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Polymer supply chain management

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Abstract: A typical polymer supply chain network includes multiple plants, large number of storage terminals, customers and consignment locations, and complex distribution requirements. Here, we describe the complexity of polymer supply chain from 'logical positivist/empiricist' viewpoint based on in-depth interviews with supply chain managers of four major polymer manufacturers and on our experience in the industry. We begin by defining marketplace and competitive environment in which polymer manufacturers do business. Then, we enumerate the requirements for manufacturing, distribution, supply chain planning and control. Next, we describe the information and decision support systems typically utilised by polymer manufacturers and present a mixed-integer network optimisation model used for decision support in Appendix A. Our objective is to allow researchers to design better studies of supply chain by providing insights into the challenges of supply chain professionals in polymers industry, and allow supply chain managers to apply more effectively in the real world the knowledge gained from research studies.

Keywords: chemicals supply chain; polymers supply chain; structured interviews; supply chain management.

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1 Introduction

Effective supply chain management is the final frontier for increasing a company's competitiveness in the global economy. The complex strategic, tactical, and operational decisions that are involved, which range from network design to production sourcing and from production planning and inventory management to scheduling, often require an in-depth understanding of industry-specific issues. This is especially true of polymer supply chain management, as we have discovered on the basis of interviews with senior supply chain managers of four major polymer companies and in our own experience. In this paper, our aims are to provide insights into the principal issues of concern to such managers through a descriptive (logical positivist/empiricist) approach that reports "people's perceptions of object reality" Meredith et al. (1989), to provide a valid context in which to study various aspects of supply chain management, and to formulate and discuss a mixed-integer network optimisation model for polymer distribution (see Appendix A).

2 Background

The supply chain literature is rich with studies of the management of complex global supply chains (Lee and Billington, 1995; Fisher, 1997; Lee, Padmanabhan and Whang, 1997; Ayers, 2000; Brewer and Speh, 2000; Lee, 2000; Frolich and Westbrook, 2001; Lee and Amaral, 2002; Meixell and Gargeya, 2005; Christopher, Peck and Towill, 2006). Some of the important managerial decisions to be made in the supply chain management include the following:

- network modelling and design (Arntzen et al., 1995; Beamon, 1999; Min and Eom, 1999; Karabakal, Gunal and Ritchie, 2000; Vidal and Goetschalkx, 2000; Nozick and Turnquist, 2001; Min and Zhou, 2002; Blackhurst, Wu and O'Grady, 2005; Kallrath, 2005; Stingel and Componation, 2006)
- production/distribution planning (Robinson and Satterfield, 1998; Ross and Venkaramanan, 1998; Wei and Krajewski, 2000; Gavirneni, 2001; Jayaraman and Pirkul, 2001; Krajewski and Wei, 2001; Young and Sook, 2002; Yilmaz and Catay, 2006)
- effect of demand/supply uncertainty (Metters, 1997; Chen et al., 2000; Park, 2005; Ray, Shanling and Yuyue, 2005; Hua, Li and Liang, 2006)
- information sharing and inventory management (Lee and Billington, 1992; Ganeshan, 1999; Cachron and Fisher, 2000; Lee, Kut and Tang, 2000; Lin et al., 2000; Viswanathan and Piplani, 2001; Sahin and Robinson, 2002; Fiala, 2005; Sahin and Robinson, 2005; Abuhilal, Rabadi and Sousa-Poza, 2006; Chu and Lee, 2006)
- supplier relations (Anupindi and Bassok, 1999; Tsay, Nahmias and Agrawal, 1999; Donohue, 2000; Spina and Zotteri, 2000; Golicic, Foggin and Mentzer, 2003; Joshi and Campbell, 2003; Lemke, Goffin and Szwejczewski, 2003; Kwon and Suh, 2004; Rinehart et al., 2004)
- supply chain performance management (Beamon, 1999; Tan et al., 1999; Ramdas and Spekman, 2000; Ganeshan, Boone and Stenger, 2001; Craig and Hannes, 2006; Sengupta, Heiser and Cook, 2006).

Various company-specific and empirical studies have also been published whose findings clearly provide valuable insights into the principles of supply chain management. However, the effective application of these cumulative insights and further research in a particular industry necessitate the in-depth understanding of the specifics of its supply chain. The specifics of supply chains in many industries remain unknown to most academicians as well as to practitioners, who do not always have the opportunity to appreciate the full scope of the supply chain.

By describing and characterising a chemical supply chain, we aim to identify the specific issues of most concern to researchers and to supply chain professionals. This in turn should allow researchers to design better studies of the supply chain and allow supply chain managers to apply more effectively in the real world the knowledge gained from research studies. To this end, we will treat specifically of the supply chain for manufacturers of polymers. Polymers, which are principally used to make plastic goods, constitute about 80% of the chemical industry's production output. In fact, polymers are the most widely used material per unit volume, being used more than steel, copper, and aluminium combined. Polymers are used by industry (e.g. in manufacturing film and in manufacturing aerospace, automotive, and electronic equipment) and by the general public (e.g. in the milk and shampoo bottles).

To frame our discussion of the polymer supply chain and its scale and complexity, we have relied on our own structured interviews of senior supply chain managers of four major polymer manufacturers and on our experience in the industry. This descriptive approach, which falls into the ‘logical positivist/empiricist’ category on the rational/existential level, and reports ‘people’s perceptions of object reality’ on the natural/artificial level Meredith et al. (1989) represents a move toward a more naturalistic and existential (interpretive) research paradigm of operations management (Meredith et al., 1989; Wacker, 1998) that complements more rational, analytical/statistical research methodologies by defining and validating the environments in which they are applied.

In doing so, we will begin by defining the marketplace and competitive environment in which polymer manufacturers do business. Then, we will enumerate the requirements for manufacturing, distribution, and supply chain planning and control. Next, we will describe the information and decision support systems that are typically utilised by polymer manufacturers and present a mixed-integer network optimisation model used for decision support. Finally, we will summarise the issues that affect the effective management of the polymer supply chain and draw our conclusions.

3 Market characteristics and competitive priorities

Most polymer manufacturers are global companies located in North America, Western Europe, and Asia. The main driving forces behind such globalisation are the proximity to global markets and the need to increase profitability, which is generally hurt by increased feedstock prices (which are inextricably linked to the prices of crude oil and natural gas), by reducing production costs. In recent years, these two main factors have led to mergers and consolidation within the industry and the emergence of large, global manufacturers that are typically owned by large, vertically integrated petroleum companies. As a result, about 80% of polymer output is now supplied by a handful of companies that are even now bringing new production facilities online in places such as the Middle East and Asia. The major cost factors are raw materials, energy, labour, operating costs, and transportation.

Given the size and strength of each of these global companies, the market for polymers is extremely competitive. Product is considered a commodity, and the technical quality of the product is considered a market qualifier. The principal order winner is price. Less important but still influential order winners are product variety, quick or early introduction of better technology (products with improved chemical properties), and product availability. Typically, polymers are made-to-stock and delivery is expected to be instantaneous. On the other hand, customers of the large, global polymer manufacturers tend to stay with the same supplier because of the high cost of switching suppliers. Instances of a customer switching back and forth between different suppliers are relatively rare, since it may require the customer to change the technology used to process the polymer. However, polymer manufacturers that lose a customer for one sale often end up losing the customer completely. In the light of ongoing industry consolidation, customers’ heightened expectations of quality and the drive towards greater efficiencies, polymer manufacturers are looking for new ways to improve returns on assets, reduce supply chain costs, develop new product grades, and expand into new markets.

4 Polymer manufacturing

Polymer manufacturing is a hybrid of batch and continuous processing. Polymer manufacturing plants are typically very large, capital intensive, costly to operate, and difficult to change. Because profit margins are slim, plants typically operate at full capacity; thus, operational efficiency at the processing level is extremely important. Downtime and transition time can be assigned dollar values per second, and eliminating inefficiencies in order to gain a few more productive days can save millions of dollars. Similarly, the cost of shutting down a chemical plant for a day can easily exceed \$1,000,000, including the cost of lost production, the fixed costs incurred in the mean time, the cost of time to restart, the cost of returning to a steady state of operations, and the cost of off-spec production.

Manufacturers typically produce 10–30 ‘campaigns’ in a cycle. A campaign is basically the production of a family of products in a particular sequence, or a ‘wheel’ that is dictated by transition requirements. A simplified production wheel and a production wheel with sub-wheels are shown in Figures 1 and 2 below.

In the figures, the letters A–N represent products, and the arrows indicate the preferred sequence of production. For example, in the simplified production wheel, the production of product A is followed by the production of product B, then C, then D, then E, and so on, until the wheel returns to A. A typical campaign may result in the production of 5–30 different products. The resulting number of end products typically ranges from 50 to 400. However, as will be discussed later, the number of Stock Keeping Units (SKUs) is much greater because of the various types of packaging that can be used. Product demand may also vary. High demand typically results in the production of at least 1 million pounds per month, and can reach as high as 10–20 million pounds of production per month.

Figure 1 Simplified Production Wheel

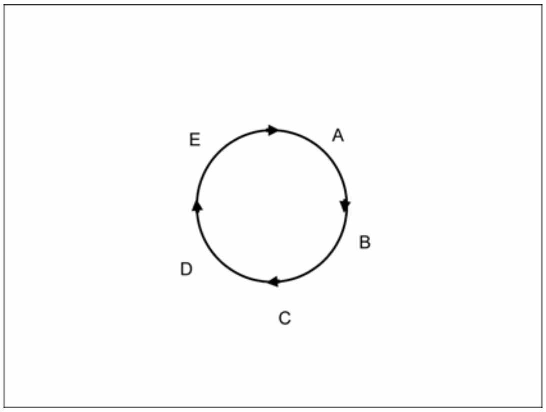
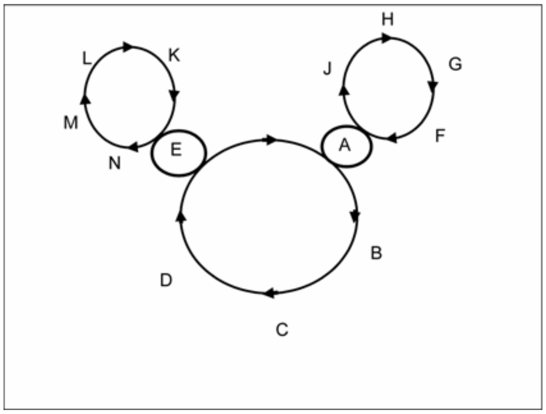


Figure 2 Simplified Production Wheel with Subwheels



In any campaign, the sequence is followed even if some of the products are skipped in between. A typical campaign lasts 20–40 days, depending upon demand. Transitioning from the production of one product to another does not necessarily mean that the production equipment is stopped, but that the output during transition is of lower grade than normal. Lower grade material is sold for 5–10 cents less per pound. So, for a 24-h transition in which 1 million pounds of low-grade product is made, the cost of the transition could be as much as $50,000. Typically, transition costs range anywhere from $5,000 to $100,000. On the other hand, transitioning from one campaign to another takes longer (than transitions within campaigns) and sometimes requires stopping the equipment to perform a physical set-up. Thus, they are costlier in terms of transition time, equipment downtime, and ultimate product price (lower-grade products may be priced up to 15 cents less per pound). To avoid such costly transitions, most polymer manufacturing plants have a line of equipment dedicated to a particular campaign. Changes in production schedules rarely involve changing the production sequences or breaking a campaign in order to start another one; more often, schedule changes involve changing the production quantities of particular products within a campaign.

Raw materials for polymers, often referred to as ‘feedstock’, are by-products of petroleum or natural gas production such as ethylene and propylene. Suppliers typically belong to the same group of companies as the polymer manufacturer does, and suppliers determine the feedstock price. This price can fluctuate and is a very important factor in profitability. Polymer manufacturing plants are typically located near pipelines that supply the raw materials. In general, polymer manufacturers have different plants serving different regions (e.g. the USA, South America, Europe, the Middle East and Africa, and Asia and the Pacific Rim). These plants operate relatively independently and do not receive stock transfers from other plants. Thus, when managers refer to the supply chain, they are referring to the network of plants, distribution centres, and customers within a region rather than the global supply chain.

A typical polymer manufacturer produces in 3–6 plants that are located closer to the necessary raw materials than to the customers. It is possible to find these plants located within the same state and close to each other, but serving USA customers through strategically placed distribution centres. Plants typically have multiple (2–10) lines of equipment dedicated to one or more campaigns. Dedicating a production line to a family is preferred whenever possible, since this can reduce transition requirements, which, as stated above, can be very costly.

5 Logistics and distribution

Polymer customers are typically manufacturers that process the polymer into plastic products (e.g. plastic containers such as milk and shampoo bottles), which are then sold to other manufacturers (e.g. consumer packaged-goods companies), which are in turn filled with a consumer product (e.g. milk or shampoo) and sold to retailers. The final users are thus fourth-tier customers. Other polymer customers produce parts that will be used in electronics or aerospace equipment. Immediate customers of the polymer manufacturers are often squeezed in terms of price margins, which emphasises the importance of price competition. Typically, the number of immediate customers, small and medium, for a polymer manufacturer ranges from 250 to greater than 1,000. It is common for customers to have multiple sites. Thus, it is possible for a polymer manufacturer with 300 customers to have about 900 customer (ship-to) locations. The customers are dispersed throughout the region that is being served.

The structure of the distribution network is primarily a function of the region of the world in which the network exists. In South America and Europe, product is stored in warehouses near the plant that produces it and is available for customer pickup truck shipment in bulk (i.e. in bulk-hopper trucks) or in packages (i.e. in trailers). Middle Eastern manufacturers ship all of their production output in sea containers. Asian manufacturers ship theirs via a combination of trucks and sea containers. In North America, about 90% of shipments are made via bulk railcars. It is the North American distribution network that we will discuss in the remainder of this section.

In North America, the structure of the distribution network is largely dictated by the railroads. Because plants have limited storage capacity, polymers are often stored in railcars that can each hold about 200,000 pounds of polymer. Once loaded, these railcars are moved from the plant to one or more holding yards owned or operated by the railroad. From there, the finished goods are typically shipped to forward distribution points (bulk terminals) and onto leased tracks, which are also usually owned or operated by the railroad. The bulk terminals and leased tracks, which can range in number from 10 to 60, are dispersed throughout the region and serve as forward inventory storage locations. From these distribution points, the polymers are either packaged or shipped to customers in hopper trucks or railcars. The lead-time for shipment from plants to distribution points is 10–14 days; the lead-time for movement from terminals to customers is on average two days. Some bulk shipments (an estimated 10–30%) are made directly from plants to customer locations, typically in cases where the customer is a large consumer of polymers and has its own railcar holding yard. The typical holding yard can handle between 5 and 30 railcars; when a rail car is empty (tapped), the customer informs the polymer manufacturer, who then replenishes it.

The combination of long transit times (14 days) and lengthy production campaigns (30 days) often force polymer manufacturers to hold inventory. About 90% of bulk polymer is shipped and stored in rail cars and hopper trucks. However, as already mentioned, polymer manufacturers do not own bulk terminals but instead lease rail tracks from railroad companies; therefore, transportation costs are directly related to inventory costs. Regardless of whether railcars are owned or leased, the more days' supply of inventory carried, the higher the transportation costs for a given supply chain. The remaining 10% of product is shipped from plant warehouses in pre-packaged boxes (1,100 pounds) and bags (60 pounds). This represents a relatively small percentage of total shipments, and it is not as much a concern as bulk shipments and bulk inventory are.

6 Supply chain planning and control

Given the high cost of holding inventory and the importance of product availability, an important task of the supply chain manager is forecasting. The different modes of packaging and distribution (bulk, box, or bag) and the large number of customer locations create over a 1,000 possible product–location combinations. In addition, the monthly demand volume for polymers varies from 10 to 20%, with random fluctuations. Thus, forecasting demand is a difficult task. By the same token, determining how much safety stock to hold at terminals is also quite a challenge. Calculation of demand forecasts and determining the amount of safety stock to be held at terminals are very important processes that drive the production plan. Production has to be planned so as to utilise as much plant capacity and spend as little transition time as possible. Typically, monthly production/distribution planning is projected out over the next 12–18 months and updated monthly or quarterly. Production output can vary from 50,000 to 100,000 pounds per hour and theoretically can reach 2,400,000 pounds per day. Scheduling is typically performed weekly and includes daily time buckets and a rolling 90-day horizon. Schedule updates may result in up to 30% change in production quantities. Breaking a production wheel is possible but not desirable.

Another important planning task is to identify the preferred distribution network. Such planning occurs on a higher level than does production/distribution planning and is performed less often. Its purpose is to determine whether the preferred distribution network might have to be altered or updated in response to

1. mergers in which more than one existing network needs to be reconciled
2. contract renegotiations with railroad companies
3. company growth that has led to the need to reevaluate the distribution network in response to the addition of new ship-to locations or new products.

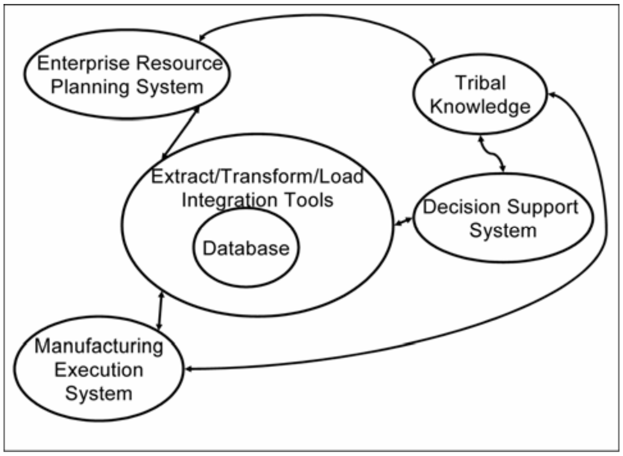
Distribution network planning is performed at least once a year to determine which plants should supply which terminals and which terminals should supply which customers. This information can then be used as a constraint in monthly production/distribution planning to appropriately restrict the distribution to the preferred routes. Reevaluating and changing the distribution network in each planning cycle would typically lead to changes not only in production levels and the product mix in the plants, but also in safety stock requirements at the terminals.

7 Decision support systems and performance tracking

Most polymer manufacturers have an Enterprise Resource Planning (ERP) system in place. Most also utilise Decision Support Systems (DSS) with some degree of sophistication to help improve forecasting and demand management, distribution network planning, production and distribution planning, and scheduling. Figure 3 shows a generic representation of the DSS and its interactions with the ERP and Manufacturing Execution Systems (MES), and the Database via Extract/Transform/Load (ETL) Integration Tools.

The highest level of planning in a typical DSS is distribution network planning. As previously stated, this level of planning is done 'as needed' to evaluate alternatives. It typically utilises information about demand and customers passed on to it from a Demand Management application (discussed in a later section). More sophisticated DSS software utilises mathematical modelling techniques such as mixed-integer programming to optimise the distribution network, i.e. to determine the best set of terminals to use in the network and to determine which of these terminals will supply each customer. For production/distribution planning, different DSS would again use different methodologies; however, the more sophisticated ones typically use mixed-integer programming to optimise the production plan and balance plant efficiency with customer service and inventory levels. For more detailed, near-term decision-making, scheduling methods are used to help minimise transitions, reduce off-spec production, and manage inventory levels. Description of a general mixed-integer model for distribution network optimisation is given below.

Figure 3 Data Interface Schematic



7.1 Distribution network optimisation

A general Mixed-Integer Programming (MIP) model for distribution network optimisation is a high-level strategic decision analysis tool that helps users to design a minimum cost network. The model is formulated for a single time period whose duration is determined by the amount of forecast data that is available for modelling. To avoid misleading results due to seasonal demand, it is recommended that a cumulative forecast for an entire year be made. This forecast drives the model to produce a plan in which products are shipped from plants to customers in the most cost-effective manner, given the constraints of the model.

The primary objective of the MIP is to minimise the costs being modelled. The algebraic formulation for a generic network optimisation model is provided in the

Appendix A. The four basic costs being considered in the model are transportation costs (rail and truck), terminal costs (fixed and variable), railcar leasing costs, and inventory in-transit and cycle stock holding costs. The model itself is restricted by constraints such as trucking service areas restricted by distance, throughput maximums at bulk terminals, and contracted rail volume commitments.

The network optimisation model has the following underlying assumptions:

1. Product sourcing and plant capacity decisions are not made in this model. However, the network may be limited by how much of each product may be sourced from each plant location.
2. Shipments are modelled in terms of continuous volume (e.g. pounds or tons of product) rather than in terms of full railcars or truckloads. Since the model considers an entire year's demand at once, it is reasonable to assume that the volume shipped over an entire year will be broken down into reasonable shipment sizes during the course of that year. Thus, using a per volume cost based on full shipments is a reasonable approximation of the network costs and avoids an extra layer of complexity that would be required to model railcar and truckload shipments.
3. Inventory is not being modelled explicitly. Since there is only one time period, the ability to pre-build inventory to meet future demand is no longer relevant. Some inventory costs, though, are included in the optimisation without actually needing to model inventory directly. The costs related to in-transit inventory and cycle stock inventory are calculated based on the transportation decisions made by the model, so inventory levels do not need to be specific variables in the model. On the other hand, safety stock costs are not easily defined based on the throughput of a given location, because safety stock levels also depend upon factors such as demand variability and customer satisfaction. Although a report can be generated after optimisation in order to provide the user with a location-by-product throughput report, decisions concerning safety stock should typically be made outside the network optimisation model.

The first constraint of the model implies that everything shipped into a location must either be shipped out of the location or go to satisfy demand at the location. The second through fifth constraints enforce the definition of the zero–one variables U and C. These variables allow costs to be applied to each distribution centre that is ‘in-use’ and to account for cycle stock costs for each different material shipped through a distribution centre. The sixth and seventh constraints track the truck throughput volume at distribution centres, so that a variable cost can be applied appropriately. And finally, the eighth constraint allows for the enforcement of contractual rail obligations.

7.2 Production planning

There are many ways to formulate the MIP problem so as to solve a production/distribution planning problem. All such models utilise multiple time periods during which the following decisions have to be made: purchasing, production, capacity, transportation, inventory, and satisfaction of customer demand. Models typically maximise profit, but may be configured to simply minimise costs. The transportation network may be limited to one route that satisfies each demand or expanded to multiple routes from which the optimiser may select the best option. The model may also include minimum run constraints, in which the optimiser selects whether to produce a product or a group of products, knowing that if it does choose to produce there has to be a minimum quantity of the product or group of products that is produced. If minimum-run constraints are incorporated into the model, it may also be necessary to model the production of transition material and the loss of production time that occurs due to transitions between runs. Minimum runs and transitions must be modelled at an appropriately high level, as production planning models do not determine the actual sequence of these runs, but instead determine only the number of different runs required within a time period. It may be important in some cases to make the time periods long enough to ensure that the production sequence will follow the production wheel.

No algebraic formulation of the production/distribution problem has been provided here, as there are many valid formulations that may take different forms depending upon the business-specific goals for the model and the dimensions by which the data vary. Nevertheless, all such planning models are likely to have the following base set of constraints for each time period:

1. The starting inventory of a purchased material, as well as new purchases of this material, at a location must either be consumed in production or stored in the ending inventory.
2. The starting inventory of a produced material, as well as new production of this material, at a location must be consumed in another production operation at the location, stored in the ending inventory, or shipped out of the location.
3. A material shipped into a non-demand location must be consumed in a production operation, stored in the ending inventory, or shipped out of the location.
4. Material shipped into a demand location must be used to satisfy demand (in some cases, inventory may be allowed at the demand location, as well).
5. Production operations must consume capacity, which is limited in turn by the operating calendar and maintenance plan. If minimum run constraints are required in the model, they are modelled by using a binary variable that tracks whether a run is produced; if a run is produced then the production quantity associated with this run must be greater than or equal to some minimum run value. This binary variable may also be used to reduce the available capacity based on the time required to make the transition from one minimum run to the next.

7.3 Demand management, available-to-promise functionality, and inventory management

Demand management applications collect all demand data and have the capability to ‘slice and dice’ the data in many ways, such as by product, by product by customer, by product by shipment destination, etc. Demand management applications also closely collaborate with and provide input to supply chain planning applications – both for distribution network optimisation and for tactical production/distribution planning. Most demand management applications use forecasting techniques that search for and use the best fitting models among those featured within a particular DSS.

Some companies utilise the Available-To-Promise functionality to accurately determine and promise delivery dates. Again, sophisticated software can create a real-time data exchange between the order promising system (which would typically be part of the ERP system), the DSS, and the scheduling system. However, this area of supply chain management has significant room for improvement. While most ERP systems advertise the Available-To-Promise function, the promise dates are based on a static supply network, which means that neither changes to the schedule nor to the distribution routing are considered. An advanced Capable-To-Promise functionality with the ability to perform dynamic rescheduling is available from some DSS software vendors, but it is seldom deployed.

Finally, it is possible that an inventory planning functionality may exist as a separate application that determines safety stock levels and monitors inventory performance, thus providing feedback into the planning applications. DSS software vendors offer these applications in modular form (i.e. a given company can use one, several, or all applications of the software).

DSS software promises – and in many cases – delivers great benefits for manufacturers. Better, more realistic, and actionable production and distribution planning; improved customer service; improved resource utilisation; and facilitation of new product introductions within existing capacity are among the cited benefits. Other benefits include improved planner efficiency, better understanding and integration of supply chain processes, and improved ability to evaluate what-if scenarios.

It is worth noting that good data are essential to good supply chain planning and execution. Thus, the old adage 'garbage in, garbage out' is nowhere more true than in DSS. None of the senior supply chain managers of the four major polymer companies that we interviewed regret their investment in DSS. However, the biggest challenge to be faced in using the DSS is the integration of data from many sources including plant systems, ERP systems, Excel spreadsheets, and tribal knowledge and the necessary use of multiple data interfaces. Historically, the electronic integration of such data was a major challenge, but the problem has been more or less eased by the development of Extract/Transform/Load (ETL) integration tools.

Now, the most challenging problem is data mapping. Data mapping refers to the process of taking data from one system (e.g. an ERP system) and transforming it for use in another system (e.g. a DSS). For example, the ERP system may have a production rate, but that rate will not be directly useful to the DSS because the ERP production rate will be an annual average rate (including shutdowns and transitions), which is not useful for detailed scheduling.

7.4 Other related issues

Other issues critical to supply chain planning and control are the determination of data requirements and the timing of data exchange among demand management, production planning, and scheduling applications. Definition of new roles and responsibilities within this new framework is a natural consequence. These issues present all polymer manufacturers with the major challenge of defining new performance measurement systems (e.g. holding sales managers accountable for the forecasts they provide and for the consequences of inaccurate forecasts), modifying corporate behaviour, and managing change within this new framework. When these issues are handled well, the installation of the DSS should actually help define the supply chain planning and execution processes. This is a very useful exercise with great payoffs, clearly, requiring the inclusion and coordination of every related function (i.e. sales, demand management, production and distribution planning, inventory and materials management, production scheduling). Moreover, as we have learned from our interviews with the senior supply chain managers of four major polymer companies, the installation of the DSS may provide a healthy return on investment (i.e. millions of dollars of return on an investment of hundreds of thousands of dollars).

Information sharing directly between polymer manufacturers and their immediate suppliers and customers is not done to any great extent. Typically, their relationships are not governed by Vendor Managed Inventory arrangements. Instead, their relationships are more typically constrained by the price, not the availability, of the main raw material (i.e. the feedstock). Integration with suppliers, as was stated in all our interviews, is not a core problem. On the customer side, some polymer manufacturers receive orders electronically from their customers. On the distribution side, they have service contracts with railroad companies and manufacturers have the ability to track rail cars electronically. For consignment locations, the customer notifies the manufacturer when an empty rail car needs to be replenished. In general, information sharing does not seem to be of major concern.

Finally, most polymer manufacturers do not appear to have a very strong handle on overall supply chain costs. Most instead utilise various performance indicators. Among the most commonly tracked indicators are inventory levels, days of inventory, order fulfilment, late orders, and forecast accuracy.

8 Challenges in polymer supply chain management

To streamline and optimise their supply chain networks, many polymer manufacturers utilise sophisticated information systems and operations systems (DSS). However, several problematic issues still prevail. Here, we will limit our discussion to operations-related issues rather than those related to information technologies.

One of the major issues is the determination of safety stock requirements at bulk terminals, plants, or both. Safety stock requirements naturally depend upon the time between subsequent production runs, transportation lead-time (from the manufacturing plant to the distribution terminals), and manufacturing lead-time. For example, a particular product campaign may run for 20 days (manufacturing lead-time), but it may take 10 days for the material to be shipped from the plant to the distribution terminal (distribution lead-time) and the next run of the same campaign may start in 40 days (time between two runs of the product campaign). Depending upon all these values, a certain level of safety stock is calculated using the available standard safety stock formulas. Typically, companies use DSS software, which may utilise the standard safety stock formulas, or an in-house methodology. The safety stock quantity is then included in the production planning process, and plans are developed accordingly.

The traditional safety stock calculations are not used very effectively by the companies whose senior supply chain managers we interviewed. This is partly due to a lack of knowledge on the part of the managers and, partly, due to the fact that effective safety stock policies are not imbedded in all of the available DSS software. Furthermore, if the estimates for production lead-time, distribution lead-time, or both become outdated, or if demand fluctuates extensively over time, there is no built-in structural support within the DSS for updating the safety stock levels. Furthermore, valid estimates of variability are often lacking, especially in estimates of manufacturing lead-times.

On the other hand, changes in production schedules, which are typically updated weekly, complicate the problem. As schedules are updated, production quantities may change, and the time between the production runs of a campaign may vary. This may in turn alter the manufacturing lead-time beyond the limits of variability imbedded in the safety stock calculation. Most schedule changes are driven by demand and by the desire to satisfy demand at all costs. However, in the environment of cyclic scheduling, some changes may jeopardise the ability to meet an increase in demand that occurs in the future but before the next production run. The difficulty of forecasting demand in an area served by a bulk terminal amplifies the problem. The impact of production schedule changes and the amplifying effect of forecasting errors have been studied by several researchers (Sridharan and Berry, 1990a,b; Lin and Krajewski, 1992; Zhao and Lee, 1993, 1996). Some studies considered capacity (Ho and Carter, 1996; Kern and Wei, 1996; Venkataraman, 1996; Zhao, Xie and Yang, 2001; Van Donselaar and Gubbels, 2002; Xie, Zhao and Lee, 2003), and some addressed the use of safety stocks to dampen the effects of schedule changes (Sridharan and LaForge, 1989, 1990; Kadipasaoglu and Sridharan, 1995). Yet, besides providing valuable insights, none of these studies provided findings that were readily applicable to polymer manufacturing. Thus, there seems to be a great need for developing better, more effective safety stock policies for the cyclical manufacture of polymers and for conducting additional research in this area (Hill et al., 2000; Floudas and Lin, 2005).

Another issue is the lack of knowledge of scheduling techniques that address product campaigns and sequence-dependent set-ups. While a few DSS incorporate sophisticated algorithms for scheduling individual production lines, most typically do not perform global scheduling for a plant. Consequently, some manufacturers use ‘days of inventory’ in scheduling the next campaign. Others use the cost of transitions and demand information to create schedules that will maximise resource utilisation, but again mostly on a rudimentary trial-and-error basis. Typically, a scheduler devises a schedule that is biased toward the costs and pain most often encountered in his or her experience and judgment. And, as stated above, schedules are typically updated based on short-term goals, without considering the effect of these changes on the ability to satisfy future demand. In this environment, effective scheduling is crucial for minimising low-grade production and maximising resource utilisation while remaining able to meet demand. This is another area that would greatly benefit from further research.

Finally, polymer manufacturers face the difficult issue of how to manage the process of organisational change involved in implementing the DSS. While investments in DSS have typically been good investments for polymer manufacturers, managing the process of change has been problematic. This includes the management of both data and personnel. As stated above, the biggest data-related challenge is that the data come from multiple sources and require multiple data interfaces for their alignment. Data interface and mapping are the two parts of project implementation that most often exceed the initial time and cost estimates, most often because project teams underestimate the effort required to transform data. The most difficult part of data integration is the transformation of data from one system to another. When data are extracted from one system and used in another, the context of the data in the initial system must be understood before it can be properly used in the second system. Then, this initial data context must be programmed into the automated transformation logic. It is the transformation that takes the most effort.

The biggest personnel-related issue is the definition and acceptance of the new roles and responsibilities that come with implementing a DSS. Behaviour modification and change management are among the most difficult tasks, and they must be clearly and visibly defined and supported by senior management.

9 Summary and conclusions

As the discussion above has hopefully made clear, the supply chain network for polymer manufacturers is quite complex. The typical polymer supply chain network includes multiple plants, a large number of storage terminals, a large number of customers and consignment locations, and has complex distribution requirements. This paper describes the complexity of the polymer supply chain from a 'logical positivist/empiricist' viewpoint based on in-depth interviews with supply chain managers of four major polymer manufacturers and on the authors' experience in the industry.

The paper presents, in detail, the market characteristics and competitive priorities, manufacturing environment, logistics and distribution activities, and supply chain planning and control activities for polymer manufacturers. Within supply chain planning and control, we discuss, in detail, polymer distribution network optimisation, production/distribution planning, production scheduling, demand management, available-to-promise, and inventory planning activities. In addition, the paper describes the applications available in a commercial DSS that support these activities. A general mixed-integer network distribution optimisation model is also provided in Appendix A. The paper also discusses various issues that continue to challenge supply chain managers in polymer manufacturing. These issues include forecasting for the large number of product–customer combinations, determination of safety stock requirements, handling of production schedule changes, business process management during DSS implementation and data mapping for decision support.

The present paper contributes to the supply chain literature by providing a valid context for studying supply chain-related issues. By describing and characterising the polymer supply chain, this paper identifies the specific issues of concern to potential researchers and to supply chain professionals. This in turn should allow researchers to design better studies of the supply chain and allow supply chain managers to apply more effectively, in the real world, the knowledge gained from research studies.

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Appendix A

Network optimisation model

Sets and indices:

m = material

o = origin

d = destination

rte = rail route identifier, could be name of railroad, or could be more detailed route identifier for alternate routes in use by the railroad

shp = truck shipment identifier, usually carrier name

t = tier identifier for throughput volume breaks

dc = distribution centre that is not a plant or customer ship-to location

sup = subset of origin locations

RR = subset of rail route identifiers – could refer to all route identifiers for a specific railroad

SUPPLY = list of valid source locations for material *m* at origins *o*

RAIL = list of valid (*m,o,d,rte*) combinations

TRUCK = list of valid (*m,o,d,shp*) combinations

Decision variables:

$R_{m,o,d,rte}$ = rail shipment of a material *m* from origin *o* to destination *d* via a valid rail route *rte*

$T_{m,o,d,shp}$ = truck shipment of a material *m* from origin *o* to destination *d* via a valid truck carrier *shp*

$V_{dc,t}$ = volume shipped by truck within a tier *t* out of a distribution centre *dc* (assumes that cost increases as volume increases – used if the first *x* amount of volume is built into the fixed cost (and thus has no per unit cost), but any volume above this quantity *x* is charged an additional variable cost)

U_{dc} = indicates if a terminal *dc* is used (=1) or not (=0)

$C_{m,dc}$ = indicates if a terminal *dc* is used for a material *m* (=1) or not (=0)

$Z_{m,d}$ = amount of demand not satisfied of material *m* at destination *d*

Input data:

$RC_{m,o,d,rte}$ = cost per volume of material shipped via rail (this may be a combination of railcar cost, loaded and empty railcar in-transit costs, and the cost of holding the inventory in the railcar)

$TC_{m,o,d,shp}$ = cost per volume of material shipped via truck

$VC_{dc,t}$ = variable cost per volume of trucking throughput at a distribution centre for each tier

UC_{dc} = fixed cost associated with operating a distribution centre

$CYC_{m,dc}$ = cycle cost per volume associated with holding a material at a distribution centre

$DEM_{m,d}$ = demand forecast for a material *m* at a final destination *d*

$MT_{dc,t}$ = max throughput of a tier *t* at a distribution centre *dc*

$MIN_{m,dc}$ = smallest demanded quantity of a material *m* that can be supplied from the distribution centre *dc*

$MAX_{m,dc}$ = largest demanded quantity of a material *m* that can be supplied from the distribution centre *dc*

$SHPFRAC_{\mathrm{sup},\,RR}$ = required minimum shipment fractions (usually due to contracts with railroads) that must be enforced (i.e. 80% of total rail volume must be shipped via BNSF)

$PNLTY_{m,d}$ = high penalty cost for not satisfying demand

The model:

Minimize TC:

$$\begin{aligned} TC = & \sum_{(m,o,d,rte)\in RAIL} RC_{m,o,d,rte} R_{m,o,d,rte} + \sum_{(m,o,d,shp)\in TRUCK} TC_{m,o,d,shp} T_{m,o,d,shp} \\ & + \sum_{m,dc,t} VC_{m,dc,t} V_{m,dc,t} + \sum_{dc} UC_{dc} U_{dc} + \sum_{\substack{m \\ dc}} CYC_{m,dc} C_{m,dc} \\ & + \sum_{\substack{(m,d)\,such \\ that\ DEM>0}} PNLTY_{m,d} Z_{m,d} \end{aligned} \tag{1}$$

Subject to:

$$\text{(NO1)} \quad \sum_{\substack{(o,rte)\text{such that}\\(M,o,L,rte)\in RAIL}} R_{M,o,L,rte} + \sum_{\substack{(o,rte)\text{such that}\\(M,o,L,shp)\in TRUCK}} T_{M,o,L,rte}$$

$$= \sum_{\substack{(d,rte)\text{such that}\\(M,L,d,rte)\in RAIL}} R_{M,L,d,rte} + \sum_{\substack{(d,shp)\text{such that}\\(M,L,d,shp)\in TRUCK}} T_{M,L,d,shp} + DEM_{M,L} - Z_{M,L} \tag{2}$$

$$\forall\ M \in materials,\ L \in destinations$$

$$\text{(NO2)}\ U_{dc} \le \sum_{m} C_{m,dc} \qquad \forall dc \tag{3}$$

$$\text{(NO3)}\ U_{dc} \ge C_{m,dc} \qquad \forall m,dc \tag{4}$$

$$\text{(NO4)}\ 0 \le U_{dc} \le 1, \qquad C_{m,dc} \in \{0.1\} \tag{5}$$

$$\text{(NO5)}\ MIN_{m,dc}C_{m,dc} \le \sum_{(m,o,dc,rte)\in RAIL} R_{m,o,dc,rte} + \sum_{(m,o,dc,shp)\in TRUCK} T_{m,o,dc,shp} \le C_{m,dc} \qquad \forall m,dc \tag{6}$$

$$\text{(NO6)} \quad \sum_{(m,dc,d,shp)} T_{m,dc,d,shp} = \sum_{t\in TRUCK} V_{dc,t} \qquad \forall dc \tag{7}$$

$$\text{(NO7)}\ V_{dc,t} \le MT_{dc,t} \qquad \forall dc,t \tag{8}$$

$$\text{(NO8)} \quad \sum_{\substack{(m,o,d,rte)\in RAIL,\\ o\in SUP, rte\in RR}} R_{m,o,d,rte} \ge SHPFRAC_{SUP,RR} \sum_{(m,o,d,rte)\in RAIL} R_{m,o,d,rte} \qquad \forall SUP, RR \tag{9}$$