Tactical Shipping and Scheduling at Polaroid with Dual Lead-Times

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***Abstract*—We report on a project with Polaroid Corporation in which we developed a supply chain model to provide decision support for planning production and transportation. Production occurs in Asia to serve world-wide demand. Production planners must determine both the production quantities as well as whether to ship by sea or by air. We develop a model to optimize a static version of this problem and then show how to use this static model in a dynamic setting. We test the model with data from Polaroid and show its effectiveness.**

***Index Terms*—dual replenishment modes, inventory and transportation planning, supply chain application, supply chain modeling**

I. INTRODUCTION

Many U.S. companies attempt to reduce labor costs by shifting production to overseas locations with lower wage rates. This decision greatly impacts supply chain performance, increasing the lead times for replenishing finished goods. One counter measure is to use priority shipping via air, instead of normal modes of transport (ocean, rail, truck) to reduce the lead times.

This paper reports on a project undertaken with Polaroid Corporation, the world leader in instant photography. Polaroid had shifted the production of its consumer-branded cameras to Asia. To address the increasing transportation costs associated with frequent air shipments, the transportation group at Polaroid began an initiative to develop a shipping decision support model. The first co-author was hired as an intern during the summer of 2000, and conducted subsequent research during the 2000-2001 academic year to develop and test a model for Polaroid to use for tactical shipping and production decisions.

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This paper focuses on the development and validation of a tactical model that makes production-scheduling recommendations and specifies shipping options to reduce total supply chain cost. The paper describes Polaroid, reviews literature on inventory management with two replenishment modes, and develops a simple static network model that can be used for decision support. We exercise the model by simulation to determine the relationship between transportation costs, inventory costs, forecast error and manufacturing capacity in a typical framework where production and shipping decisions are made periodically. Finally the paper recommends a course of action for Polaroid regarding model implementation.

II. BACKGROUND

Polaroid is the leading instant imaging company in the world and is the only manufacturer of traditional instant cameras and film in the United States, with revenues in 2000 of $1.85 billion.[1] The Company's principal products are instant film, instant and digital cameras, digital peripherals and secure identification systems with software and system solutions.

The Company's products divide into two segments, business solutions and consumer products. Business solutions include photo ID systems (primarily used by corporations and government agencies), digital peripherals (scanners, photo quality printers, high-end digital cameras and specialty digital camera), and high-end instant photo cameras and equipment. Consumer products include a broad line of hand held instant cameras, digital cameras, 35mm cameras and a wide assortment of media such as instant and 35mm film, videocassettes, and digital printing media.[2] Because consumer products account for the majority of sales, Polaroid's largest customers are major U.S retailers, supermarket chains and drug stores. Polaroid's business products are sold through specialty channels and also direct channels within the company.

The Company is organized into five segments: the Americas Region, the European Region, the Asia Pacific Region, Global Operations, and Research and Development. The regions focus on sales and marketing, while global operations

[1] 2000 Polaroid Corporation 10K, Income Statement
[2] Polaroid Corporation 10K

centralizes procurement, logistics and manufacturing. R&D provides engineering research and development for all the regions, as product functionality is not necessarily region specific. The Americas Region covers to the Western Hemisphere. The European Region is comprised of the United Kingdom, Continental Europe, Russia, Africa, and the Middle East. The Asia Pacific Region includes Japan, Australia and the majority of the Asian continent.

Polaroid has not been a strong financial performer in the last 11 years, and filed for Chapter 11 bankruptcy protection in October 2001. Polaroid's revenue tailed off in the late 1990's as the market for Polaroid's traditional consumer instant cameras became saturated. Polaroid responded by marketing new lines of small, trendy and relatively inexpensive cameras (Pop-shots, I-zone, Joycam) that would appeal to the youth market. Polaroid also shifted much of its focus to digital technology, focusing on the sale of high technology digital cameras. These two newer product categories account for nearly 25% of sales and have offset the decline in traditional products to some extent. However, sales of these new products have many disadvantages compared to Polaroid's traditional instant camera lines. The higher-growth youth-focus instant cameras deliver smaller margins, have shorter life cycles and higher incidence of obsolescence, and typically use lower margin film. Though they have higher margins, the digital cameras do not give Polaroid the benefit of a steady stream of film revenue, and are also characterized by short product life cycles and high costs of obsolescence.

This trend of poor performance and new product mix has forced Polaroid to reduce costs, streamline operations and find ways to increase supply chain flexibility. Polaroid shifted camera production to the Far East, and shut down U.S. manufacturing operations in an attempt to increase flexibility and reduce costs. Polaroid has also tried to improve its financial performance through corporate wide inventory reductions.

A. *Logistics at Polaroid*

Polaroid's logistics organization is part of the Company's Global Operations segment, with primary responsibility for the movement of raw materials and product between manufacturing sites and from finished goods manufacturing to the retailers. Production planning, forecasting, and inventory management (except for specialty package inventory) are not responsibilities of the logistics organization. Logistics has three primary functions, customer service, packaging and handling, and transportation.

Customer service: The customer service arm of the group is responsible for handling and processing customer orders, working one-on-one with Polaroid's sales force and individual customers to ensure the timely delivery of product to the retailer. Large customers are assigned a dedicated service representative that will deal with all contracts, orders and deliveries nationwide. These customers typically make orders through an Electronic Data Interface (EDI) system, which is instantly delivered to the service rep and company distribution centers. The service representative ensures that the orders are realistic and attainable (i.e. the time frame and terms of the order are feasible and meet contract specifications) and that the distribution centers are taking appropriate action to meet the order. The role of the service rep becomes more critical when there is a problem with an order. It is their responsibility to expedite orders that were not processed on time, and to handle stock-outs with the customer.

Packaging and handling: Polaroid has three major distribution centers in the U. S., located in Oak Brook IL, Anaheim CA, and Norton MA, which store finished goods inventory for delivery to the customer. Norton also has a centralized packaging operation. Retailers typically order Polaroid products in unique and specially design package platforms. These package configurations change frequently for various special offers or promotions retailers have throughout the year. Hence bulk cameras are not necessarily finished goods to the retailer. Rather, there is a large explosion of specific product codes at the retail distribution level. To reduce inventory, Polaroid postpones the packaging step until a customer order is received. Typically two weeks is allotted for packaging and delivery of product.

Transportation: The transportation group coordinates deliveries of finished goods from the distribution centers to the retailers, movement of product between distribution centers, and international and national transshipments of manufactured components. Most deliveries and product movement from the distribution centers are arranged through third party truckload companies, though the company does own and operate a small fleet of its own trucks. Overseas transshipments are air freighted or shipped on ocean carriers by the container load. Products arriving by ocean from Asia typically are shipped to Anaheim, transferred to railcars and then shipped to Norton. Sea shipments from Europe are sent to Boston or New York and are then trucked to Norton. Air shipments from most places worldwide arrive at JFK airport in New York and are trucked to the Norton distribution center.

There are two possible modes of ocean transport, less than container load (LCL) shipments and container load shipments. LCL shipments have longer lead times than container load shipments , as items must go through a consolidation stage prior to shipment and after delivery. They also have a higher per unit cost due to the additional tracking and handling necessary to process a LCL shipment. However, this mode can be preferred if units are shipped in small volumes. Full container load shipments have a fixed cost regardless of the weight and quantity of items shipped as long as the weight does not exceed maximum container capacity requirements. Shipping companies usually offer two container sizes, 20ft and 40ft. The 40-ft container is more economical on a price per cubic foot basis. For air shipments, units are arranged on palletized loads, and pricing is based on weight only.

B. Manufacturing Planning

The manufacturing planning organization is responsible for short term and long term scheduling of manufacturing and management of raw material and finished goods (pre packaged product) inventory. Members of this organization primarily base their plans on forecasts generated by the sales force in the various regional segments. Once goods have been scheduled and produced, the planners rely on the logistics organization to handle the shipment, packaging and distribution of finished goods.

The planning function differs for products that are manufactured in house, from those that are manufactured by contractors. There is less schedule flexibility with contract manufacturers. Most contracts require a minimum order level to be specified at least two-three months in advance of the monthly production period. This requirement limits the planner's ability to adjust production if actual demand is significantly different from the two or three-month forecast. All camera contracts invoice Polaroid at the time of shipment, so Polaroid takes ownership of inventory immediately as it leaves the contract manufacturer's loading docks.

Planners review the inventory in the pipeline and distribution centers, and monthly sales forecasts, and create build and shipping schedules (or generate orders for contract manufacturing planners). Most of the consumer camera planners try to maintain four weeks of inventory (based on the forward forecast) at the distribution center and an additional four weeks of inventory in the shipping pipeline. This rule of thumb is followed regardless of product demand patterns, or forecast error.

III. Problem

Manufacturing planners have increasingly relied on costly air transport to transship goods manufactured in Asia to the United States. Airfreight costs have grown to account for over 50% of the transportation budget, while being an insignificant portion only three years prior. Production planners decide to ship products by air to reduce pipeline inventory, to expedite orders when safety stock levels are lower than the four-week minimum, or to meet specific new-product launch dates. Due to production capacity constraints, the planner might have to resort to a series of air shipments to keep pace with demand. New products are shipped by air more frequently than existing products due to the importance of having sufficient stock on hand during the launch.

The transportation group requested the development of a decision support tool that would: allow planners to decide the quantity of goods to be shipped by air and by sea on a weekly basis; help planners to achieve and maintain desired inventory levels; and provide an ability to compare the cost impacts of inventory, capacity and shipping decisions

We limited the focus of this project to considering the shipping decisions of a single product between Asia and the Norton packaging facility in the United States, as this transshipment route was the source of the majority of the air transport cost increases. Polaroid also wanted to keep the initial project simple, to increase the probability of success, to make it easier to gain insights from the decision tool, and to make the eventual tool implementation as simple as possible.

IV. Literature Review

The topic of inventory management with two replenishment modes has appeared in management literature since the early sixties. Barankin (1961) developed a one period model with two lead-time options of one period and instantaneous delivery. Daniel (1962) extends this model to include multiple periods bounding the size of the emergency order. Fukuda (1964) extends Daniel's model to include set up costs for orders and to allow more flexibility in the timing of the orders over multiple periods. Wright (1968) and Rosenshine and Obee (1976) develop more complicated models that allow for arbitrary lead-times as long as the emergency option is one period less than the regular mode. Whittmore and Saunders (1977) further generalize the model to allow for the lead-times of the emergency and normal orders to differ by more than one period, but with no fixed ordering cost.

These papers utilize dynamic programming, which is tractable for finite horizon problems when lead times are one and zero periods. However, the generalization to arbitrary lead times creates a multi-state problem that is time consuming to solve. And these papers do not consider capacity constraints, which would further complicate the dynamic program.

Moinzadeh and Nahmias (1988) develop a more general model that utilizes an order-point, order-quantity policy for each replenishment mode. They develop a heuristic policy under a continuous review inventory model that is locally optimal. Moinzadeh and Schmidt (1991) examine the dual-mode inventory system for Poisson demand using an (S-1, S) replenishment policy. Moinzadeh and Aggarwal (1997) extend these results to account for a two-echelon inventory system.

V. Solution Methods

In determining a solution method we considered three factors: the usefulness and applicability of a model to Polaroid's situation; the model simplicity and ease of use; and the potential for adoption and implementation.

We first attempted to modify Moinzadeh and Nahmias's heuristic approach to more accurately reflect the Polaroid problem. These modifications included adding pipeline inventory costs to the cost equation, setting limits on the expected number of backorders, and changing the solution method to account for production capacity constraints. Unfortunately, the model requires as input a demand distribution in each period for each product, which Polaroid deemed to be infeasible due to their monthly forecasting format and the highly variable nature of the forecasts. Also, since the planners were to run the model, they needed to understand how it worked.

Any solution technique would to some degree have to make intuitive sense to the users of the model and be easy to use and update. Lay user might be incapable of understanding model output in the case of a multi-state dynamic program, or incapable of generating useful input in the case of a stochastic inventory model. As a result, we chose a solution strategy, by which we solve a simple deterministic model in each period in order to solve approximately the dynamic problem

A. Polaroid Network Scheduling and Shipping Model

For our initial formulation we use a minimum-cost network flow model[3] to determine the production and transportation decisions for a single product over a finite horizon of n weeks, where production occurs in Asia and the product is to be shipped to the distribution center in Norton MA. . We depict the network in Figure 1. We assume all costs are linear.

The network entails a root node **s**, a production node $\mathbf{p_i}$ for every period, a demand node $\mathbf{d_j}$, for every period, and a sink node **t**.

There is an arc from the root node **s** to each production node $\mathbf{p_i}$. Flow on this arc represents production in the period. An upper bound on this arc corresponds to a capacity constraint on production, while a lower bound represents a minimum production level as might be dictated by contract. The flow cost for these arcs is the variable production costs.

We define arcs between the production nodes and the demand nodes to correspond to shipment decisions. Let t**1** represent the lead-time associated with airfreight and t**2** represent the lead-time of ocean shipping. There is an air-shipment arc from the production node $\mathbf{p_i}$ in period i to the demand node $\mathbf{d_{j=i+t1}}$ in period i+t**1**, and a sea-shipment arc from the production node $\mathbf{p_i}$ in period i to the demand node $\mathbf{d_{j=i+t2}}$. in period i+t**2**. The cost on each of these arcs is the relevant transportation cost for shipping by that mode, plus the inventory holding cost for the lead-time.

There is an arc from each demand node $\mathbf{d_j}$ to the next demand node $\mathbf{d_{j+1}}$. Flow on this arc corresponds to carrying inventory from one week to the next week. The cost of this flow is the holding cost for the inventory. We can set a lower bound on this arc to assure a certain level of safety stock in each week.

There is an arc from each demand node $\mathbf{d_j}$ to the sink node **t**, where flow on this arc equals the demand satisfied in the period. The lower bound on each arc equals Polaroid's demand forecast in the period, thus assuring that the plan satisfies the demand forecast. There is no cost on the flow on these arcs.

We can solve this problem with any minimum-cost network flow algorithm. The solution provides the amount to produce in each period, the amount to ship by each mode in each period, and the inventory levels in the distribution center in each period.

There are several extensions that are worth mentioning. We can permit multiple destinations and multiple production sources, and still preserve the network structure. We can also permit serial productions stages, whereby one stage produces a component that feeds into a downstream stage that produces an assembly or subassembly, and so forth.

B. Model Limitations and Recommended Use

Because this model is deterministic, we do not achieve an optimal solution when demand is stochastic. There are two counter measures to overcome this limitation. First, by imposing constraints on the inventory, the model will build a buffer against demand variation in order to prevent stockouts and to achieve a desired service level. Second, the model is to be re-run at regular intervals (e. g., weekly) over a tactical planning horizon (12 weeks in Polaroid's case). Every week, forecasts are updated, in-transits are added, new inventory targets are calculated, and the model is run again. The shipment decisions recommended by the model for period 1 only are carried out, and the model is re-run the following period using the previous periods shipments as in-transit inputs to the model. This iterative process allows the model to correct mistakes caused by forecast inaccuracy in early periods in subsequent periods.

For more strategic decisions involving new product introductions the model can be a valuable planning aid. Before a new product is introduced, an integrated new product team consisting of representatives from manufacturing, sales, marketing, and logistics meet to formulate strategic product parameters such as: the product launch window, tooling investments and manufacturing capacity, the ramp up period for the product, etc. The network model can be useful in identifying tradeoffs between these strategic decisions. By setting the model horizon to represent the product lifecycle, the model can reveal the effects that launch date and tooling capacity decisions will have on lifecycle transportation costs. The model will find the additional costs due to filling the pipeline with air, rather than ocean, shipments, as well as the benefits from additional tooling capacity. By allowing strategic committees to examine these tradeoffs, the model should help new product teams make more educated decisions.

So far we have assumed that shipping costs were linear in the volume shipped. Unfortunately, this is not true for shipping via ocean containers, for which there is a fixed price regardless of the amount shipped within a container. We can model this by modifying the ocean-shipment arcs in the network problem. In particular we need to add a fixed cost to these arcs, as well as an upper bound equal to the size of the container. And we need to permit the possibility of multiple ocean-shipment arcs being used in a week, representing the shipment of multiple containers. These modifications result in an integer program, for which a more complex algorithm is

[3] Ahuja, R. K., T.L. Magnanti, and J. B. Orlin, Network Flows: Theory, Algorithms, and Applications, Prentice Hall, 1993, pg 749.

needed.

VI. MODEL TEST

To test the model we collected shipping, forecast, and demand data for three Polaroid products over a six month interval. We then did a retrospective simulation for how the model would have performed. We ran the simple network model week by week using the current week's 12-week forward forecast. For example, the January 2000 forecast's predictions for January, February, and March, were used to drive the model for the first four weeks of January. The next four iterations utilize the February forecast, and so on. The shipping decisions of the model are then compared to the actual shipping decision made by the company to compare costs and service levels. Many assumptions were necessary to conduct this validation test.

1. Shipping by air requires a lead time of two weeks
2. Sea shipments require a seven week lead time
3. Monthly forecasts were converted into weekly forecasts, assuming uniform demand over the mo nth
4. Safety stocks were set to four weeks of forward demand, as was the policy used by the planners
5. There were no costs associated with stock-outs
6. For the purpose of comparison, we determined the actual costs and stock-outs assuming two and seven week lead-times.

Though the average delivery times for air and sea shipments are one and five weeks respectively for most products, we assume worst-case lead-times to make our inferences on model performance more conservative. Weekly periods were used instead of monthly since products are typically shipped from Asian factories in weekly batches.

We selected two color versions of the small consumer instant camera, Joycam, along with Polaroid's low-end digital camera, the PDC 300. Joycams were a perfect test case because they fit the mold of the new breed of Polaroid products. They were introduced in the beginning of 2000, were shipped from Asia to the U.S., and over the course of the year were shipped both by air and sea. After seeing the Joycam model results, we chose the PDC300 to determine if a product that had been exclusively shipped via airfreight could have been moved to the ocean in retrospect.

We simulated the Joycams for the first seven months of 2000, and the PDC300 during the later half of 2000. In Table 1 we present the summary statistics (scaled to disguise actual costs and volumes); more details on the simulation results are in Threatte (2001).

Table 1: Simulation results for network model. * Total costs computed for simulation, assuming the same number of units shipped as for actual.

	Joycam 1	Joycam2	PDC300
Average per unit shipping cost - simulation	0.28	0.37	0.58
Average per unit shipping cost - actual	0.40	0.56	0.90
Total cost – simulation*	770	1030	2436
Total cost - actual	1528	1308	2235
Inventory holding cost - simulation	317	616	1666
Inventory holding cost - actual	887	684	972

We see from the table that the per-unit shipping costs are much lower, reflecting the greater use of ocean rather than air. The inventory holding costs are also lower for the Joycam, even following the safety stock policy of maintaining four-weeks of stock on hand. For the PDC300, the actual inventory costs are lower than the simulation, largely because the actual inventory was allowed to slip below the four-week target. We also compared the total of the shipping and inventory costs, where we adjusted the simulated shipping costs to assume the same amount shipped as for the actual. There were no differences in service level as there were virtually no stock-outs in any of the cases.

One criticism of the prior test is that in many cases there were small shipments. This is not much of a concern for air transport as goods are loaded onto small pallets and transportation costs are assessed by weight. However, small batches shipped on ocean containers would have an extremely high cost per unit. We redid the simulation, using the integer programming model with three modes of shipment: LCL shipments, container load shipments, and airfreight. We made the following additional assumptions for the IP model simulation:

1. LCL shipments require a seven week lead time
2. LCL shipments were priced at twice the assumed per kilo weight of the sea shipments
3. Full container load shipments require a lead-time of six weeks and have a fixed cost of $6500.
4. Inventory arcs were added between production nodes to allow for the storage of inventory necessary to fill a container prior to shipment.

The simulation with the IP model revealed a surprising result. For products with limited tooling capacity, the model never recommended the use of a full container shipment. The simulated policies were the same as found from the linear-cost network model. Average shipping costs were higher due to the higher assumed cost of LCL shipments, but all transportation and production decisions were the same.

Container shipments were never made because there was never enough slack production capacity to accumulate inventory at the factory (see Threatte, 2001 for more details).

VII. INVENTORY OPTIMIZATION

So far we have assumed Polaroid's inventory policy to maintain four weeks of forward inventory. In this section we examine this policy, and use the simple network model to explore how parameters such as manufacturing capacity, safety stock levels, and forecast error variance affect transportation and inventory cost.

We examined seven new products that were recently introduced to characterize their monthly forecast errors. When comparing one-month forecasts with actual results (example: January's forecast for February compared to February's actuals), it appears that Polaroid's forecasts are consistently higher than actual sales. From subtracting actuals from monthly forecasts and averaging this result across the life of the product, the average forecast overstates actual results. The following table summarizes the forecast results for seven new Polaroid products[4].

Table 2: Forecast Accuracy

Product	Average One-Month Forecast Error	Standard Deviation	Implied Stock-out %, with no safety stock	Months Observed
Silver Joycam	3085	3091	13%	9
Spectra 1200	136	158	16%	18
PDC320 Cam	4686	4490	12%	18
Blue Pocket	3085	4408	13%	12
Red Pocket	4478	1975	5%	12
Green Pocket	7168	4423	7%	12
Black Joycam	1967	2386	12%	9

The fourth column of the chart specifies the percentage of actual demand that would have been subject to shortages if Polaroid built to forecast and made no attempts to hold any safety stock. Polaroid's strong positive forecast bias creates a scenario where a no safety stock policy would result in service levels between 84% and 93%. If the forecast were unbiased, we would predict a 50% service level with no safety stock.

We developed a simulation to examine the relationships between transportation costs, system costs, and shortages to changes in manufacturing capacity, safety stock, and forecast error. We randomly generated demand for a hypothetical product with a cost function and demandprofile similar to the Polaroid Joycam. We assume an unchanging forecast for the entire year that featured quarterly periodicity and Christmas seasonality. We simulate the actual demand for a period by generating a normal random variable with a mean equal to the forecast and with a standard deviation that was a fixed fraction of the mean. Running 12 model iterations successively simulated a year. The yearly transportation costs, adjusted total costs, and shortages are then compared across scenarios. Total costs are adjusted to reflect the cost assuming a fixed number of goods are shipped across scenarios.

In the simulation we set the safety stock levels using a fixed manufacturing capacity and forecast error ratio. The first series of runs were performed using a maximum production capacity of 135 units/week, representing a manufacturing capacity 110% above the average forecast. The standard deviation of actual demand values was set at .1 of the forecast. Target inventory levels for the model were calculated by setting inventory at the forecasted value for the number of lead-time weeks specified, plus two standard deviations of the generated forecast error for the lead-time period. The experiment was repeated for scenarios with a maximum capacity 143% of average demand with demand standard deviations equal to .1 and .33 of the mean. The results of the simulation are displayed in Table 3.

Table 3: Results of simple network parameter simulation (averages, n=20)[5]

Results with demand standard deviation =0.10 of mean and capacity = 135 units/week			
Weeks of safety stock	Unit shipping cost	Adjusted total cost	Stock-outs
2	0.2281	4112	150
3	0.2927	4890	0
4	0.3015	5529	0

Results with demand standard deviation =0.10 of mean and capacity = 175 units/week			
Weeks of safety stock	Unit shipping cost	Adjusted total cost	Stock-outs
2	0.1921	3253	1568
3	0.2048	3742	27.8
4	0.2416	4271	0

Results with demand standard deviation =0.33 of mean and capacity = 175 units/week			
Weeks of safety stock	Unit shipping cost	Adjusted total cost	Stock-outs
2	0.2686	3899	29.15
3	0.3606	4583	6.55
4	0.4505	5213	1.35

[4] Note: The data of this table has been transformed in order not to reveal the true Polaroid data which is confidential

[5] Adjusted total costs reflect simulated inventory and shipping costs assuming a fixed number of items are shipped in each simulation run.

The simulation reveals several relations for the range of tests considered:

- Shortages increase with reduction in weeks of safety stock
- Total costs decrease with reductions in weeks of safety stock
- Transportation costs decrease with lower safety stock, because more expediting is required to maintain high inventory levels
- Reductions in manufacturing capacity increase transportation and total costs while increasing incidence of shortages
- Reductions in manufacturing capacity increase the variability of simulated results
- Increases in the forecast error percentage mimic the effects of reduced manufacturing capacity

Most of these results are what would be expected in any inventory model. However, the fact that transportation costs/unit decrease with reductions in safety stock levels may seem counter intuitive. The reason is due to the increased pressure placed on manufacturing to sustain high inventory levels. Though demand is satisfied, often it must be met without being able to also match the particular period's inventory target. This leads to more incidences of expediting shipments via air, and hence increases the relative unit transportation costs. Transportation cost in the model is especially sensitive to forecast error and constraints in manufacturing.

VIII. Recommendations and Conclusions

For a manager making discrete periodic shipping decisions, the results of the simulation demonstrate that flexibility and cost are actually improved when inventory levels are reduced, even when manufacturing capacity is only 110% of average demand. This discovery when combined with the implicit bias in the forecasts, should provide the basis for reducing the current inventory target of four weeks of inventory. As further evidence, we note that the Joycam simulation had little if any shortages, even though the lead-times were set conservatively.

This paper develops a simple network-based model and demonstrates its usefulness for tactical scheduling and shipping decisions. Validation of the simple model and its more complicated IP counterpart demonstrated the following results:

- The models can save transportation costs by recommending increased use of ocean transport
- The models are effective in maintaining desired inventory targets
- The simple network model is easier to implement than the integer programming model

Simulations using the simple network model were performed to analyze the relationships between transportation costs, system costs, and shortages to changes in manufacturing capacity, safety stock, and forecast error. For the range of parameters that were tested, these simulation runs revealed the following:

- Shortages increase with reduction in weeks of safety stock
- Total costs decrease with reductions in weeks of safety stock
- Transportation costs decrease with reductions in weeks of safety stock due to the need for less expediting
- Reductions in manufacturing capacity increase transportation and total costs while increasing incidence of shortages
- Reductions in manufacturing capacity increase the variability of simulated results
- Increases in the forecast error percentage mimic the effects of reduced manufacturing capacity

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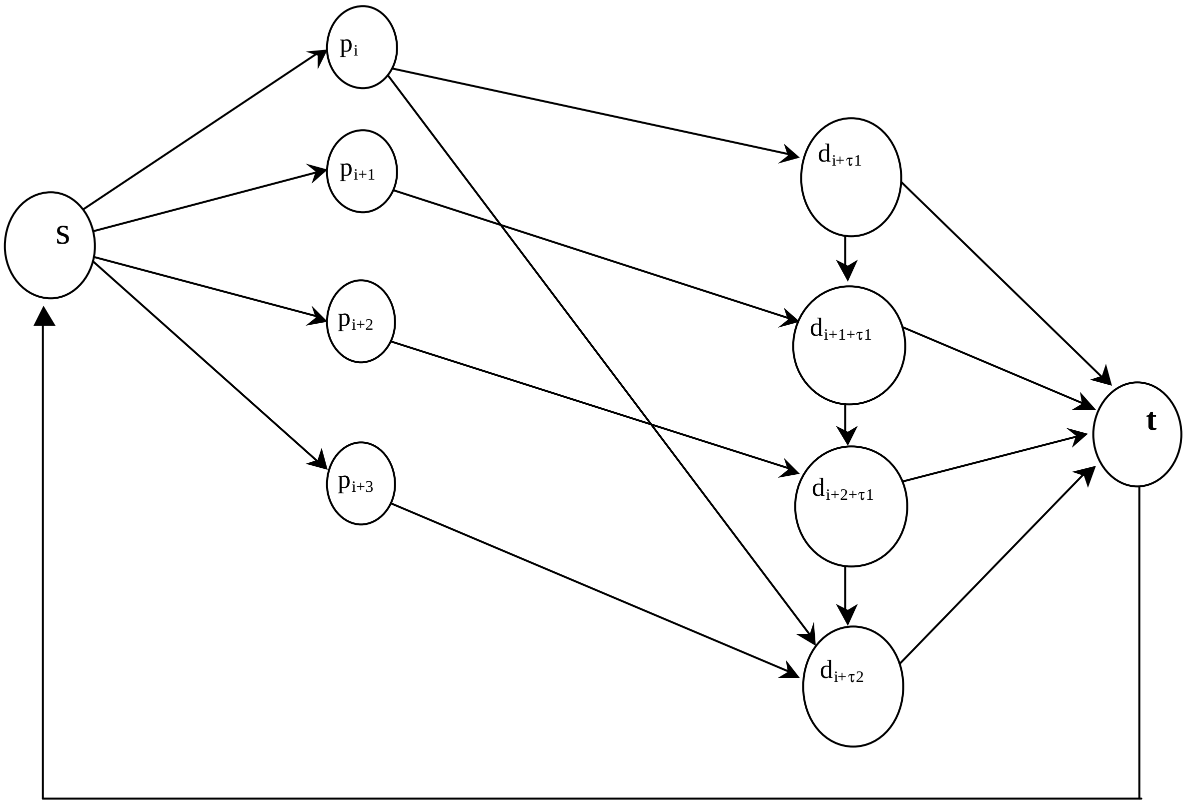

Figure 1: Network Flow Model