the company as a whole. The purchasing function may negotiate a lower price on a particular product component, but the cost to produce the finished product, as a whole, may rise on account of consequent inefficiencies in the plant. Companies must look across the entire supply chain to gauge the impact of decisions in any one area.

Advanced Manufacturing Research, a Boston-based consulting firm, developed a supply chain model which emphasised material and information flow between manufacturers and their trading partners (Davis, 1995). They believed that greater awareness was required of the following areas

- Greater sharing of information between vendors and customers.
- Horizontal business processes replacing vertical departmental functions.
- Shift from mass production to customized products.
- Increased reliance on purchased materials and outside processing with a simultaneous reduction in the number of suppliers.
- Greater emphasis on organizational and process flexibility.
- Necessity to coordinate processes across many sites.
- Employee empowerment and the need for rules-based real time decision support systems.
- Competitive pressure to introduce new products more quickly.

Consequently, companies are streamlining all operations and minimising the time-to-customer for all their products. For these reasons, expertly managing the supply chain has become critical for most companies. As the vice president of product supply/customer service at Procter and Gamble put it, "Winning in the marketplace of the 1990s is going to require a far different kind of relationship - one that recognizes that the ultimate winners will be those who understand the interdependence of retailer/manufacturer business systems and who work together to exploit opportunities to deliver superior consumer value" (Drayer, 1994). Managers in companies across the supply chain take an interest in the success of the other companies. They work together to make the whole supply chain competitive. They have the facts about the market, they know a lot about competition, and they coordinate their activities with those of their trading partners. They use technology to gather information on market demands and exchange information between organizations. Critical to managing the supply chain is managing the link between each node within the chain to synchronize the entire supply chain.

1.6 Accelerated growth of interest in supply chains in the 21st century

It had become increasingly evident, especially since the beginning of the 21st century, that much international research effort has been expended on supply chain planning. In this regard the emphasis has been on enhancing the operational configuration and performance of supply chains, so that they may be aligned with both the planning requirements and the prevailing conditions of operational uncertainty. Some examples of previous supply chain, under uncertainty, research works, in this regard, include Grossmann and You (2008), Chen and Lee (2007), Awudu and Zhang (2012), Liu and Papageorgiou (2012), Guillen and Grossmann (2009), Al-Othman et al. (2008), Tsiakis and Papageorgiou (2007), Chen et al. (2007) and Chen and Lee (2004). Other examples of related supply chain under uncertainty research work include Optimisation of Production-Distribution Systems under Uncertainty, Li et al. (2008), Optimisation of Delivery Systems under Uncertainty, Bit al. (1992), and Optimisation of Decentralised Supply Chains, Raj and Lakshminarayanan, (2008).

The term, ‘Uncertainty’ was not applied consistently in all cases. Sometimes it referred to ‘fuzzy uncertainty’ or impreciseness, Carlsson and Fuller (2002), and represented by $<$, $\leq$, $>$, $\geq$ e.g. fuzzy market demand $<$, $\leq$, $>$, $\geq$ 1,500 t/yr and sometimes it referred to ‘stochastic uncertainty', i.e. probability, e.g. market demand follows a Gaussian distribution with population age-group. In these two cases, expressions such as Fuzzy Optimisation, Stochastic Optimisation and Stochastic-Fuzzy Optimisation were coined to describe the procedures involved in determining the best operating solutions under those uncertain operating conditions. To add to the confusion, the planning term, 'Multi-Objectivity was occasionally added to these expressions whenever there was a planning requirement to consider multiple supply chain objectives, be they maxima, minima or a combination of both in nature, in solutions for uncertain supply chain operations, e.g. Multi-Objective-Fuzzy Optimisation, Multi-Objective-Stochastic Optimisation and Multi-Objective-Stochastic-Fuzzy Optimisation.

A supply chain optimisation capability that could cater for any prevailing conditions of operational uncertainty and that could also cater for any desired number of performance objectives would be of great interest to the commercial industrialised world where various combinational instances of operational uncertainty and corresponding planning requirements frequently occur. A good example of this is ammonia, (NH_3), from coal production and also the downstream production of fertiliser and explosives. Operational uncertainty is manifest in many ways. Firstly, with the production of NH_3 from coal, the concentration of hydrogen (H) in coal is probabilistically, or stochastically uncertain, which impacts not only upon ammonia production plant design considerations, but also upon the predictability of downstream product production, i.e. nitric acid (HNO_3) and ammonium nitrate (NH_4NO_3). Secondly, there is a need to maximise the production of NH_3 and downstream fertiliser and explosives products, in accordance with market demand, whilst simultaneously minimising the generation and discharge of hazardous production effluent, i.e. carbon monoxide (CO) and nitrogen dioxide (NO_2), which, taken together, are uncertain multi-objective planning requirements. (Note: this is an example of multi-objectivity where, one objective needs to be maximised while the other needs to be minimised. More frequently, all objectives need to be either maximised or minimised). Thirdly, the market demand for fertiliser product is imprecise, i.e. fuzzy ($<$, $\leq$, $>$, $\geq$) uncertainty. There are many other examples of commercial instances where multiple instances of planning and uncertainty exist, e.g. farming with downstream product beneficiation, the precious metal mining industry etc.

The availability of a planning and optimisation methodology for supply chains operating under any prevailing conditions of uncertainty would therefore be tantamount to being able to deliver ***'realistic'*** and planned supply chain operating solutions since all prevailing conditions of operational uncertainty would be accommodated.

In most business process or operational environments, there is usually a need to plan and function optimally, usually with regard to any number of operational objectives. However, since such operating environments are normally beset by problems of operational uncertainty, i.e. fuzzy uncertainty and stochastic (probabilistic) uncertainty, it is often very difficult to determine the best common operating conditions that will satisfy all process objectives, simultaneously and satisfactorily. Therefore, the opportunity is as follows:

An operational process, i.e. supply chain network, subject to prevailing conditions of operational uncertainty, i.e. fuzzy uncertainty and/or stochastic uncertainty, will undergo a realistically improved optimum performance should the impact of these uncertainty effects be taken into account and accommodated during the process design phase, irrespective of the planned number of operational objectives involved.

1.7 Planning with Uncertain Supply Chains

The primary purpose of this work is to define and derive a planning, i.e. multi-objective, and optimisation methodology for a supply chain network that is operating under conditions of uncertainty, i.e. fuzzy and stochastic (probability) uncertainty, and that may be successfully applied to any Supply Chain Network.

The secondary purpose of this initiative is to apply the derived methodology to a number of different supply chain infrastructural/operational configurations for the purpose of:

a) demonstrating how the methodology would be applied in different supply chain scenarios

b) demonstrating the different types of benefits that can be gained from the implementation of this new technology