Co-ordinating Flows across Supply Chains in the Low Volume Gas Turbine Industry

by

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Submitted to the Sloan School of Management and the
Department of Materials Science and Engineering
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Master of Science in Management
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Abstract

The industrial gas turbine (IGT) market is experiencing exponential growth where competition is based upon technical performance and time to market. Product sales are limited by the ability of the Original Equipment Manufacturer (OEM) to coordinate manufacturers and assemblers to deliver turbines to customers in a timely manner. The company's logistics and supply chain systems have evolved from a traditional low volume job-shop environment and must now cope with a marked increase in product demand. OEM's must now manage the manufacture and assembly of thousands of turbine parts across an international and complex supply chain in a robust and agile manner. This requires the effective integration of internal and external logistics, supply chain and engineering talent. Current performance has been plagued with poor sourcing reliability, low quality and exploding lead times. This has resulted in sluggish response to customer demand and loss in earnings. This thesis seeks to recommend inventory placement strategies to improve sourcing reliability while identifying root causes and recommending improvements. It will also address the importance of the time-value of material in addressing investment and materials management decisions.

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1. CHAPTER 1 - INTRODUCTION

'The agility with which the supply chain is managed at the tactical and operational levels in order to enable timely dissemination of information, accurate coordination of decisions and management of actions among people and systems, is what will ultimately determine the efficient, coordinated achievement of enterprise.'[1]

To optimize performance, supply chain functions must operate in an agile and coordinated manner. The dynamics of markets and organizations make this a challenging goal. Rather than being a rarity, it is common for materials not to arrive and production facilities to fail. It is critical that any overarching supply chain management system enables the revision and deployment of plans and schedules across supply chain functions. This coordinated effort will ensure effective customer response.

This thesis is concerned with the supply chain strategy of a complex product and the control and coordination of its material flow. The project was completed over a seven-month period within the supply chain and logistic department of an original equipment manufacturer (OEM) of industrial gas turbines (IGTs). The organization was in the process of adopting a combination of push and pull techniques to enable it to meet ambitious customer service targets. Performance had not met expectation on many dimensions and two evident symptoms were chronic delivery lateness and excessive inventory spread unevenly throughout the chain, leading to poor customer service.

Industry and competitive pressures are forcing companies to offer quicker response times to customer needs. Ever shortening product development cycles necessitate effective coordination of all stakeholders. Companies with complex products find themselves juggling the activities of internal and external engineering, manufacturing quality, logistics, transportation and supply chain departments. In a global competitive environment with increasing clockspeed, it is becoming more challenging to meet customer demands.

Previously, it was sufficient to maintain large inventories to meet customer needs. "Today, rapid technological change and smaller profit margins make such a strategy uneconomical – literally forcing companies into the tighter control systems necessary to run with low inventory levels."[2] These diametrical drivers of inventory and customer service are challenging to balance in an environment of complexity and change.

"In the production and distribution of goods, inventory is the currency of service. An increase in service can virtually always be achieved through an increase in safety stocks, so a supplier inevitably faces a trade-off between service levels and inventory costs. Just how much service can inventory buy?" [3] The question then arises as to what level of inventory the control system requires to cost effectively provide a desired customer service level; and where in the chain that inventory should be placed.

In an effort to establish this marginal value, the thesis aims to:

- Improve the sourcing reliability of the supply chain for various supply chain cost options. This is achieved through de-coupling processes through the strategic placement of inventory in the chain, thereby reducing variation propagation
- Identify internal and external root causes of current supply chain performance
- Identify key drivers and their impact on the time-value of material
- Identify strategic supply chain issues and recommend improvements

The ultimate goal of this thesis is to present a generic approach to addressing supply chain issues. It presents concepts and methodologies that can be applied to many industries. By adopting the principles in this thesis, a company prevents the waste of precious capital.

The remainder of this chapter provides an industry and organizational context. It highlights the interaction amongst industry and departmental players. Chapter two reviews the performance and root causes of current issues, and recommends strategic improvements. Chapter three details the mechanics of the inventory scenario model that integrates all manufacturer information to simulate scenarios of inventory placement versus cost. Chapter four describes the model results, interpretation, validity and conclusion.

1.1 INDUSTRY BACKGROUND

With increasing de-regulation of the electricity market the profile of the power plant customer is changing. Over the last twenty-five years, Independent Power Producers (IPPs) have increasingly dominated power plant demand. In 1975, traditional 'Large Utility' companies made up 95% of the gas turbine customer base, with IPPs only making up the remaining 5%. In today's de-regulated market it is the IPPs that have grown to form 65% of the customer base for turbines.[4] Key IPP markets have developed in the United Kingdom, USA and Scandinavia. The trend of deregulating power supplies is gradually affecting customer profiles in Chile, Argentina and some European countries.

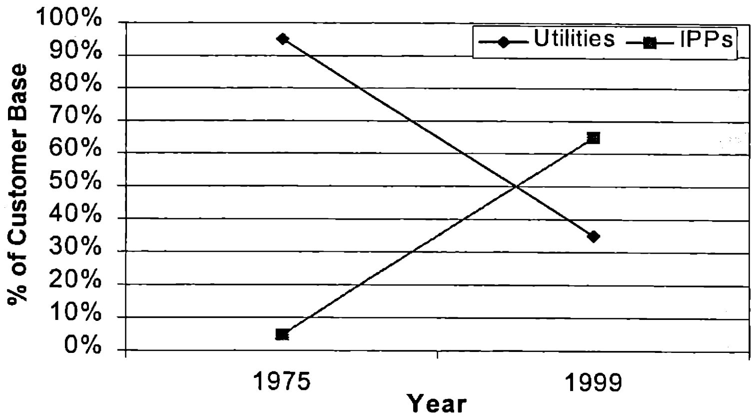

Figure 1: Mix of Power Plant Customer Base (1975-1999)

The foremost impact of the change of customer base is the level of mutual risk sharing. IPPs are predominantly concerned with making a return on their investment in a timely manner. In the current environment this has resulted in OEM's absorbing most of the delivery and investment risks. Therefore customer service and ability to deliver a product on time have become increasingly important in an environment of 'late delivery' penalties.

Competition

Competition in the power plant (and gas turbine) industry is fierce. The use of natural gas in electricity production is increasing in dominance. Technical designs to increase efficiency are intensely competitive and comparable amongst the key industry players. Customer purchasing decisions are made on the basis of market price, efficiency, operation and maintenance costs.

Efficiency is a critical factor as 50% of the electricity cost of a power plant is due to operating fuel cost. In the industry, efficiency is defined as:

$$N = \text{Price (electricity)/Fuel Flow}^5$$

For example, to operate a Combined Cycle Power Plant containing one gas turbine may cost approximately $US 100M in fuel costs per year. In comparison, the capital cost of such a power plant is approximately $US 200M. Therefore over a twenty-year period, one can be outputting $US 2 billion in fuel costs. In this environment, every increase in efficiency counts towards reducing the cost of electricity production and leads to immense savings.

The shift of core competence and business focus

Traditional large utility companies possessed large engineering resources. This environment created an engineering-intensive environment where both utility engineers and OEM engineers spent a large amount of effort on optimizing turbine components to suit individual power plant requirements. Every site had different environmental conditions, and engineers optimized each power plant to increase the efficiency marginally (e.g. from 57.7% to 57.8%). The engineering process involved in optimizing the plant was resource intensive and time consuming. Figure 2 is an illustration of the efficiency-cost tradeoff. This end product ensured marginal cost savings for the utility customer but greatly increased the cost of an engine.

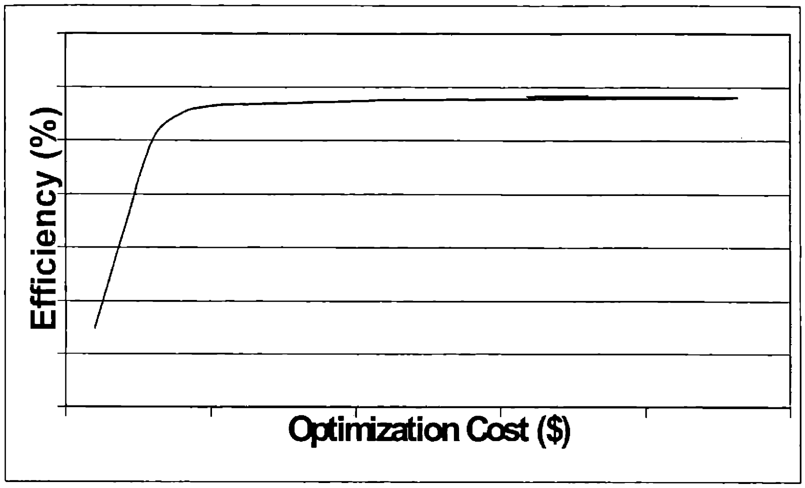

Figure 2: Efficiency and Cost Tradeoff Curve

In contrast, IPPs are financially independent entities that usually possess a small engineering base and do not have the resources to check technical specification on power plant contracts. IPPs are money-making entities that are satisfied with standard parts. Their focus is on high reliability and return on investment. From an IPP's perspective, the plant itself is viewed as a black box with little emphasis on optimizing the hardware to gain the last marginal efficiency increase. In light of this changing customer profile, OEM's have begun to implement the concept of a reference plant with standard hardware.

1.1.1 The Company

The company is the provider of 'cost-effective, efficient and environmentally friendly' energy solutions to an international customer base. It specializes in the provision of turnkey power plants, in retrofitting existing plants, and in the long-term operation and maintenance of plants. The turnkey approach provides the customer with an integrated solution to their power plant requirements from 'well to wire'. Essentially this means that the customer is provided a plant that can be turned on immediately without needing to install any further equipment. The company believes one of the most critical factors to its success is delivery on time and short time to market. It wants to improve the reliability, availability and manufacturability of its products.

The organizational scope of this thesis deals with the gas turbine division of the company (which the author will refer to as Division A). The gas turbine is on the critical path of power plant delivery, and therefore plays an important role in customer service and the prevention of potential penalties. Division A's charter is to develop and deliver modern competitive gas turbines and auxiliaries. It possesses a current product line of six family groups segmented according to different Megawatt outputs.

1.1.2 The Product

The overall product is the turnkey power plant. The company provides this product in a number of configurations that the customer can customize to specific sites. Although the configurations are customized, reference plants exist in which 70-80% of all components are common across configurations. One of the most popular products is the 'combined cycle' power plant. These plants consist of a gas turbine, boiler and steam turbine (see Figure 3). Exhaust gases from the gas turbine are used to generate steam. This steam is then used to power steam turbines. The process recovers some of the energy in the original exhaust thereby leading to very high fuel efficiencies. Using an IGT to drive an electric power plant is also desirable because of the flexibility in fuel types that a customer can use.

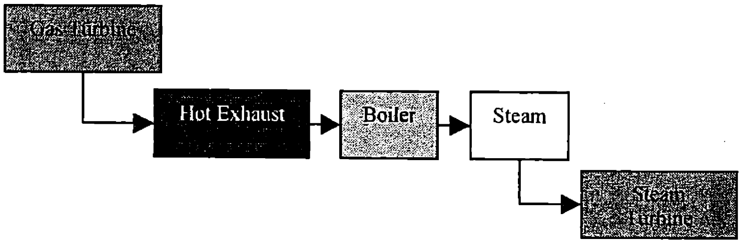

Figure 3: Illustration of Combined Cycle Power Plant

The technical scope of this thesis will cover only the gas turbine, which is part of the thermal block. An IGT is made up of a compressor, combustion chamber and one turbine. Air enters the compressor and is compressed to the appropriate combustion temperature and pressure. Within the combustion chamber the fuel and air mixture is burned and the resulting gases feed into the turbine. These expanding gases drive the turbine, which comprises of rotating stages of airfoils. The turbine in turn drives the power plant generator to create electricity.

In theory all gas turbines at Division A are 100% standardized, while the periphery of a power plant, such as cooling systems, fuel tanks and civil works are 100% customized. All further data and information will be made in reference to two gas turbine Models M (191 MW) and L (277 MW). These newly developed turbines are envisioned to be the future cash cows of the company.

1.1.3 The manufacturing process

The manufacturing scope of this thesis will focus on blades (rotating airfoils) and vanes (stationary airfoils) - precision cast components on the critical path of the gas turbine. These components comprise of both low-pressure and high-pressure parts. Since assembly is done in a sequential manner, it is essential for these components to arrive for installation at a specified point in time in full set[1] quantities. Blades are attached in a row onto the center shaft of a turbine, while vanes are attached to the engine housing and guide the flow of air through the gas chambers. Both blades and vanes undergo similar manufacturing processes that can comprise of up to four distinct steps.

Step 1: Casting

First the components are cast at a casting house. The complexity of shape and type of metal (superalloy, directionally solidifed or single crystal) determines the cost and process time for each component type. Parts are typically cast at near net shapes and may even have some cooling holes already incorporated. However some machining steps are still necessary to meet specification and cooling hole requirements.

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[1] A set is defined as the quantity of identical components necessary to complete a row on the turbine or housing. This quantity can range from 30 – 90 parts depending upon component type.

Step 2: Machining 1

After casting, the component undergoes several machining processes in which the net shape is defined through milling and grinding processes. At this stage, further cooling holes may also be added using Electric Discharge Machining (EDM) and Electrochemical Machining (ECM).

Step 3: Coating

After machining, the component is typically covered with a heat resistant ceramic coating. This is essential for protecting the airfoils from the high temperatures they are exposed to during operation.

Step 4: Machining 2

After the coating process further cooling holes are added to the component. These are done via laser beam machining (LBM). After final inspection, the completed part then travels to the assembly site for insertion into the rotor.

1.2 SUPPLY CHAIN AND LOGISTIC FUNCTION

Within Division A, the supply chain and logistic function is broken into various departments corresponding to sections of the turbine. This thesis focuses on the precision cast component department, which the author will refer to as Department B. Procurement and logistics are conducted at an aggregated level across all engine types. This provides Division A with the ability to purchase raw materials and equipment in much higher volumes.

Since Division A is a matrix organization, responsibility and accountability are widely shared amongst Department B and across other functions – delineating across products and processes. Procurement engineers interact closely with development, quality and manufacturing to share responsibility for the delivery of components. Department B's supply chain spans multiple countries and suppliers of various revenue sizes.

1.2.1 Scope of Responsibility

Department B acts as a cost center to its internal customers - the power train project managers. As a cost center, the department does not get penalized for any delays in its deliveries. These penalties are only experienced at the project manager level. The department is responsible for the following activities:

- Annual Requirements Planning
- Key Account Supplier Selection and Pricing
- Capacity Planning and Allocation
- Production Planning
- Purchase Order Preparation and Activation
- Monitoring Manufacturing and Delivery Progress

These activities involve multiple products and suppliers leading to an information dependent management system.

The author was present in Department B during the pre-serial production phase of the company's new gas turbine family, Models M and L. Although the production of gas turbines occurs in relatively low volumes, the growth of sales has doubled over two years. This translates into medium volume parts manufacturing and sourcing of blades and vanes.

Larger volumes increase the complexity of Department B's responsibility as more suppliers are added to increase capacity. An example of the complexity is illustrated in the Figure 4. Precision casting suppliers A to G produce cast parts of identical and/or different form and function. A unique shaded block in Figure 4 identifies each casting supplier. The travel of parts produced at a specific casting supplier can be traced over the remaining three manufacturing stages and the assembly stage by tracing the path of its shaded blocks. Parts from a specific casting supplier may be processed at any of the three Machining 1 suppliers (H-J), any of the three Coating suppliers (L-M) and any of the three Machining 2 suppliers (Q-J). These parts can then end up at any of the three international assembly sites. Such varied material flow complicates Department B's task.

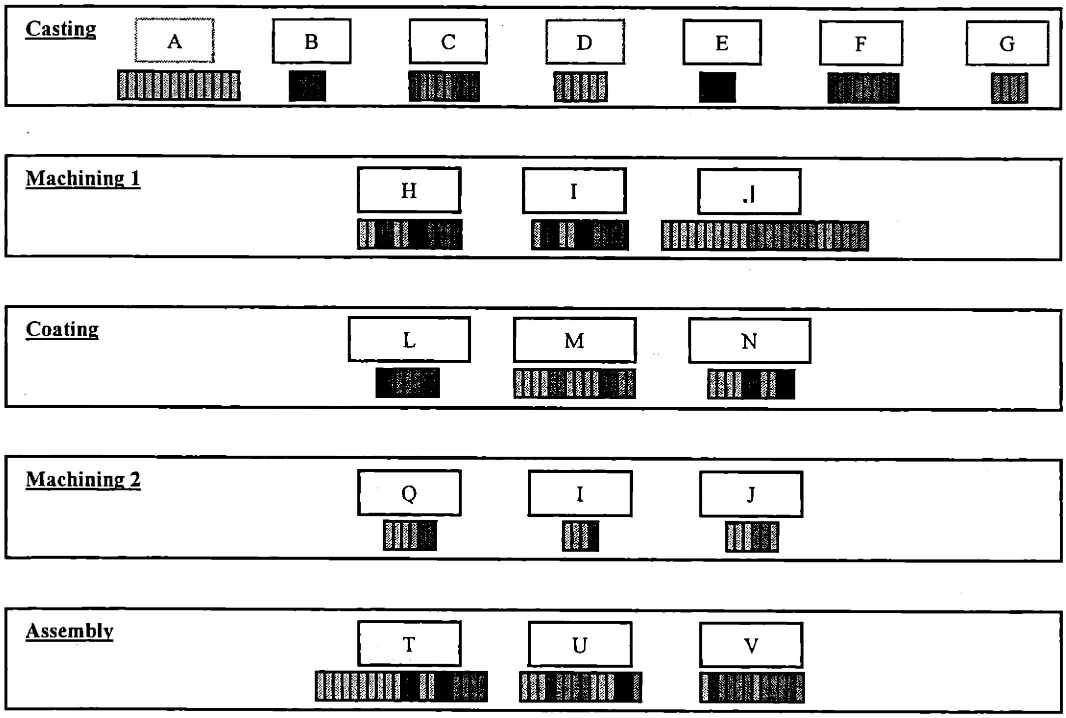

Figure 4: A diagrammatic illustration of Department A's material flow[6]

Letters represent suppliers. Shaded blocks represent parts from a specific casting vendor

The management and coordination of Department B's supply chain is further complicated by:

- Yield rate and scrap losses
- Material delivery shortages and infrequencies
- Differing procurement and replenishment lead times
- Engineering changes in component form and function

The smooth and efficient coordination of this supply chain is dependent upon effective dissemination and interpretation of accurate information.

1.2.3 Design and Development Integration

In an environment of concurrent engineering, integration between Design and Development and Department B is critical. Product development cannot progress until commitment to work with a supplier is made. This commitment is Department B's responsibility via the issuing of long-term contracts and purchase orders. However, these usually cannot be issued until the supplier

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provides firmer pricing quotes. Firmer pricing quotes are dependent upon Design and Development iterating through the existing designs with suppliers. And this iteration is of course pending on Department B committing a contract to a specific supplier.

Upon selection of suppliers, both Design and Development and the Quality Department work in close partnership with Department B during pre-serial production. Constant daily communication is essential during this period as the components are refined and numerous versions of the component pervade the chain. Department B must be kept up to date with engineering change orders so that it can manage the flow of trial and pre-serial parts effectively. All material flow is controlled via manual spreadsheets at Department B's headquarters.

1.3.2 Manufacturing/ Supplier Integration

Department B adopts part push and part pull strategies. It delivers made to stock parts that are then pulled by the various projects in the pipeline. Since the department is making to stock, it has the flexibility to level load its requirements according to capacity.

Department B grew from a manual system handling low volumes and a small network of suppliers. Due to the rapid increase in demand, this old and manual system is now trying to cope with a much more complex set of interactions amongst many first, second and third tier suppliers. Although integration with suppliers is fairly good, principal-agent problems have the potential to arise.

Principal-agent[7] problems are a result of information asymmetry. *Agency* relationships exist whenever one company's welfare depends on what another company does. The agent is the company who acts, and the principal is the company whom the action affects. The principal-agent problem in this case is that suppliers may pursue their own production goals at the expense of Department B's quality, cost and delivery targets.

Due to the manufacturing expertise required in the production of IGTs, some suppliers are in a powerful position. Their production schedules and capabilities have a profound influence on the operation of the supply chain. For example, there are only a few precision casting suppliers in the world that can reliably produce the product that Division A seeks. This results in a high degree of supplier power.

2. CHAPTER 2 – CURRENT PERFORMANCE

Competition in the IGT sector is fierce. Three OEMs hold the volume of market share. Division A differentiates its product on technical performance. In comparison to the other two OEMs, Division A is the Rolls Royce of the industry, while the other two are the Fords of the industry. Such product positioning has implications for the ease of manufacturability of the product.

This portion of the project focused mainly on establishing the current state of Department B's supply chain. It compares what other industries with similar clockspeeds are doing in supply chain management. Information was gathered through benchmarking conducted via email, factory visits and phone interviews. For the purposes of confidentiality, all company data is masked. The findings provide a baseline for current performance, root cause identification, and recommendations for the supply chain.

2.1 SUPPLY CHAIN METRICS

Metrics are essential in establishing the 'health' of an organization. The coordination of internal and external stakeholders is reliant upon metrics. They provide a means for communicating from a common baseline and establishing goals in successive periods. When used in an open and transparent manner, metrics aid in the revision of plans and schedules across the chain. This allows the organization to capture, respond to and disseminate changes.

Metrics for Division A's entire value chain did not exist. Therefore it was operating sub-optimally as each department established and strove to meet its own independent measures. Department B was a relatively new group with limited resources. It was in the challenging position of coordinating pre-serial production whilst developing and refining its own metrics and processes. The adherence to and establishment of processes was problematic. Consequently metrics were not monitored and processes lacked consistency.

2.1.1 Forecasting ability

Department B's responsibility was to ensure that the aggregate demand for engine sets were met. This proved to be difficult as engine set demand came from three segments: new engines and spares, service parts, and retrofits. The forecasted requirements for new engines and retrofits were fairly reliable. Spare sets forecasting was more problematic as orders for these sets were made at the point of new engine purchase and were highly dependent upon the customer's preference for risk. Forecasting for service parts was empirical and almost non-existent. The interaction between Department B and the service function lacked process rigidity. The service function booked new parts out of the system to use as replacement parts without notifying Department B, leading to unexpected engine set shortages.

At an operational level, Department B and its suppliers engaged in highly fluctuating forecasting practices. The department's aims were to level load production through providing a stable unchanging demand forecast. Manufacturing problems, quality issues, design iterations and overoptimistic supplier commitments resulted in corruption of this level demand forecast. Department B strove to provide a rolling four-week forecast to its suppliers which they would then confirm or adjust via excel spreadsheets. However suppliers frequently broke these commitments the week prior or the days prior to the anticipated delivery of the product - leading to disruption of forecasts throughout the chain.

Department B is limited in its ability to handle the forecast information flow across a four-stage process amongst many suppliers. Its utilization of manual spreadsheets lacked reliability and accuracy. Benchmarking highlighted that many established companies employ some proportion of Kanban systems (for stable demand products) in their chain. This simplified the information flow and forecasting component. To simplify the management of the supply chain further, Honeywell Garrett only placed orders with the last supplier in the chain, who was then responsible for upstream supply. At both General Electric and Boeing, forecasts and weekly requirements were sent via the web or EDI once a week without the reliance on manual systems. This is a stark contrast to the tools Department B utilized.

2.1.2 Throughput time

Nearly 85% of the precision cast parts were manufactured externally. A large amount of Department B's time was spent indirectly dealing with issues of throughput time (TPT). Standard throughput times (see Table 1) were quoted by suppliers at the onset of the development projects. These quotes were based on initial knowledge of the product and varied dramatically in the ensuing months.

Part No.	**Casting (wks)**	**Machining 1 (wks)**	**Coating (wks)**	**Machining 2[2] (wks)**	**Total TPT (wks)**
1	6	5	4	6.5	21.5
2	6	5	4	6.5	21.5
3	8	5	4	6.5	23.5
4	8	5	4	6.5	23.5
5	6	7	4	6.5	23.5
6	6	6	4	6.5	22.5
7	8	5	4	0.5	17.5
8	8	6	4	0.5	18.5

Table 1: Quoted TPT for Engine M critical parts

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[2] Includes final inspection period of 0.5 weeks

The actual throughput times for each manufacturing stage were vastly different from the quoted TPTs. Generally, Machining 1, Coasting and Machining 2 take anywhere from two to four times longer than anticipated. Sample TPTs can be viewed in Section four of this thesis. Department B's suppliers were comparatively slower in producing the manufactured part than industry counterparts. The throughput times also fluctuated dramatically thereby impacting Department B's ability to forecast accurately to the next downstream suppliers. There is a tradeoff between variability and inventory, however the department did not account for the TPT fluctuations in planning material flow across the chain.

Benchmarking conducted by the author suggests that other industries were less susceptible to throughput time variation, leading to more stable supply chain management. This may have been due to the stability of component designs. For instance, Honeywell Garret qualified suppliers' process capabilities through statistical techniques ensuring manufacturing stability. Boeing associated supplier incentives with the achievement and reduction of throughput times, motivating suppliers towards achieving agreed TPTs.

2.1.3 Cost

The manufacturing costs were negotiated with suppliers on multiple set quantities. Manufacturing quotes were fairly competitive in comparison to the industry. Department B had selected suppliers on the basis of relationship, cost and perceived capability. Large volume purchase orders were written for 10 sets at a time and then re-negotiated thereafter. A price history of each supplier was kept for evaluating that supplier's 'preferential' status.

2.1.4 Quality

Quality during the pre-serial production phase was poor by any industry standard. Concurrent design iterations and limited manufacturing capability resulted in many non-conformance reports. Scrap rates were up to 4.5% of each manufacturing step. The real number was not established, as accurate data were not available.

The components are technically complex and the quality feedback loops had a time delay of up to three months. This resulted in inventory throughout the chain of varying quality levels and forms. Table 2 presents sample data from a study conducted by the author on Machining 1 processes from a quality perspective. It is evident that many batches were being halted due to non-conformance reports, thereby directly affecting the throughput time.

	Batches	Parts
Sample size	17	624
NCR's raised	10	426
% of sample NCR'd	59%	68%
Rework		58
Scrap		28

Table 2: Machining 1 Quality Data for Component A

2.1.5 Customer Service

Department B's internal customer service was dependent upon suppliers' external customer service. Department B was measured on its ability to meet promised component set deliveries. To date Department B had missed every single promised delivery date to its internal customer (Order Managers – Thermal Block). The actual time delays were hard to gauge as projects were shuffled in terms of priorities in order to minimize the effect of 'late' penalties. Usually a numbered set of components in the pipeline is assigned to a specific project in terms of cost allocation. When delays occur, the most pressing projects might be assigned to that set rather than to the original project, leading to a disruption in customer schedules.

An added difficulty of internal customer service was that all components needed to arrive at assembly in full set quantities at the same time. An uneven spread of type and amount of components in the chain caused further delays. It was estimated that sets were a minimum of 6 weeks late. At the end of 1999 yearly targets had not been reached. Table 3 data indicates that customer service (excluding timeliness of deliveries) was at around 57% for Engine M and 80% for Engine L. Recognizing the tradeoff between customer service and inventory, at this continued pace of performance Year 2000 quantities would not be reached.

Engine Type	Set Quantities 1999 (target)	Set Quantities 1999 (actual)	Set Quantities 2000
Engine M	14	8	22
Engine L	5	4	10

Table 3: Set Completion Targets per Engine Type

Component set delays and poor performances were strongly influenced by the delivery performance of Department B's suppliers. Department B required that all suppliers deliver on a stable weekly schedule. In reality deliveries occurred in monthly cyclical patterns. The first two weeks would result in few shipments while the last two weeks would see deliveries increase dramatically. All suppliers demonstrated this hockey stick effect. The hit rate, defined as the number of orders filled on time, was less than 30%. The poor delivery performance of upstream suppliers would exacerbate the situation at downstream suppliers whose capacity was not able to cope with large fluctuations in deliveries.

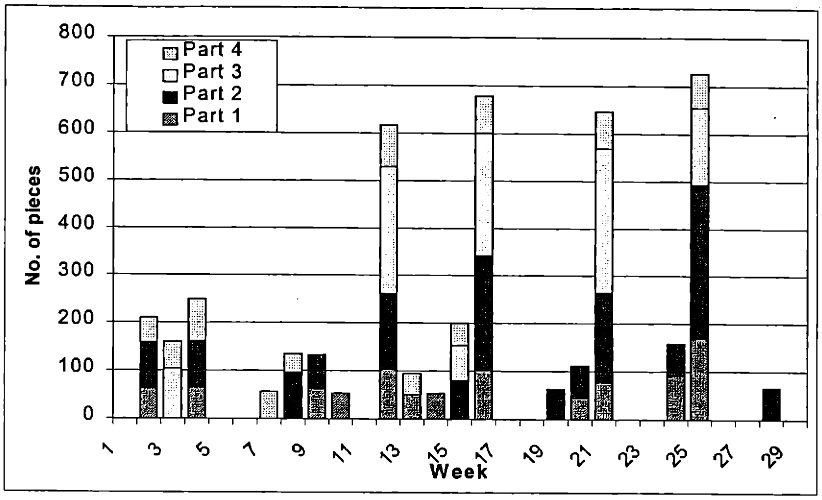

Figure 5: Engine M – Parts 1-4 Machining Supplier Shipments

In comparison, industry players in the aerospace turbine segment coordinate supplier deliveries on a monthly delivery schedule. Many of Department B's suppliers also worked for the aerospace industry. In contrast, the turbocharger industry coordinates the deliveries of its supplier shipments on a weekly and sometimes daily basis. There is a tradeoff between replenishment frequency and inventory, and Department B has selected higher replenishment frequencies to minimize cycle inventory held at each stage.

2.1.6 Inventory evaluation

One of the most chronic problems in the supply chain was the spread of inventory and the lack of control mechanisms. No inventory measures such as inventory turns existed within Department B. The department issued large volume purchase orders to suppliers. These purchase orders were then reconciled as parts moved downstream. With the continued issuance of purchase orders and lack of integrated database monitoring, the chain filled with a large amount of Work in Progress (WIP) that was disproportionately spread across the chain.

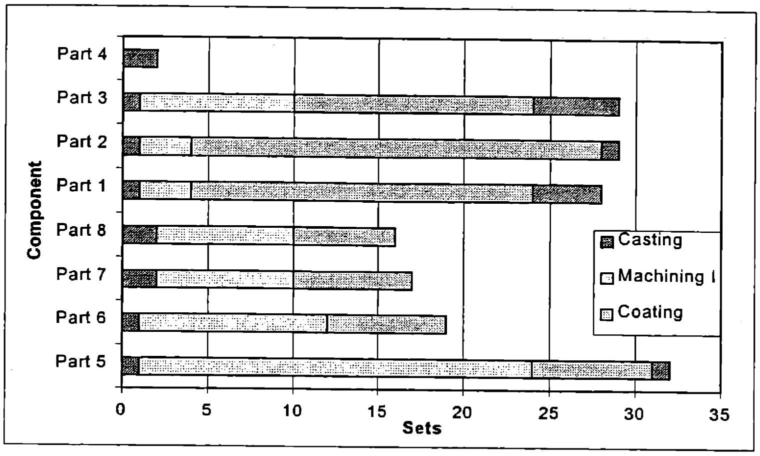

Figure 6: Inventory for Critical Components across the Chain (Wk 27)

From Figure 6, it is evident that the amount of inventory varies according to part. Some disproportionate spread of inventory is acceptable due to the fact that service parts are required for the maintenance of engines already in the field. However the large variation in set quantities amongst part type is a concern. Figure 7 illustrates that within a manufacturing stage there is an uneven completion of sets by part type, of which root causes will be discussed later in this chapter.

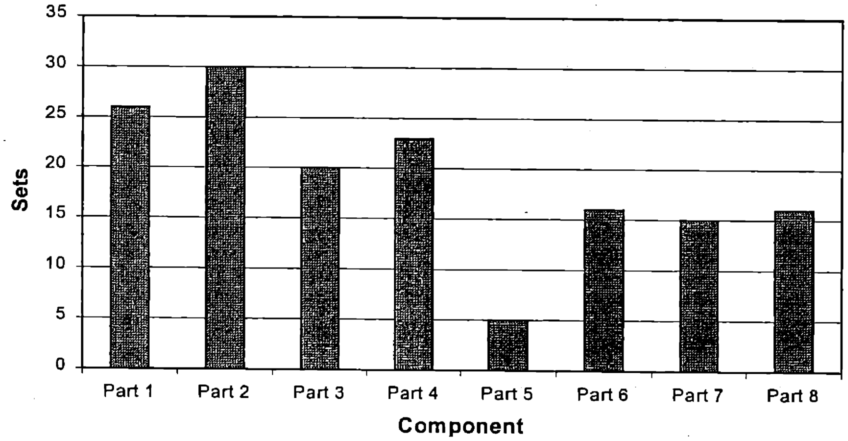

Figure 7: Model A Component Type Completion at Machining 1 Supplier

2.1.7 Financial Evaluation: Time value of material

The lack of overarching metrics across the division resulted in sub-optimal performance to meet departmental targets. In general, the financial justification for a project was that it needed to make at least a 5% return on investment. Within the organization, the impact of supply chain and design decisions on overall project cost is not well understood. The financial costs resulting from fluctuations in throughput time, manufacturing costs, designs and quality were not quantified. Increasing procurement times, complexity of parts, variation and parts failure all drive up the cost of inventory investment. The dynamics of these cost drivers are currently not linked to project costs.

The relationship between inventory investment and aggregated project costs is illustrated in Figure 8. There is an optimum point in time that Department B should deliver all promised component sets for assembly on to the rotor or housing. This point A theoretically minimizes all combined costs of rotor assembly and procurement. If sets are delivered earlier than point A, the added cost of holding inventory applies, and the cost is proportionate to the number of days it was delivered early. However if the components arrive later than Point A, holding costs accumulate for parts that are already at the rotor assembly site, and transportation costs accrue for expedited parts. At a certain point B in time, the rotor cannot wait any longer for the missing components and is shipped to the site for installation. Hence there is a marked jump in costs if parts are delivered after point B because they must now be expedited to the plant site, the engine reopened and the parts installed. Any delay beyond point B deducts from the time available to conduct commissioning. At a certain point C, the provisional hand over of the plant usually occurs. However if the precision cast parts do not arrive at this point, 'late penalties'[3] apply. These penalties can be a couple of million US dollars per week, and hence the dramatic jump in the graph and its upward sloping curve. The financial impact of Department B's delivery delays on overall projects has never been quantified.

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[3] These penalties are incurred on a daily basis once the provisional hand over date has passed.

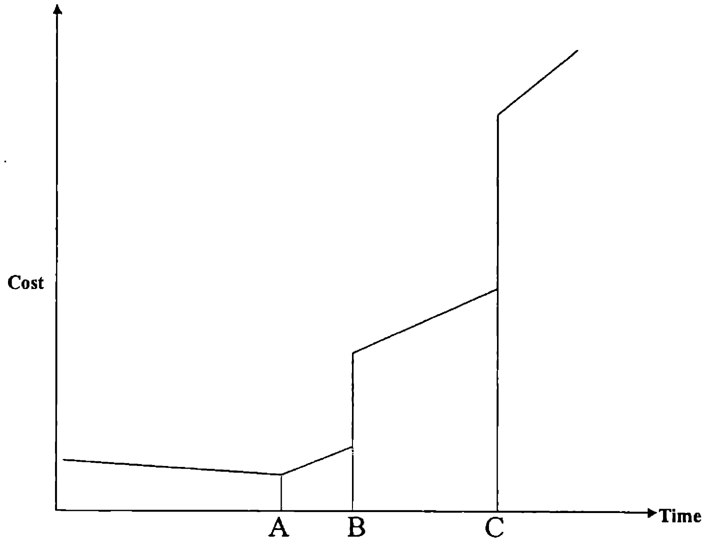

Figure 8: Cost versus Project Time for Precision Cast Components

Department B acts as a cost center to its internal customers. Its goals are to minimize costs while maintaining high service levels. However only the cost of inventory and transportation are incorporated at this level. The aggregated costs of the project are not considered. This has implications for the financial decisions of inventory levels and customer service targets. From Figure 8 it is evident that the costs in delivering sets early (or holding inventory) are much lower than the costs incurred in delivery delays. There is a time value to the material and huge potential exists for exploding costs due to missed project timelines. A metric to account for this dynamic should be incorporated at Department B's level. This may change the target of acceptable level of inventory that is present in the pipeline.

The predominant cost of the department is the investment in inventory. In the pre-serial production environment, Department B was not balancing its costs. Of foremost priority was the output of material in order to meet customer delivery targets rather than the efficient management of costs. The WIP value for critical parts rose steadily during an 18-week period (see Table 4), as the criticality of delays became more apparent. What was not being asked was what the acceptable level of inventory investment should be given the procurement variation and large penalties.

Week	Value ($US)
27	30.42 M
34	35.73 M
45	50.40 M

Table 4: Comparison of Inventory Investment

The impact of supplier behavior on aggregated project costs was also not well understood. Financial metrics at the supplier level were non-existent. Department B calculated the dollar volume share of business that each supplier had. It did not compare what proportion of the costs were due to rework and scrap levels. No risk was shared between suppliers and Department B for exceeding scrap levels, rework due to supplier error or missed deliveries. As Department B paid for the castings that traveled through the chain, it took ownership for the majority of financial risk, leading to principal-agent problems with suppliers.

Department B also absorbed the financial risk of engineering design changes. The dynamics between increased costs and engineering change order were also not well understood. Change orders usually resulted in an extension of lead time, non-conformance, rework and obsolescent parts. All these additional problems affected the timeliness of deliveries and hence brought the Department a step closer to incurring late penalties for the project managers.

2.2 ROOT CAUSE ANALYSIS

Department B was faced with many symptoms that it addressed through reactive firefighting methods. The more time the department spent firefighting, the less time there appeared to be to identify and address root causes. This section will present some of the root causes to Department B's problems in terms of organization, information management, the pace of change and manufacturing capability.

To explain some of the root causes and their interactions, a systems view will be taken. The concept of the time value of material is particularly evident through the use of Figure 9. This is a representation of a single supplier as a system of actions and decisions. It is not all encompassing but includes key dynamics in the flow of material through a single stage. The discussion of root causes will refer to this diagram.

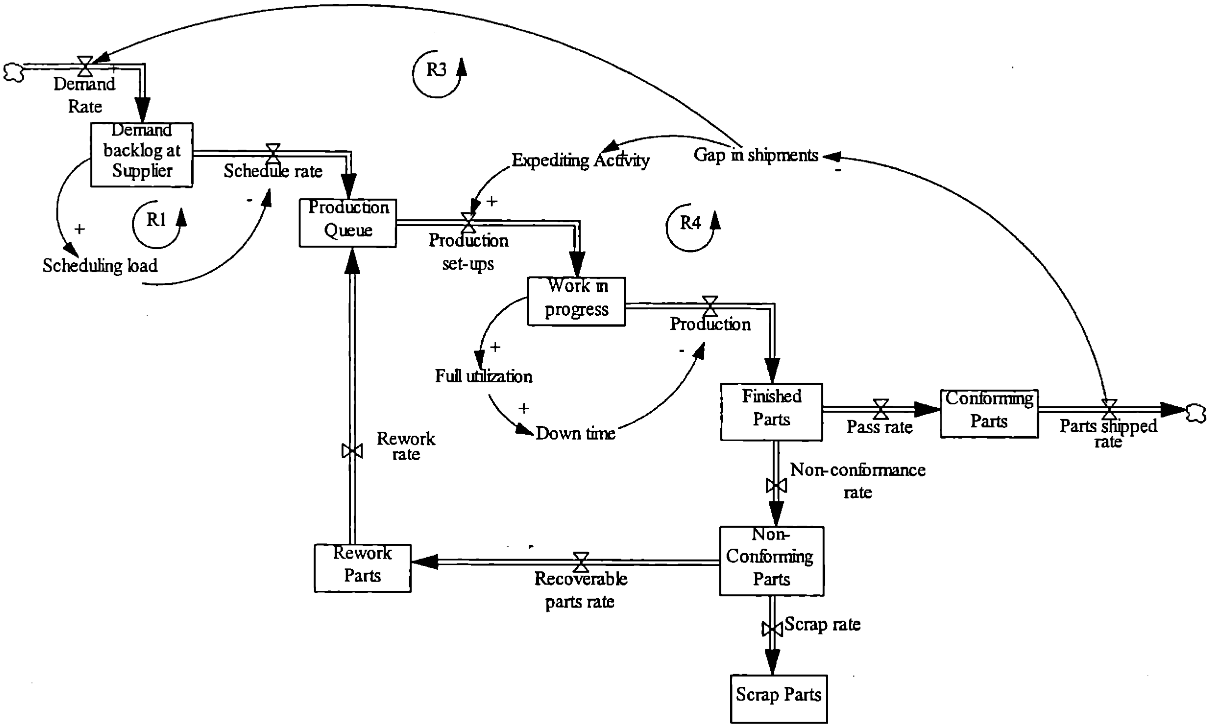

Figure 9: Systems View of Single Supplier[8]

Figure 9 shows the stocks and flows in a production process. All rectangles represent stocks that can increase or decrease as a function of the inflow rate relatives to the outflow rate. The rates in the system are represented by valves and are influenced by the factors pointing directly to those valves. These factors can either increase or decrease the flow rate through the reinforcing or correcting behavior of the loop they form. A reinforcing behavior shifts behavior further away from the desired goal, while a correcting loop shifts behavior back towards the goal. Figure 9 demonstrates that expediting actions disrupt the production process and increase equipment utilization leading to increased downtime and loss of production. The systems view also highlights that stocks have inherent time delays in them before they respond to induced changes. The volume of rework is also a critical feedback loop that affects the rate of production.

2.2.1 Internal Organization

The level of supply chain coordination is strongly impacted by internal factors to the business. Without clear processes and accountabilities there is little opportunity for improvements external to the business. The following root causes were perceived as a hindrance to progress:

- *Lack of departmental performance measures linked to overall project success and supplier performance.* This resulted in poor internal and external performance monitoring based on time sensitive data.
- *Lack of discipline and transparent processes.* Few people within the department could articulate the processes, stakeholders and information necessary to procure parts. This lack of understanding led to incorrect data entry and information handling.
- *Lack of team based approach to supply chain management.* Department B comprised of people acting independently of their colleagues. Individuals were responsible for one process only and had minimal interaction with those responsible for upstream and downstream processes. The logistics and supply chain functions within Department B acted as separate entities. To complicate things further there existed multiple Division A contacts for each supplier, causing communication difficulties and mixed incentives.
- *Failure to follow through actions.* The matrix environment at Division A did cause some accountability and responsibility issues. Even once an action was committed to within Division A, there would often be a lack of follow through actions leading to a further deterioration of the issue.
- *Treating the supply chain as a deterministic environment.* The department did not account for variation in its planning. This led to a lack of understanding of the dynamics of the system.

These organizational root causes hindered the ability of the department to respond to and adapt to changes.

2.2.2 *External Organization*

The symptoms of Department B's problems also found their roots in supplier organizations. The coordination of different sized suppliers with varying business philosophies and capabilities proved to be a challenge. The following root causes were identified as sources of conflict:

- *Quest to achieve monthly sales targets*. This is the dominating incentive for supplier performance. Each supplier needed to meet the monthly sales target causing agent-principal issues for Department B. Suppliers were not concerned with the weekly deviations from planned shipments; they compensated for these with a massive shipment at the end of the accounting month. The push to meet monthly sales target also meant that in the latter part of the month, supplier production focused on components that were easy to process and for which a premium was charged (leading to high sales volume). This exacerbated the disproportionate spread of component type in the chain.
- *Supplier production metrics.* The key metric at many of the suppliers was utilization of plant machinery. Therefore production set-ups were kept to a minimum, to ensure utilization figures in the 90-percentile band. This leads to long batch runs.

2.2.3 *Information Management*

The role of information is critical in determining the optimal replenishment strategies. The information flows are subject to delays. Since supply chain management involves the constant revision of plans and schedules across the chain, its agility is currently hampered. The ability to capture, respond to and disseminate changes is limited by the following root causes:

- *Poor planning and scheduling systems (information deployment)*. The lack of real time common information interfaces across suppliers inhibited forecasting and planning. Department B made all volume allocation and transportation decisions and its use of manual spreadsheets to manage this information flow is inadequate. In addition, SAP, as an enterprise planning tool, lacked credibility due to limited understanding of the system and poor customization and implementation.

- *Lack of validity and accuracy of data at the source.* The data used within Department B is an aggregate of data sent by suppliers. This data is often brought into question because of its failure to hold up to detailed analysis. Suppliers commit to deliveries and processing times that they then rescind on. In turn, Department B provides its internal customers with data that is based on rough projections based on supplier data, which it then rescinds.

2.2.4 Engineering Change Orders

'Changing the location of a fitting in an engineering drawing may cause subsequent changes in other subsystems such as (logistics) necessitating rework far beyond the original change. These changes may in turn cause workers to be rescheduled from one task to another, delaying some tasks and accelerating others. Such juggling of resources to handle the rework may then lead to the delays on other projects that find themselves dependent on completion of the deferred tasks.[9]

The level of rework at suppliers was considerably high due to the concurrent nature of design and manufacture. The following root causes impact the effect of engineering on the supply chain:

- *Lack of design freezes.* During the period of this thesis, there were over 200 engineering change orders for components of Engine M and Engine L causing part redundancy, delays in processing and confusion.
- *Lack of design for manufacturability and feedback.* Designs were complex and hard to manufacture leading to many revisions. There existed little feedback on the ease of processing from suppliers to Division A.
- *Lack of field experience.* Feedback on necessary part redesigns trickled in as engines in the field accumulated operating hours. This leads to continuous change orders over time.

In concert, these causes created an unstable environment in which constant redesign and non-qualified processes were the norm rather than the exception. This effect creates schedule compression. It increases the degree of concurrency in design and between design and production, resulting in excess overtime, fatigue, increased errors, reduced quality, and strain on project management team. The cost of a seemingly innocent design change can exceed by many times the direct cost of the change order itself.

2.2.5 Manufacturing Capabilities

Department B selected its suppliers based on relationship, price and capabilities. Its suppliers were a combination of small job-shop companies, to larger single source suppliers. At the onset of pre-serial production, many new features were introduced in parallel to components. This influx of change led to suppliers adopting new manufacturing processes. The following root causes were a significant source of variation in the supply chain:

- *Lack of process capability*. Many processes were new to suppliers and they had not traveled significantly down the learning curve. This resulted in a lack of understanding of process parameters, and an average scrap rate of 4.5% and rework rates of up to 68%. It also resulted in a lack of labor competency.
- *Significant set up costs*. Difficult and lengthy set-ups resulted in scheduling policies that maximized batch runs. Set-ups usually involved the preparation of complex fixtures and numerous sub-optimizations to achieve stable process flows. Equipment set-up times ranged between 2 to 8 hours.
- *Equipment reliability problems*. Critical equipment broke down on a fortnightly basis due to poor preventative maintenance. As machine utilization was an important metric, preventative maintenance time was often not scheduled. The mean time to repair for broken equipment ranged between 4 to 8 hours.

2.3 CONCLUSIONS

As outlined in the previous section, the root causes introduced both 'hard' and 'soft' operating constraints. The most significant constraints affected both flexibility and reliability and had a marked impact on the aggregated costs of the project. If these root causes are not addressed and the time value of material is not understood, then late penalties will continue to be incurred.

At a minimum, improvement efforts should commence focusing on critical parts that form 80% of the customer service problems. Efforts should use the following tactics adapted from Hopp and Spearman:[10]

1. Improving forecasting to internal customers and external suppliers.
2. Reducing cycle times by attacking top sources of variation
3. Improving internal and external scheduling through improved knowledge and tools
4. Looking for structural changes to the organization. Reorganizing internal and external responsibilities and accountabilities. Implementing and aligning overarching and local level metrics that prevent agent-principal problems. Distinguishing between critical and non-critical design changes and nominating set points in time to introduce these changes
5. Service levels. Identifying and committing to target service levels. Calculating the corresponding inventory levels (and stockout frequency) for these levels.
6. Reducing queue lengths and starvation times

The above recommendations will reduce the impact of variation in the system and the likelihood of further deterioration and late penalties. Thereafter improvement efforts can start to focus on optimizing the system.

3. CHAPTER 3 – SCENARIO INVENTORY MODEL

All models are a representation of the real world, and in that respect cannot fully reflect all interactions. However models do enable users to assess situations in a structured and quantitative manner. There are many types of supply chain models, some of which are outlined below:

- Inventory buffer models to ensure customer service levels
- Deterministic optimization models for determining production rates and allocations
- General purpose simulation
- Systems that do finite scheduling
- *Enterprise planning systems that do planning and scheduling*. These systems require high levels of information technology investment and non-value added processes such as data collection

All these models enable users to explore, decide on and implement actions to improve the performance of the supply chain.

There is ample operations research in the area of inventory management across multi-echelon systems. As the management of variance in the system is the key problem in Department B's supply chain, focus was placed on minimizing the effect of this variance via the use of inventory buffers. Chapter 2 highlighted that the management of variance in the chain was not being effectively done. This chapter will therefore focus on the strategic placement of inventory in the chain in order to minimize variance effects. An outline will be presented for a general methodology for modeling Department B's supply chain. The model objectives, inputs, algorithm and outputs and their interpretations will be explained.

3.1 INVENTORY MODEL OBJECTIVES

The previous chapter dealt with systemic issues that need to be addressed to achieve sustainable improvements and performance. Department B handled both short term and long-term issues through a combination of reactive decision making and rough 'gut-feel' estimation. The analysis and review of existing data was non existent. Therefore an understanding of the trade-off between customer service levels and inventory was lacking.

This inventory model aims to address short to medium term needs through the use of supplier data and scenario planning. It recommends strategic placement of inventory buffers. The scenario model:

- Aids in strategic planning of correct material release quantities
- Emphasizes the importance of reliable, accurate and valid data
- Gauges current service levels
- Quickly identifies where variability reduction efforts should be focused based on capital investment and process stability
- Highlights the cost trade-off of holding inventory buffer versus lower customer response levels.

The model calculates the average inventory level necessary to support a nominated customer service (protection) level. It also translates demand into the actual demand each process stage will see. Finally it allows experimentation with scenario options to de-couple and couple processes.

3.2 DATA INPUTS

The data inputs rely on both accurate and valid internal and external information. The data is divided amongst the four stages of production.

3.2.1 Demand and Cost Inputs

The first set of data needed for entry is the aggregated demand requirements. The model then calculates the weekly requirements given the following entry information per component:

- The number of sets required for the year and the associated standard deviation
- The number of pieces per set
- The actual weeks of production per year
- The allowable scrap level per stage of manufacturing

Since production occurs in series, the mean demand at each manufacturing stage is identical but the effective mean demand (μ) varies according to allowable scrap levels.

For each manufacturing stage, the user must also enter the following data:

- Value-added cost per piece. This is the monetary value of work done to a piece at that manufacturing process
- The review period 'r'
- The risk level 'z'. This is the number of standard deviations of protection chosen. It can also be viewed as the internal customer service level at that stage.
- The volume share each supplier has of that demand

3.2.2 Procurement Lead time Inputs

The model is reliant on two lead time measures. It requires both the procurement lead time and the maximum replenishment lead time at each of the four stage processes for each supplier. The procurement lead time is the average time taken from the entry point of raw material to the product exit. It is essential that users also enter the variation of that lead time. The maximum replenishment lead time is the maximum time between subsequent shipments of incoming material.

3.2.3 Supply Rate Inputs

The supply rate is a critical variable in this model as past performance suggests that this was the source of biggest variation. Users need to enter the average supply rate and variance at each manufacturing stage. The supply rate is defined as the average quantity delivered per week from that supplier.

3.2.4 Scenario Modeling Options

The modeling options allow the user to start experimenting with various supply chain strategies. Figure 10 represents an aggregated view of Department B's supply chain. The squares represent a process and the triangles represent potential inventory buffer holding points.

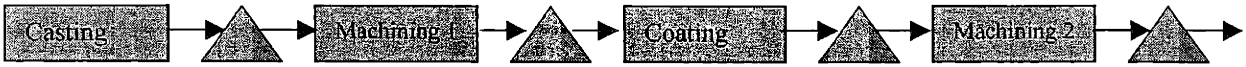

Figure 10: Inventory Buffer Options

The user can couple or de-couple manufacturing stages by holding inventory at these strategic points in the chain. 'Couple' means that inventory is not held immediately after a particular stage but rather at the next 'selected' downstream inventory holding point. 'De-couple' means that inventory is held immediately after that stage. These modeling options are made possible through Excel's 'If then' capabilities and Boolean logic. A number of comparative statements enable a scenario engine to compute the data.

Once the user nominates a desired customer service level she or he can then vary the inventory buffer locations by coupling or de-coupling stages. Examples of some of the modeling options are given in Table 5. In the table, a "1" indicates that the stage is de-coupled from the next downstream stage, and a "0" indicates that the stage is coupled with the next downstream stage. All possible inventory placement strategies for a single component can be represented as follows: 1000, 0100, 0010, 0001, 1100, 1010, 1001, 0110, 0101, 0011, 0000, 1111, 1110, 0111, 1101, 1011.

	Coupling Choices					
	Part 5 Choice	Part 1 Choice	Part 2 Choice	Part 3 Choice	Part 9 Choice	Part 10 Choice
Casting	1	0	1	0	1	1
Machining 1	1	1	1	0	1	1
Coating	1	0	1	1	1	1
Machining 2	1	1	1	1	1	1

Table 5: Coupling Choices for Manufacturing Stages

By varying the scenarios, the user can view the monetary impact of inventory placement decisions.

3.2.5 *Current Inventory Levels*

Another advantage of the model is that it can be used in reverse order. The user can enter current inventory levels in the chain at each stage and estimate the current service level. This will enable users to estimate the likelihood of meeting year-end targets.

3.3 MODELING THE SUPPLY CHAIN DYNAMICS

Standard models do not apply to Department B's situation because there are many significant sources of variation such as the lead time and the supply error. The scenario inventory model is based on an adjusted period review model that caters for the large differences between promised and actual performance.

The adjusted inventory model is based on a cycle stock and safety stock level. Let the average inventory (I), be the sum of the average cycle stock and average safety stock.

I = Average Cycle Stock + Average Safety Stock

The average cycle stock represents the amount of stock on hand between lot size replenishments. The author selected a lot size equal to the amount of material demanded over the maximum time between replenishments.

Average Cycle Stock = $$(D \times L_R)/2$$

where
$D =$ *the mean weekly demand*
$L_R =$ *the maximum time between replenishments*

The average safety stock is the stock on hand that caters for the fluctuations in demand versus supply rate during the average procurement lead time. Another way of interpreting this is to ask how long it will be before the supply chain function can affect what is being delivered. Usually one would have to wait until the time of the next order (the review period plus the lead time for that order). The safety stock is the level of protection chosen (the number of standard deviations) multiplied by the variation in the system.

Average Safety Stock = $z \times \sigma$

where
z = *the number of standard deviations of protection chosen*
σ = *the standard deviation of the process*

A graphical representation of the cycle and safety stock is given in Figure 11. The saw tooth graph represents the cycle stock that is being depleted through processing, and replenished through raw material deliveries. The height of the saw tooth graph is determined by the safety stock and lot size. The reorder point for replenishments is determined by the demand rate and lead time for raw material deliveries.

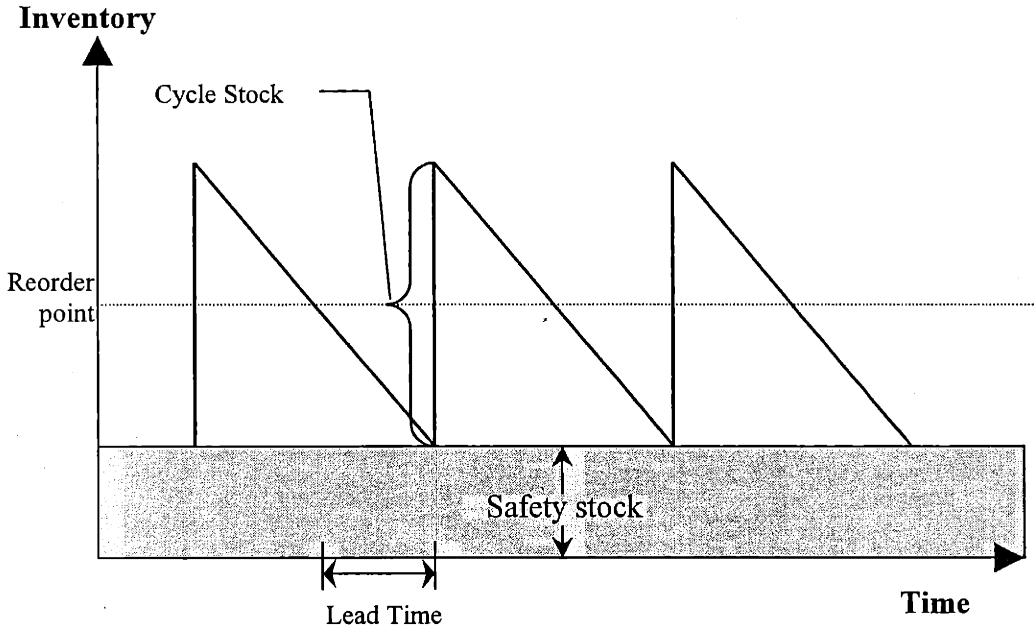

Figure 11: Illustration of Cycle and Safety Stocks

3.3.1 Variation at a single stage

When Department B places a replenishment order, it theoretically should order what it expects the demand to be at that manufacturer over the lead time. Based on historical data, suppliers have struggled to meet even these delivery targets. As a result, there exist significant supply errors in the replenishment of the four-stage process. Therefore the random variable upon which variation at each supplier will be based on is the demand plus the supply error during the lead time. This deviation between demand and the actual supply rate from the supplier is what the department must protect itself against.

Let the random variable P, be the sum of the demand and supply error:

$$P = D + S_e$$

where
$D =$ *the demand rate per unit time*
$S_e =$ *the supply error rate per unit time*
$=$ *S-E(S)*
where
$S =$ *Supply rate per unit time*
E(S) $=$ *Expected supply rate per unit time*

It follows that the mean square error (MSE) of the random variable, P, during the lead time is a function of the variances in lead time and the variance in the demand and supply error. The variance is defined as follows:

$$\sigma^2(P) = E(L+r)\sigma^2(D+S_e) + E(D+S_e)^2\sigma^2(L+r)$$

where
$L =$ *the lead time in weeks*
$r =$ *the review period in weeks*

The remaining derivation is given in Appendix A. The final MSE equation for a single manufacturing stage is:

$$MSE(P) = E(L+r)\sigma^2(D) + E(L+r)\sigma^2(S) + (E(L+r))^2 S_B^2 + (E(D))^2\sigma^2(L+r)$$

where
$S_B^2 =$ *the supply bias*
$= (E(D)-E(S))^2$
$E(D) =$ *expected demand per unit time*

3.3.2 Variation propagation: The impact of bottleneck suppliers

The four-stage serial nature of the supply chain has a great impact on the propagation of variation. In an environment where there are usually one or two highly utilized suppliers for a manufacturing stage, the process variation of those suppliers become critical. This is due to the fact that for highly utilized suppliers a portion of the process variation at that stage is propagated to all downstream suppliers. Figure 12 illustrates this point.

Figure 12: Impact of Process Variation on Downstream Delivery

Therefore if the supplier exhibits high variation, this will result in a highly variable delivery output. If the bottleneck has significant volatility then it is advisable to hold buffer stock after the bottleneck to dampen the variation propagation.

The identification of bottleneck suppliers in the four-stage process becomes critical. If the bottleneck supplier exhibits high variation and is at the beginning of the chain, then the remainder of the chain will propagate this variation and a portion of their own variation. Effectively a stage will see the variation of the bottleneck and the variation of any downstream processes before the stage in question.

To account for variation between suppliers in series, the following equation by Hopp and Spearman[11], used to calculate the propagation of variability between workstations in series, will be adapted to a supply chain context.

$$c_d^2 = u^2 c_e^2 + (1 - u^2) c_a^2$$

Where
c_d^2 =squared coefficient of interdeparture times
c_e^2 = the squared coefficient of variation of the process times
c_a^2 = the squared coefficient of the interarrival times
u = the utilization of the work station

To adapt the above equation to a serial supply chain, let the variables be redefined as follows:

Then the general equation for variation propagation becomes:

$$\sum_{i=0}^{N} \sigma_i^2(S)\cdot u_i^2 \underset{k=i+1}{\overset{N}{\pi}}\left(1-u_k^2\right)$$

The derivation of this equation is in Appendix B.

u_i = *(Bottleneck supply rate/supply rate) at stage i downstream from the bottleneck*
c_i^2 = σ_i^2 = *Variance of supply rate at stage i*
N = *the number of stages beyond the bottleneck*

3.4 OUTPUTS

The model provides the following output pages presenting the scenario information in various forms.

- Inventory and Investment Summary and Inventory Map. This spreadsheet details the safety stock required at each chosen inventory placement stage given a specified customer service level. It also calculates the corresponding inventory investment required at each chosen inventory stage. A visual inventory map (Figure 13) allows the user to represent the chosen strategy visually and with total investment necessary.

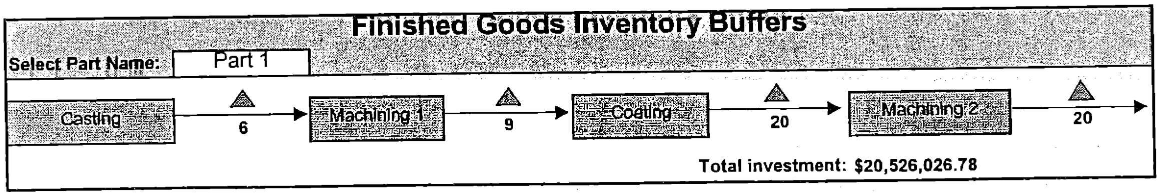

Figure 13: Inventory Map for Part 1 under a Specified Scenario

- Inventory Placement Outputs. This is a more detailed break-down of the cycle and safety stock at each stage for each supplier given a specified scenario. Inventory costs are also broken down according to stage and supplier.
- Graphs. The model provides many graphs with information broken down in various forms:
  - Inventory in Chain Graph. Comparison of annual inventory necessary to support the chain in order to meet annual demand with nominated safety factor
  - Inventory Investment Graph. Comparison of inventory investment required to meet annual demand.
  - Inventory Stage Graph. Comparison of annual inventory necessary at selected stages to meet annual demand; this includes base demand and safety stock.
  - Inventory Levels Graph by Part (Figure 14). Comparison of expected cycle stock and safety stock at each chosen process stage for a single part

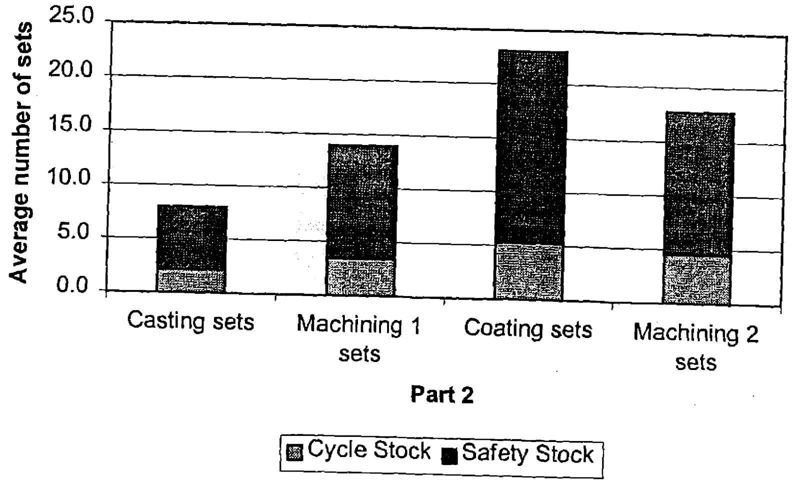

Figure 14: Safety and Cycle Stock for Part 2

- The Average Procurement Lead Time Outputs. This spreadsheet calculates the average procurement lead times and variance at each process stage given individual supplier data.

- The Average Supply Rate Outputs. This spreadsheet calculates the average supply rates for each process stage given individual supplier performance data.
- Supply Rate Variance Outputs. This spreadsheet calculates the variance of the supply rate at a specified stage given the propagation of variance through the chain.
- Current Service Levels. This provides service levels given the current inventory in the chain. Appendix D provides an example.

4. CHAPTER 4 – MODEL RESULTS AND IMPLICATIONS

This chapter presents results on Engine M's supply chain. Data for critical parts on Engine M was entered into the model. The results presented both expected and unexpected findings. Delay of critical parts on Engine M was due to the propagation of variation in the chain. Lack of controlled material release and inventory buffer placement further exaggerated the situation. The model provided cost-effective inventory placement strategies that had previously not been considered. It enabled Department B to learn about its dynamic supply chain and the numerous placement options available to meet desired customer service levels. Details of the model are outlined in the sections below.

4.1 INPUTS

Gathering accurate and valid data for the inputs was one of the greatest challenges. The existing system did not demand data in a form amenable to using in the model. Input data was gathered from a number of sources:

- Department B internal data
- Supplier internal data
- Supplier estimates

With the exception of only two suppliers, no other suppliers measured the variances of their processes. Department B did not request such data from its suppliers thereby highlighting the deterministic nature of the supply chain planning function.

4.1.1 Demand and Cost Data

Cost data was relatively easy to access via Department B's cost information. All costs were aggregated on 10 set contracts at each manufacturing stage. Demand data was more difficult to obtain because of the uncertainty of spare parts and service parts demand. An estimate based on an empirical model was used. For the purpose of this thesis, a demand of 60 sets per year was assumed for each critical part. The customer service level at each stage was selected to be 97.5%.

4.1.2 Procurement lead times

Internal data was not robust enough to provide accurate lead time estimates. Therefore, data had to be collected directly from suppliers. Suppliers felt strong ownership of lead time data for competitive reasons. This caused some problems for open and honest information sharing between Department B and its suppliers.

Table 6 is a combination of real and estimated lead times[4]. High variation and deviations from the quoted lead time (presented in Table 1) highlight the lack of process control amongst suppliers. The reader should note that all casting times are the quoted TPTs as casting houses would not divulge actual lead time information.

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[4] Estimated lead times were based on WIP data and tracing batches through the supply chain.

Process	Components					
	Part 5	Part 1	Part 2	Part 3	Part 9	Part 10
Casting Lead time	6.0	7.0	7.0	8.0	13.5	6.0
Castiing Variance in Lead Time	1.0	1.0	1.0	1.0	1.0	1.0
Machining 1 Lead time	11.0	8.0	7.25	7.5	11.7	15.6
Machining 1 Variance in Lead Time	3.0	4.1	6.2	6.2	11.2	14.2
Coating Lead time	9.6	15.4	18.9	13.9	13.6	9.4
Coating Variance in Lead Time	9.6	25.5	18.9	27.6	13.6	9.4
Machining 2 Lead time	12.0	11.0	9.0	8.7	12.0	11.1
Machining 2 Variance in Lead Time	7.0	17.8	6.0	6.0	30.2	32.9

Table 6: Lead Time Data Across Supply Chain

4.1.3 Replenishment Lead Times and Supply Rates Inputs

Table 7 presents replenishment lead times. These were calculated using WIP sheet data. What is striking about the replenishment lead time data is that no supplier fulfilled the requirement of weekly deliveries.

Process	Component					
	Part 5	Part 1	Part 2	Part 3	Part 9	Part 10
Casting maximum replenishment lead time	2.0	6.0	3.0	2.0	4.0	7.0
Machining 1 maximum replenishment lead time	6.0	5.0	5.0	5.0	9.0	13.0
Coating maximum replenishment lead time	6.0	5.0	8.0	5.0	6.0	13.0
Machining 2 maximum replenishment lead time	9.0	13.9	7.0	7.0	6.0	9.0

Table 7: Maximum Replenishment Lead Time (Wks)

The supply rate data in Table 8 is also quite sobering. Generally the further up the chain the part progressed, the less likely it was that weekly delivery quotas were met. The variance of the supply data was immense, once again highlighting unstable processes.

Process	Component					
	Part 5	Part 1	Part 2	Part 3	Part 9	Part 10
Casting supply rate	84.0	42.3	56.0	66.9	86.5	35.9
Variance of casting supply rate	2254.3	1157.8	1203.9	1132.3	2692.4	1852.0
Machining 1 supply rate	113.2	65.2	100.6	102.2	116.9	70.7
Variance of machining 1 supply rate	21872.1	2366.8	8525.4	10115.9	14276.9	6559.5
Coating supply rate	24.4	30.4	50.5	62.6	41.4	30.8
Variance of coating supply rate	401.2	808.5	2098.5	1741.9	1404.9	618.3
Machining 2 supply rate	11.0	13.9	13.5	15.0	26.1	18.3
Variance of machining 2 supply rate	4.0	2.3	42.8	45.0	425.7	232.5

Table 8: Supply Rates (Parts/wk/time)

4.2 OUTPUTS

This section presents the model outputs with respect to six critical parts on Engine M. Two parts will be investigated in further detail with respect to their inventory investment, stock levels and inventory buffer strategies.

4.2.1 Annual Inventory Necessary to Support Demand

Given the current variation in the chain, more than 180% of the base demand for each part is needed to satisfy a customer service level of 97.5%. This estimate includes the base stock and safety stock required at each level. Figure 15 provides a graphical overview of the results.

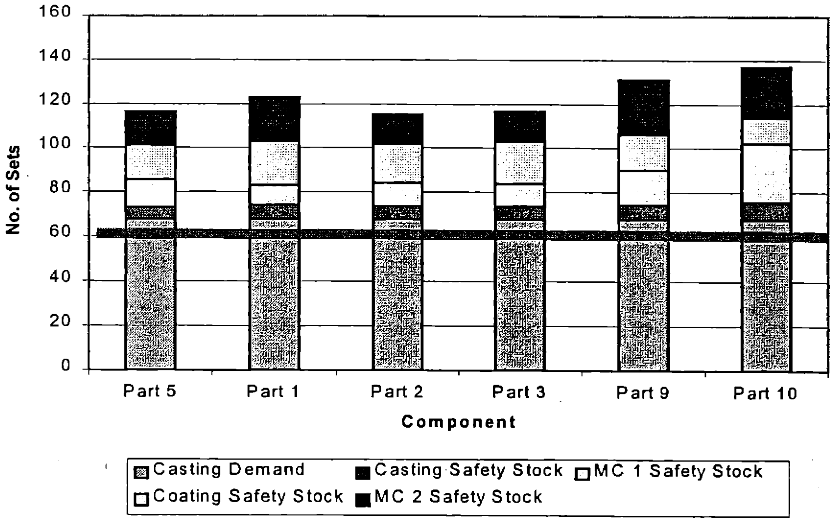

Figure 15: Annual Inventory Necessary to Meet Annual Demand

All parts possess a base stock greater than sixty because of the inherent scrap allowance. However any stock thereafter is solely due to the variation in the process. From this graph it is evident that Part 10 possesses the greatest variation because it requires over 225% of the base demand to fulfill the nominated customer service targets.

4.2.2 Monetary Investment Needed to Meet Annual Demand

This output links the input variables to monetary considerations by quantifying the cost of inventory for a desired strategy. By adjusting the service levels and inventory buffer locations, users can identify the associated investment costs. Figure 16 indicates the investment needed to meet the chosen service level and demand.

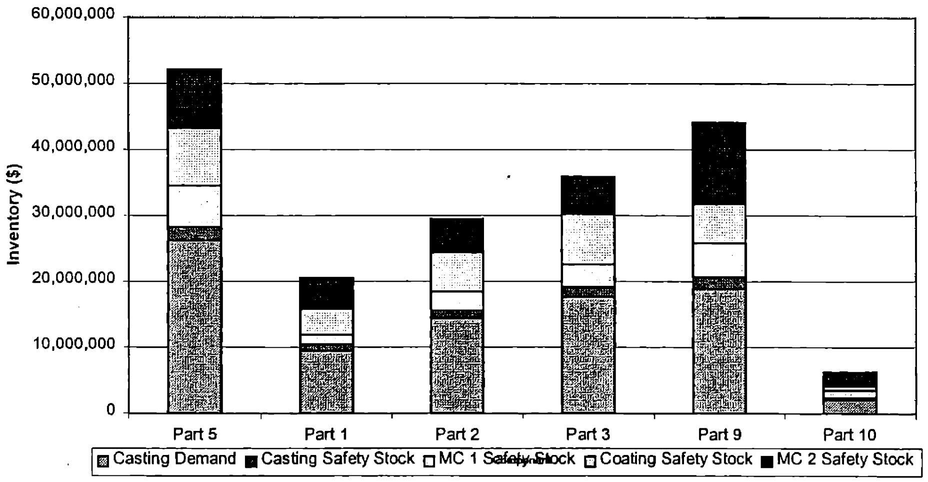

Figure 16: Monetary Investment Necessary to Meet Annual Demand

It is important to note that if the user relies only on the Annual Inventory Results (Figure 15), it would suggest that the company should focus its efforts on improving Part 10 first. However upon inspection of the investment graph, it is clear that Part 10 is the least significant cost. Instead, Parts 5 and 9 both with high variation and large investment costs, should be the focus of improvement efforts.

4.2.3 Cycle Stock and Safety Stock Levels per Part

The cycle and safety stock levels per process are a good way of understanding the procurement characteristics for each part. The cycle stock is an indirect measure of how frequently the upstream processes replenishes that stage. The safety stock is an excellent measure of the aggregated variation being experienced at that stage. Figures 17 and 18 provide graphical outputs for Part 5 (the most expensive one) and Part 10 (the least expensive one).

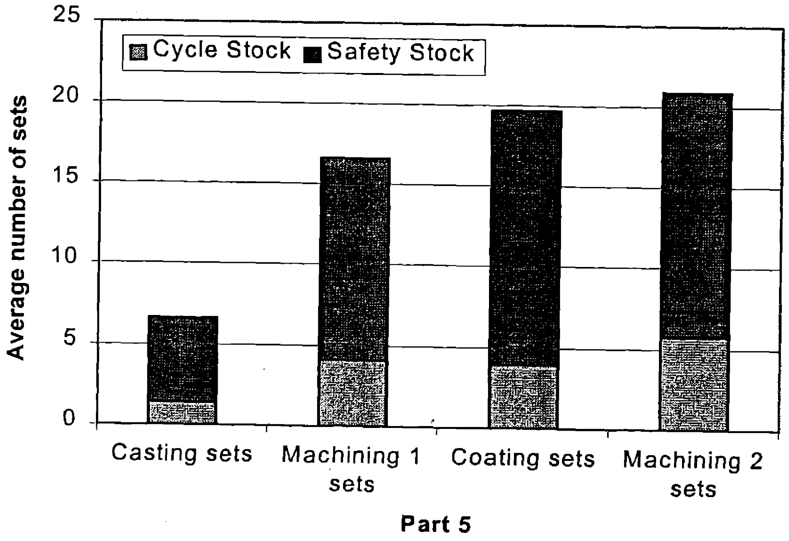

Figure 17: Comparison of Cycle Stock and Safety Stock for Part 5

A comparison of Figures 17 and 18 shows that each part is experiencing process capability issues at different points in the chain. For Part 5, the latter three stages all exhibit high safety stock levels, suggesting poor process stability. For Part 10 however, it appears that stages two and four should be the first focus of improvements. In this manner, the user can use Pareto's rule to commence improvement initiatives.

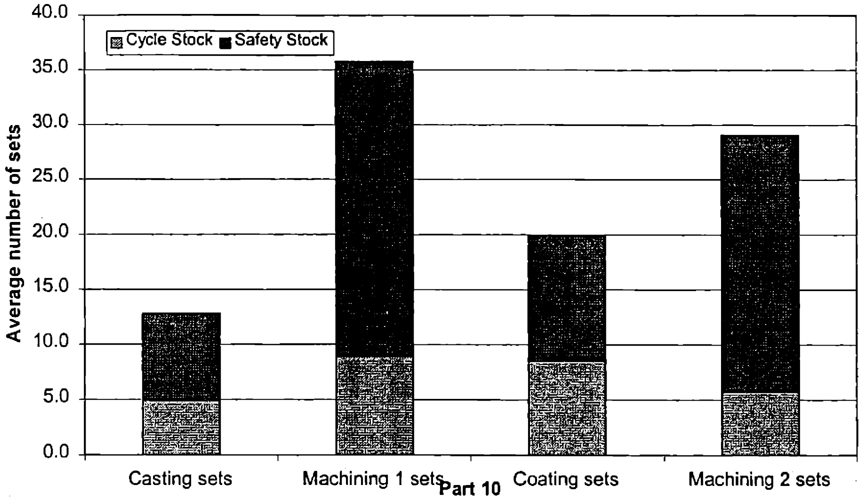

Figure 18: Comparison of Cycle Stock and Safety Stock for Part 10

In Chapter Three, the difference between demand and supply rate was identified as one of the largest sources of variation in the chain. In the model formulation, supply rates and their variation strongly influence the overall variance, which is then used to estimate safety stock. Therefore it should be noted that although a stage has high safety stock levels, this may be due to the variation in supply rates of the upstream stage. This may suggest that root causes lie further upstream.

4.2.4 *Inventory Scenario Options*

One of the most valuable aspects of the model is that it allows the user to experiment with different customer service levels and inventory buffer options. For each scenario, the associated inventory investment is then provided. Department B assumed that the most cost efficient way of ensuring customer delivery is to hold inventory at each stage. By experimenting with different coupling options, it was possible to achieve the same customer service levels given a variety of buffer inventory strategies. Figures19 and 20 exhibit the model outputs for all inventory placement options available. Triangles denote inventory holding stages.

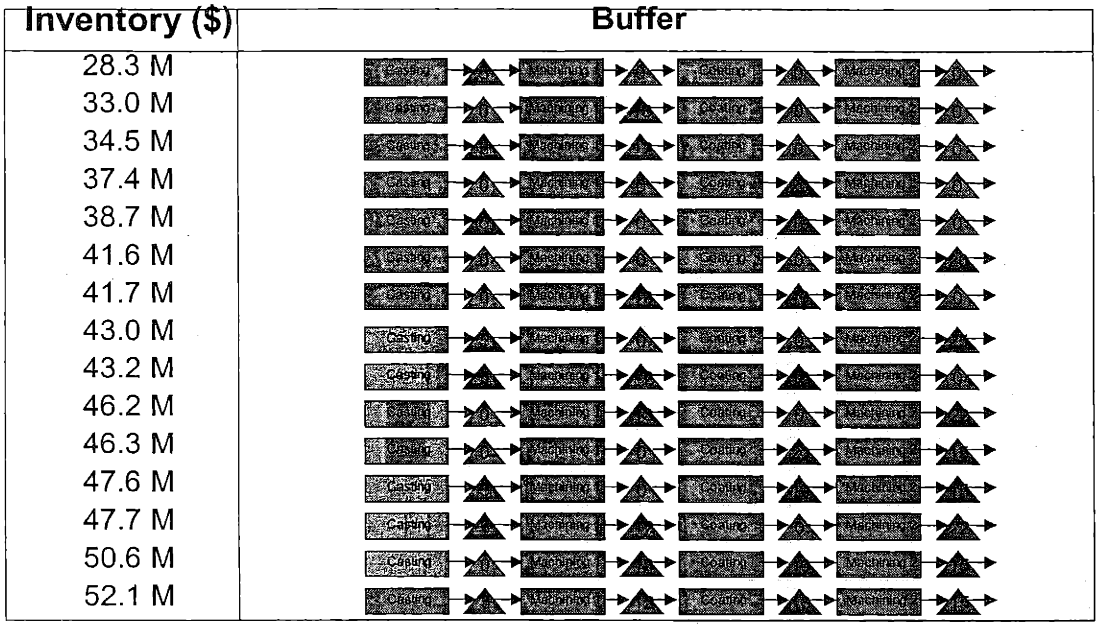

Figure 19: Inventory Buffer Options for Part 5

A comparison between Part 10 and Part 5 indicate that the buffer strategies for reducing inventory investment differ amongst the two. Holding inventory at every stage is always the most expensive option regardless of part type. However, the order of 'decreasing cost' options preceding the most expensive option, is unique to a part type. This highlights the need for managing the supply chain according to part type. Individual part management may not be feasible but parts should at least be categorized according to cost and process stability criteria, and managed according to guidelines for those criteria.

The outputs in Figures 19 and 20 enable Department B to implement strategies that will ensure specified customer service levels. The benefit of the scenarios is that placement strategies can be made on the basis of cost. For example, rather than placing inventory at all stages for Part 5 (Figure 19), Department B could opt to hold inventory at only the Machining 1 and Machining 2 stage at a total cost of $46.2M. This is $5.9M (11%) less than the most expensive option and achieves the same customer service level. Similarly, for Part 10 (Figure 20) it is $0.79M (12.7%) less expensive to hold inventory at only Machining 1 and Machining 2, rather than at all stages.

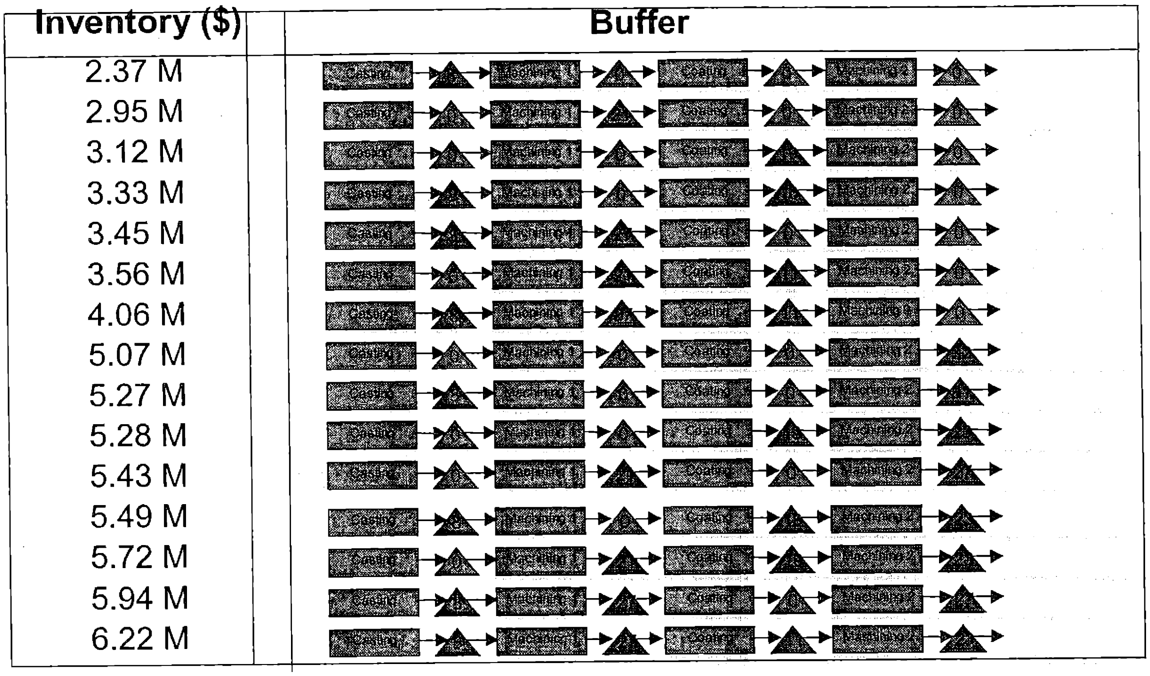

Figure 20: Inventory Buffer Options for Part 10

The scenarios also highlight the interaction of variation amongst the chain. The reader should note that adding up the independent four stage safety stocks is not equal to the safety stock held at the final point of a four-stage coupled process. The total inventory for all parts goes down as you couple more stages because the supply rate and variance of the bottleneck are the predominant influences on safety stock in the chain. Therefore one must note that strategies whose final inventory holding point is earlier in the chain make the assumption that any stages thereafter will reliably meet the delivery and supply quotas stipulated. In choosing final inventory holding points that occur before the last stage in the chain, the user must be certain that:

$$\text{Lead time of delivery to assembly stage} \leq \text{Time at which delivery is needed at assembly stage}$$

If the user does not want this level of risk, he should limit himself to only looking at the scenarios that have an inventory holding point at the last stage.

4.2.5 Current Customer Service

Given current inventory levels in the chain, users can estimate the likelihood of meeting customer needs. Appendix D provides an overview of the inputs and outputs. Department B was surprised to discover that given current inventory levels ($ 14.5M) for Engine M critical parts, it would only meet 6% to 16% of the set completion targets. Since all component sets must be ready for assembly at the same time, this reduces the overall service level to only 6% (the lowest individual part service level). Department B realized that in the current environment of process instability, it did not have enough inventory strategically placed in the chain to meet customer expectations.

In comparison, the model suggests that Department B should invest a minimum of 180% of base demand in order to meet a 97.5% service level. If all stages were de-coupled, the cost of this strategy for Part 5 would be $52.1M (as shown in Figure 18). The cost difference between the Department B's strategy and the de-coupled option is -$37.6M for Part 5. This is a significant difference in expenditures, and must be compared to the cost of project penalties of $2M per week. Given the current estimated service level of 6%, there is merit in even reconfiguring inventory placement across the chain to improve the current service levels. This result should also be fed back to the sales department so that the impact on project profitability by selling further engines is understood.

4.3 MODEL VALIDITY

The credibility of the model is dependent upon valid input data and the correct representation of real-life chain dynamics. As a first order approximation the model is sufficient in identifying interactions and trends. A list of model assumptions is given in Appendix A. The remainder of this section will detail specific model issues.

4.2.1 Supply Chain Mean Square Error

In the calculation of mean square error, the expected demand minus expected supply rate (E(D)-E(S)) plays a dominant role in calculating safety stocks. In the event that supply is greater than demand, the MSE calculated will be overestimated.

4.31 Second Order Effects

The second order effects on lead time due to holding safety stock were not incorporated in the model. The level of accuracy sought in this model did not necessitate the inclusion of these effects. A second order adjustment for holding safety stock at a stage is given as follows:

Adjusted Lead Time = Service Level*Lead Time + (1-Service Level)* Lead Time to next stage

$$= z^* L_i + (1-z)^* L_{I+1}$$

4.3.2 Delivery Hit Rate

The model addresses the need of fulfilling annual set requirements for each part. It does not explicitly consider the hit rate (order fulfillment on a specified date) of these component sets in terms of project due dates. The model interprets hit rate only as demand divided across the available working weeks. Therefore if a project actually requires the delivery of ten sets at a specific point in time, the model does not cater for this fact. The supply chain function will need to ensure that variable level loading across different time periods is modeled to meet hit rate requirements.

4.3.3 Data gathering

The model's credibility is also linked to its ease of use. The biggest impediment to ease of use is the gathering of data. Existing data is not amenable to being directly entered into the spreadsheet. The difficulty of obtaining data also makes it questionable as to how often the model can be run. In its current form it is not a real time application unless the data can be collected such that it fits the input requirements.

4.3.4 Implementing the Strategies

One of the biggest challenges of the model is its implementation in real life. Once a strategy is decided upon, how would it work? An education process at both the supplier sites and at Department B would be needed. Reporting would need to distinguish between WIP and Finished Goods at each supplier for each stage. Supplier contracts may need to be restructured to incorporate safety stock requirements. Would the supplier bear the cost of storage of the safety stock? Would the supplier be paid for the safety stock or would he be responsible for covering the insurance and costs while it was on his premises? The latter option would certainly be an incentive to reduce variation and hence the level of safety stocks. Moving from the current inventory environment to one that the model suggests may require a restructuring of current practices.

4.4 LEARNINGS

The assessment and modeling of Engine M's critical parts provided a new approach to tackling supply chain issues in Department B. Prior use of modeling in a supply chain context was virtually non-existent. Decisions were made in isolation and with limited understanding of the system. Modeling has helped the supply chain to be viewed as a system that is influenced by the perturbations in the chain. This enables the department to better manage the material flow while increasing customer satisfaction.

The concept of inventory placement strategies was also foreign to the department. To date, inventory accumulated at bottlenecks, while downstream suppliers struggled to obtain materials to meet delivery targets. The concept of strategically placing inventory to minimize the impact of variation was a valuable learning tool for the department. Future material release decisions now consider the placement of cycle and safety stocks at supplier sites. As further trust and knowledge is gained in this method of materials management, the department may become more sophisticated in its materials strategies.

Too much sophistication can also be a problem. One of the dangers of modeling is that its users treat the model as a 'black box' where inputs are entered and outputs are then given. Without an understanding of the underlying assumptions and mathematics of the model, users may receive a result that is not applicable to their situation. Therefore a big learning was to keep the model simple and yet representative of

Department B's supply chain. Where the model increased in complexity, internal transfer of knowledge was essential in order for the model to be successfully implemented.

Implementation of modeling is always a challenge. It demands the identification of users, advocates and resistors. Those people directly in contact with the model must be educated on its use. All users must use the model consistently. Without such rigor and commitment the implementation of the model will not work. The author learnt a great deal about the acceptance of new techniques in the workplace. It was both challenging and interesting to implement the model for Department B.

4.5 CONCLUSION AND SAVINGS

The model is invaluable as a learning and decision-making tool. It educates users on the dynamics of Department B's supply chain. It confirmed the department's 'gut feelings' of poor process reliability and its impact on customer service. It highlighted the importance of monitoring and analyzing data to effectively mange the supply chain. It provided a risk-free way of assessing inventory strategies.

Specifically the model demonstrates that:

- Deviations between demand and supply rate have the strongest influence on safety stock levels
- Parts with high variation and high investment should take improvement precedence over parts with equally high variation but lower investment value
- Process variation differs dramatically amongst stages and parts
- Not all inventory strategies are equal in risk level despite the same customer service level
- Current inventory levels were insufficient to meet target service levels

Financially, the model advocates greater investment in safety stock at each stage. This will increase the costs for Department B but may reduce the overall costs of the project due to the absence of incurred 'late' penalties. Greater investment in inventory may have the appearance of being foolish, but it depends on the purpose that inventories serve. In this case, inventory is present to buy service levels.

In a concurrent engineering environment, investment in inventory is also seen as problematic due to redundancy issues. However a company must decide on whether its priority is to get reliable product to the customer. Design freezes (even sub-optimal designs) are preferable to continuously changing designs. A freeze allows parts of the same form and function to be assembled in an engine for validation purposes. A controlled phase-in of design changes in assigned engines will stabilize and reduce the variance of the supply chain. The cost of structured introduction of re-designed parts, installation and improved customer delivery should be compared to the cost of non-frozen designs and penalties due to deliver delays.

In conclusion, the model is an effective tool for experimenting with inventory strategies. It does not result in direct savings but ensures that the direct costs of a project are minimized through fulfilling customer service levels. The model recommends that for Engine M, a minimum of 180% of base demand is required as inventory investment to reach service levels of 90% to 97%. Its key message is that the reduction of process variation will lead to higher customer service levels and lower inventory investment.

5. CHAPTER 5 – STRATEGIC SUPPLY CHAIN CONSIDERATIONS

Many of the issues discussed in this thesis stem from the strategic design of the supply chain. Tactics to manage the logistics of materials and inventories across the existing chain are provided in earlier chapters. This chapter will provide an overview of Division A's supply chain in the context of concurrent engineering and dependency upon suppliers. In a true partnership both product, process and supply chain design should occur concurrently. Historically Division A has not tightly integrated its supply chain design with product and process design. This leaves opportunities for improvement in future engine iterations.

5.1 PRODUCT ARCHITECTURE

Product architecture is an essential element in designing the supply chain. In Fine's Clockspeed[12], product architecture is defined along two dimensions:

- *Integral Product.* These components perform many functions or are in close proximity or tightly synchronized
- *Modular Product.* These components are interchangeable or individually upgradable or posses standard interfaces

The design of the airfoils should have been conducted by the design department (responsible for architecture and detailed design choices) in close partnership with Department B and Manufacturing.

In the context of these definitions, Department B's products are highly integral. The airfoils are assembled in close proximity to each other. The successful assembly of the blade and vanes is dependent upon the form and fit of both the rotor and the airfoils. Due to overarching guidelines related to harmonics and vibrations, these components are not easily upgradable or interchangeable with other components. The performance of the airfoils is tightly synchronized to the overall performance of the engine. This implies that Department B's supply chain design should complement the highly integral product. Each supplier is essential in ensuring the overall performance of the engine.

5.2 SUPPLY CHAIN ARCHITECTURE

The concept of supply chain architecture as defined by Fine[13] directly impacts the coordination, maintenance and adaptability of the chain. There are four tenets of supply chain architecture:

- Geographic proximity. What is the physical distance separating those working together in the chain?
- Organizational proximity. Who has ownership and managerial control? What inter-person and inter-team dependencies exist?
- Cultural proximity: Are there common languages, ethical standards and laws amongst the stakeholders?

- Electronic proximity: What level of virtual communication via email, intranets and electronic data exchange exists?

The supply chain architecture and logistics systems influence the efficiency at which the chain operates. Evaluations of Department B's supply chain against these four dimensions presents an interesting picture.

The supply chain is globally dispersed with some concentration of suppliers at a regional level. The geography of the chain significantly affects the success of the project. In Division A's case, design engineers are concentrated at the head office, while supplier-engineering teams are spread around the globe. For such a highly integrated product this distance creates time and communication lags in an environment of continuous iteration. This has already been observed at Division A during the pre-serial production of Engines M and L.

Division A has both ownership and control of the product. It attempts to manage all material flow and communication interfaces. In this respect, Department B has somewhat close organizational proximity to its suppliers. This proximity is diminished by the independence of the suppliers, some of whom are sole-source suppliers. In fact these sole-source suppliers wield high control because they are critical for product delivery. As evidenced in earlier chapters, these suppliers will often choose to work to their own targets rather than those of the customer. Department B is then dependent upon interaction with its suppliers in order to manage the chain, this supports the notion of only moderate organizational proximity.

The suppliers are spread around the globe in different countries with different norms and ethical standards. The major source of commonality amongst them is that they are all part of the western world. Division A has stipulated that common language of business for all its stakeholders be English. However design, engineering, quality and logistics personnel in a few of the supplier companies are not fluent in this language. This may result in difficulties of communication between upstream and downstream suppliers in the chain. Based on these considerations, the cultural proximity is only moderate.

An essential part of the supplier relationships with Department B is communication. Information sharing is centered mainly on telephone conversations, face to face meetings and email. The level of electronic proximity between the suppliers and the department is moderate. Emails and unwieldy spreadsheets are used to communicate material flows. More sophisticated IT tools such as EDI and web sites have not been utilized.

5.3 PROCESS ARCHITECTURE

Process architecture also influences supply chain decisions. It is expressed as the development of unit processes needed to produce the product. Fine[14] defines process architecture along two dimensions:

- Time. How critical or integrated is time to product manufacturing and customer delivery?
- Space. How spatially dispersed are the manufacturing processes?

Industries usually find their process architecture highly integrated in both time and space, integrated along one dimension or modular along both dimensions. An example of an industry that is integrated along both time and space is the made-to-order computer industry. The computers are built in a few hours (tightly integrate in time) and the workstations are also physically close to one another (tightly integrated in space). Such process architecture influenced the supply chain design.

The process architecture for Department B's precision casting components has been configured to be modular across space and dispersed across time. The manufacturing processes are dispersed geographically across multiple facilities resulting in independent processing activities. Time is also dispersed. Processing of the parts is comparatively lengthy and lead times in the industry are long. Time is critical because of the completed product's reliance on the promised delivery of each supplier in the chain. Without reliable deliveries, the next process cannot take place in the chain, resulting in product delays. However if the chain's processes are under control, these delivery delays are minimized and the criticality of time is diminished. Table 9 presents a process architecture matrix for Division A's airfoils with respect to the dimensions of time and space. It is evident that such process architecture is incompatible with the 'desire' of a fast-response supply chain. Department B's modular and dispersed process architecture is in conflict with the tightly integral product architecture of the airfoils.

Time	**Space**	
	Tight/Integral	**Loose/Modular**
Tight, integral, fast		
Dispersed, modular, slow		Airfoils

Table 9: Process Architecture Matrix

5.4 LINKING PRODUCT, SUPPLY CHAIN AND PROCESS ARCHITECTURES

Companies with competitive advantage typically mirror their product and supply chain architectures. They tend to be mutually reinforcing. Modular (low proximity) supply chains accompany modular product architectures. Similarly integral (high proximity) supply chains tend to accompany integral product architectures. Successful process architectures typically also reflect their supply chain and product counterparts. In this respect, precision cast critical parts for Division A do not align with successful architecture designs.

Division A's strategy for its airfoils is interesting because it shows signs of deviating from any complementing product and supply chain architectures. Precision cast components are integral products, yet the supply chain (along its four dimensions) veers more towards a modular architecture. Such a strategy would be more suitable to the turbine housing rather than the precision cast components. The housing is a modular product that would succeed with a modular supply chain. Table 10 illustrates the relationship between product and chain for precision cast components and turbine housing.

Product Architecture	**Supply Chain Architecture**	
	Integral	**Modular**
Integral		Airfoils
Modular		Turbine Housing

Table 10: Product and Supply Chain Architecture Matrix

5.5 KNOWLEDGE AND CAPACITY CONSIDERATIONS

Designing the supply chain also involves the strategic questions of knowledge and capacity. A Company's internal 'learning' assets determine the type and level of projects it is willing to embark upon. This in turn will develop further capabilities. In systems dynamics there exist two models capability development:

- The dependency loop. A reinforcing loop where the more work given to suppliers, the more they learn, and the greater their capabilities become, which in turn attracts further work.
- The independence loop. A reinforcing loop where the more work done inhouse, the greater the learning and capabilities, leading to even more work being done inhouse.

Capacity should also be considered in terms of the flexibility that it offers the chain. With these dynamics in mind, a company should design its supply chain such that it is explicit about its independence level for knowledge and capacity.

Due to the burgeoning market in gas turbines, Department B is dependent upon all its suppliers for capacity in airfoils production. It is particularly dependent upon capacity for all casting and machining 1 processes where there may only be single source suppliers. Along the knowledge dimension, the user should distinguish between design and manufacturing knowledge. Department B is dependent upon manufacturing knowledge for both casting and machining 1 stages. It possesses an internal supplier for both coating and machining 2, which ensures that some manufacturing knowledge is developed internally. Division A is independent for design knowledge but in an environment of concurrent engineering, manufacturing knowledge and design knowledge should not be mutually exclusive. Therefore although Division A's views it core competence as design, this cannot be isolated from designing for manufacturability, which demands intimate knowledge of manufacturing processes (Table 11).

	Independent for Knowledge	**Dependent for Knowledge**
Independent for Capacity		
Dependent for Capacity	Coating Machining 2 Component Design	Casting Machining 1 Component Design

Table 11: Knowledge and Capacity Matrix

5.2 OUTSOURCING AND INSOURCING CONSIDERATIONS

Once the product, supply chain and process architectures have been defined, issues related to insourcing and outsourcing are more easily identified. Companies can then design their chains in the context of present and future knowledge development and capacity flexibility.

Table 12 illustrates the current positioning of Department B's precision cast components with respect to manufacturing stages. According to Fine[15], possessing an integral product and being dependent for both knowledge and capacity is the worst outsourcing situation possible. This strategy will result in much rework and rethinking. Being only dependent upon capacity is a much better alternative as the company has intimate knowledge of how to integrate the items. Department B's situation is not quite as serious as suggested by the positioning in Table 12. Both casting and machining 1 are dependent for manufacturing knowledge but independent for design knowledge (how all parts integrate). Therefore these processes veer slightly towards the 'dependent for capacity only' category.

INTEGRAL PRODUCT	**Dependent for Knowledge and Capacity**		**Dependent for Capacity only**	
	Fast Clockspeed	**Slow Clockspeed**	**Fast Clockspeed**	**Slow Clockspeed**
Few Suppliers		Casting Machining 1		Coating Machining 2
Many Suppliers				

Table 12: Integral Product Matrix

The fact that few suppliers exist with the capability to manufacture the airfoils is a concern. Department B may want to capture learning curve effects by having as few suppliers as possible. This increases the volume production per supplier and hence increases progression down the learning curve. Equally important however is the Department B's ability not to end up in supplier bind through sole sourcing, as this has the potential to increase costs. The switching costs for suppliers are great, therefore the best way to maintain a potential base of many suppliers is to ensure that designs are easy to manufacture.

5.5 RECOMMENDATIONS

The reassessment of the airfoils supply chain is immensely valuable to Division A. In its present form the supply chain is vulnerable and incompatible with its product architecture. This results in sluggish response and the potential for suppliers to place the division in a bind. It highlights the need for Department B to develop incentives and systems that eliminate agent-principal problems and encourage suppliers to meet common goals across the chain.

Future design introductions should consider the design of the chain in two parts:

- Pre-serial production design: An integral supply chain should support an integral product structure. During the product development phase engineers from both suppliers and Division A should be co-located. Pre-serial production suppliers should be chosen on the basis of long term partnerships. They should include internal suppliers so that development and manufacturing knowledge is fostered internally.

- Serial production design. The emerging chain may veer towards a modular design, as parts may be considered stable and perhaps more modular. This is only possible if the components are easy to manufacture through robust processes. Then there is potential to establish a chain that is only dependent for capacity. However if the product remains integral, then Division A may seek independence for knowledge and capacity through insourcing all of its manufacturing thereby enabling continuous iterations.

Division A must consider what is most important to its continued survival and guard that knowledge and skill. It is dangerous to let suppliers develop a skill that is later determined to be essential for competing in the marketplace. Therefore knowledge and skills crucial to performance or customer visibility should be kept internally. As there is so much system complexity in the gas turbine industry, the clockspeed for manufacturing is relatively slow while the clockspeed of technical innovations is moderate. Competition in the industry has sped up the clockspeed considerably. Hence Division A has some breathing space within which to act, but must do so quickly.

The operational level of the supply chain can be improved immensely through reduction of variation in the chain, the establishment of transparent processes, controlled material release and simple communication interfaces. The previous chapters identify many more opportunities for improving short and long-term performance. Models can be used to minimize the impact of variation in the process to determine buffer inventory. However all these suggestions will have limited effectiveness if the design of the supply chain is incompatible with the product and process. A re-assessment at this strategic level may ensure that competitive advantage is maintained into the future. The design of both product, process and supply chain architectures is extremely critical for Division A. The current incompatibility of architectures is part-responsible for the lack of current performance in the supply chain. Without a re-configuration of existing architectures, performance will only improve moderately for Division A.

Appendix A: Model Assumptions and Derivations

Scenario Inventory Model Assumptions:

1. Demand occurs over a set time interval
2. Demand for a period has:

   Expectation = Time intervals in period x mean demand per time interval

   Variance = Time intervals per period x (standard deviation of demand)^2
3. Demands in non-overlapping time intervals are independent
4. Replenishment orders are placed on a regular cycle based on the review period "r"
5. At each replenishment point we order an amount equal to the demand since the last order point. For example, at time t=3r, we order D(2r,3r) and the order is received at time 3r+L
6. All distributions are normal

Derivations

Let the random variable P, be the sum of the demand and supply error:

$$P = D + S_e$$

where

D = the demand rate per unit time

S_e = the supply error rate per unit time

$= S - E(S)$

where S = Supply rate per unit time

$E(S)$ = Expected supply rate per unit time

It follows that the variance of random variable, P, during the lead time is a function of the variances in lead time and the variance in the demand and supply error.

$$\sigma^2(P) = E(L+r)\sigma^2(D+S_e) + (E(D+S_e))^2\sigma^2(L+r) \tag{1}$$

where

L = the lead time in weeks

r = the review period in weeks

Now:

$$\sigma^2(D+S_e) = \sigma^2(D) + \sigma^2(S_e) + 2\times\operatorname{cov}(D,S_e) \tag{2}$$

Assume that D and S_e are independent, that is $\operatorname{cov}(D, S_e) = 0$

Therefore, substituting (2) into (1):

$$\sigma^2(P) = E(L+r)\left(\sigma^2(D) + \sigma^2(S_e)\right) + E(D+S_e)^2 \sigma^2(L+r) \tag{3}$$

where $E(D)$ = expected demand

Now $\sigma^2(S_e) = \sigma^2(S)$ and E(S_e)=0, then:

$$\sigma^2(P) = E(L+r)\sigma^2(D) + E(L+r)\sigma^2(S) + (E(D))^2 \sigma^2(L+r) \tag{4}$$

However if there is a systematic bias where $E(S) \neq E(D)$, then the mean square error (MSE) becomes significant.

$$\begin{aligned} MSE &= E(D + S_e - E(S))^2 \\ &= \sigma^2(D+S_e) + E(E(D+S_e) - E(S))^2 \\ &= \sigma^2(D+S_e) + (E(S) - E(D))^2 \\ &= \sigma^2(D+S_e) + S_B^2(E(L+r))^2 \end{aligned} \tag{5}$$

where S_B = the bias per unit time in the supply rate

Combining equations (4) and (5):

$$MSE = E(L+r)\sigma^2(D) + E(L+r)\sigma^2(S) + (E(D))^2\sigma^2(L+r) + (E(L+r))^2 S_B^2$$

Appendix B: Variation Propagation and Averages Calculation

The Propagation of Bottleneck Supplier Variance

To account for variation between suppliers in series, the following equation by Hopp and Spearman[16] for a single queuing station, will be applied to calculate the propagation of variability between workstations in series in a supply chain.

$$c_d^2 = u^2 c_e^2 + (1-u^2) c_a^2 \qquad (1)$$

where

$c_d^2 =$ *squared coefficient of interdeparture times*

$c_e^2 =$ *the squared coefficient of variation of the process times*

$c_a^2 =$ *the squared coefficient of the interarrival times*

$u =$ *the utilization of the work station*

$=$ *the ratio of arrival rate to process rate*

To adapt the above equation to a serial supply chain, let the variables be redefined as follows:

$c_e^2 = \sigma_i^2(S)$

where S denotes the supply chain

= variance of process rate at stage I

u_i *= bottleneck supply rate/supply rate at the 'i^{th}' downstream stage from the bottleneck*

= the utilization of stage i

Substituting in (1), variance of supply rate after the first downstream stage from bottleneck[5] is:

$$u_1^2 \sigma_1^2(S) + (1-u_1^2)\sigma_0^2(S)$$

Variance of supply rate after the second downstream stage from bottleneck is:

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[5] This assumes that the utilization at the bottleneck is 100%. If this is not the case then the bottleneck is the arrival process, which we denote at stage 0

$$u_2\sigma_2^2(S\ ) + u_1^2(1-u_2^2)\sigma_1^2(S) + (1-u_1^2)(1-u_2^3)\sigma_0^2(S)$$

Then the general equation for variation at the end of the process is:

$$\sum_{i=0}^{N}\sigma_i^2(S)\cdot u_i^2 \underset{k=i+1}{\overset{N}{\pi}}\left(1-u_k^2\right)$$

where

N = the number of stages downstream from the bottleneck

Average Lead Time Calculations

Let N be the number of suppliers

L_i be the procurement lead time for supplier i

$\sigma(L_i)$ be the standard deviation of lead time for supplier i

Then,

$$E(L\ ) = \sum_{i=0}^{N} L_i \Big/ N$$

$$\sigma^2(L\ ) \approx \sum_{i=0}^{N}\sigma^2(L_i) \Big/ N^n$$

Average Supply Rate Calculations

Let S_i be the supply rate for supplier i

$\sigma(S_i)$ be the variance of supply rate for supplier i

$$E(S) = \sum_{i=1}^{N} S_i \Big/ N$$

$$\sigma^2(S) \approx \sum_{i=1}^{N}\sigma^2(S_i) \Big/ N^n$$

Note:

These computations assume that suppliers are uniformly selected. The variances are approximate as long as L_i and S_i do not vary significantly with respect to i as there is a variance term reflecting the variance of $E(L_i)$ and $E(S_i)$ among suppliers.

Appendix C: Scenario Engine Logic

Engine Logic

The Engine utilizes IF THEN statements to assign or calculate statistics based on the output pages. Each part has logic assigned that allows any of the coupling options outlined in the Table 9 or any combinations thereof (e.g 1010). A "1" denotes an inventory buffer and de-coupled stages.

Coupling Choices			
Cast	MC 1	Coat	MC2
0	0	0	0
1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1
1	1	0	0
1	0	1	0
1	0	0	1
0	1	1	0
0	1	0	1
0	0	1	1
1	1	1	0
1	0	1	1
1	1	0	1
0	1	1	1
1	1	1	1

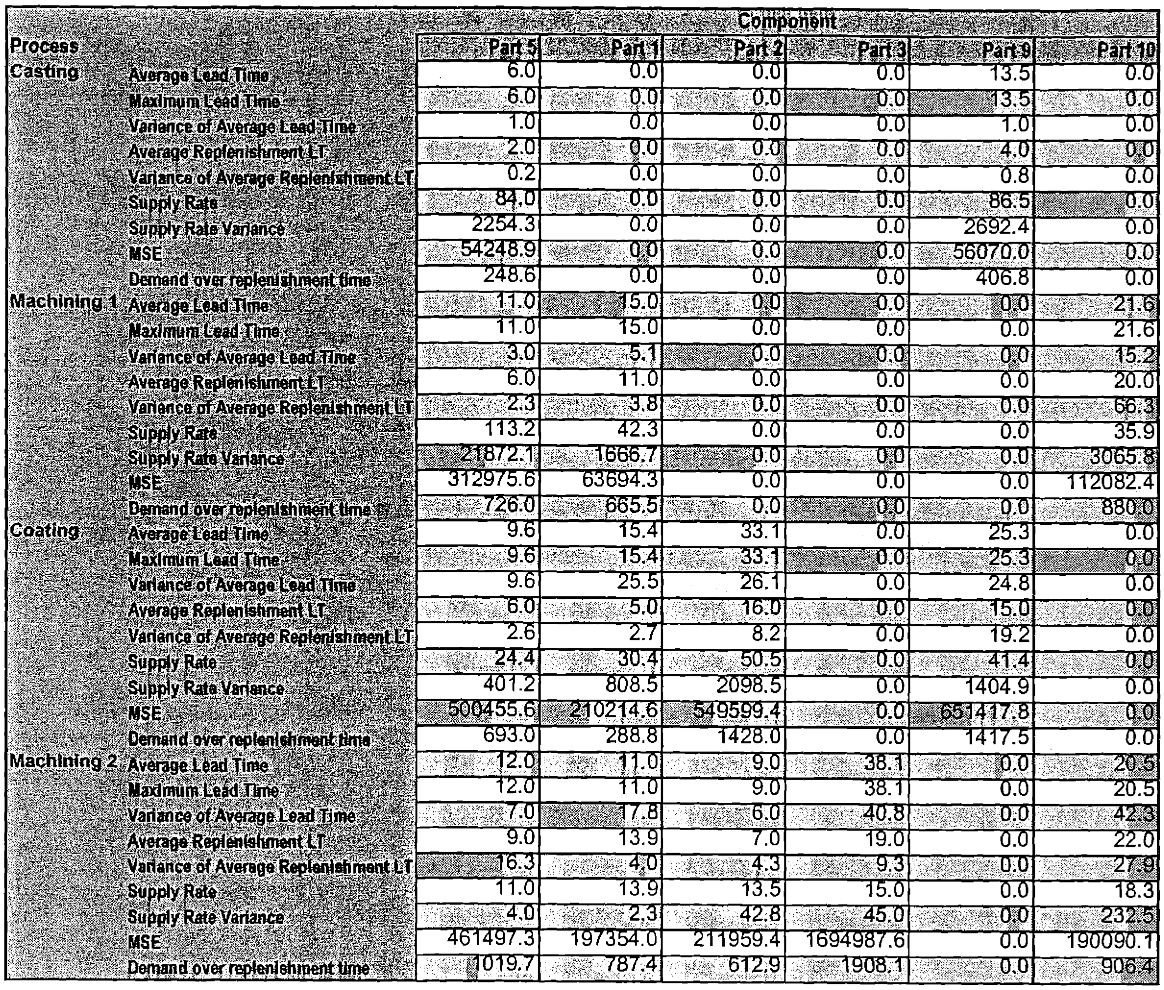
Table 13: Inventory Coupling Options

The average lead time and variance are respectively the sum of the stage and any immediately preceding stages denoted by a zero.

The supply rate is the minimum rate amongst that stage and any immediately preceding stages denoted by a zero.

The supply rate variance is a combination of the bottleneck variance and the variances of the stages downstream from the bottleneck.

The overall variance is a combination of the supply, lead time and demand variances as outlined in Appendix A.



		Component					
Process		Part 5	Part 1	Part 2	Part 3	Part 9	Part 10
Casting	Average Lead Time	6.0	0.0	0.0	0.0	13.5	0.0
	Maximum Lead Time	6.0	0.0	0.0	0.0	13.5	0.0
	Variance of Average Lead Time	1.0	0.0	0.0	0.0	1.0	0.0
	Average Replenishment LT	2.0	0.0	0.0	0.0	4.0	0.0
	Variance of Average Replenishment LT	0.2	0.0	0.0	0.0	0.8	0.0
	Supply Rate	84.0	0.0	0.0	0.0	86.5	0.0
	Supply Rate Variance	2254.3	0.0	0.0	0.0	2692.4	0.0
	MSE	54248.9	0.0	0.0	0.0	56070.0	0.0
	Demand over replenishment time	248.6	0.0	0.0	0.0	406.8	0.0
Machining 1	Average Lead Time	11.0	15.0	0.0	0.0	0.0	21.6
	Maximum Lead Time	11.0	15.0	0.0	0.0	0.0	21.6
	Variance of Average Lead Time	3.0	5.1	0.0	0.0	0.0	15.2
	Average Replenishment LT	6.0	11.0	0.0	0.0	0.0	20.0
	Variance of Average Replenishment LT	2.3	3.8	0.0	0.0	0.0	66.3
	Supply Rate	113.2	42.3	0.0	0.0	0.0	35.9
	Supply Rate Variance	21872.1	1666.7	0.0	0.0	0.0	3065.8
	MSE	312975.6	63694.3	0.0	0.0	0.0	112082.4
	Demand over replenishment time	726.0	665.5	0.0	0.0	0.0	880.0
Coating	Average Lead Time	9.6	15.4	33.1	0.0	25.3	0.0
	Maximum Lead Time	9.6	15.4	33.1	0.0	25.3	0.0
	Variance of Average Lead Time	9.6	25.5	26.1	0.0	24.8	0.0
	Average Replenishment LT	6.0	5.0	16.0	0.0	15.0	0.0
	Variance of Average Replenishment LT	2.6	2.7	8.2	0.0	19.2	0.0
	Supply Rate	24.4	30.4	50.5	0.0	41.4	0.0
	Supply Rate Variance	401.2	808.5	2098.5	0.0	1404.9	0.0
	MSE	500455.6	210214.6	549599.4	0.0	651417.8	0.0
	Demand over replenishment time	693.0	288.8	1428.0	0.0	1417.5	0.0
Machining 2	Average Lead Time	12.0	11.0	9.0	38.1	0.0	20.5
	Maximum Lead Time	12.0	11.0	9.0	38.1	0.0	20.5
	Variance of Average Lead Time	7.0	17.8	6.0	40.8	0.0	42.3
	Average Replenishment LT	9.0	13.9	7.0	19.0	0.0	22.0
	Variance of Average Replenishment LT	16.3	4.0	4.3	9.3	0.0	27.9
	Supply Rate	11.0	13.9	13.5	15.0	0.0	18.3
	Supply Rate Variance	4.0	2.3	42.8	45.0	0.0	232.5
	MSE	461497.3	197354.0	211959.4	1694987.6	0.0	190090.1
	Demand over replenishment time	1019.7	787.4	612.9	1908.1	0.0	906.4

Table 14: Scenario Engine Output

Appendix D: Customer Service Levels

Defintions:

Expected Inventory Level = Cycle stock + safety stock
Cycle Stock = $r*_{\mu}/2$
Safety Stock = $z*_{\sigma}v$
z = (Actual inventory - (review period*demand over replenishment time/2))/standard deviation of supply during lead time
The formula assumes that you subtract a cycle stock value from the actual inventory to work out the safety stock (finished goods)
The service levels will actually be worse that those quoted, if all the inventory is WIP.
From the safety stock you can then approximate the standard deviation and work out the z level
The customer service level is defined as how likely we will meet the next upstream customer's annual demand
The customer service levels may actually be higher if you are coupling stages!
The customer service level is calculated as the standard normal cumulative distribution function as a function of z
Total Supply Chain Service Level = The customer service levels at each stage (M/C1, Coat, M/C2) multplied together
= The liklihood we will meet the demand of engine sets per year given the current inventory
and supply chain performance data

	Component					
Process	Part 5	Part 1	Part 2	Part 3	Part 9	Part 10
Casting inventory (actual)	200.0	200.0	200.0	200.0	200.0	200.0
Machining 1 Inventory (actual)	1699.0	315.0	164.0	474.0	1210.0	187.0
Coating Inventory (actual)	419.0	100.0	485.0	100.0	288.0	189.0
Machining 2 inventory (actual)	176.0	264.0	408.0	390.0	426.0	134.0

Table 15: Actual Inventory Throughout Chain

	Component					
Process	Part 5	Part 1	Part 2	Part 3	Part 9	Part 10
Casting service level	63.8%	52.7%	59.7%	66.5%	49.5%	60.4%
Machining 1 service level	99.2%	79.6%	42.4%	69.4%	90.6%	41.1%
Coating service level	54.1%	46.1%	58.2%	42.1%	50.3%	32.5%
Machining 2 service level	31.2%	38.5%	58.7%	52.9%	56.5%	44.6%
Supply Chain Service level	16.7%	14.2%	14.5%	15.5%	25.7%	6.0%

Table 16: Customer Service Level given Inventory

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