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THE IMPORTANCE OF INTEROPERABILITY IN A SIMULATION PROTOTYPE FOR SPARES INVENTORY PLANNING

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ABSTRACT

Spare parts control and inventory planning for Boeing commercial aircraft is a large, complex, and mostly automated process. Management inventory policies are exercised through a set of control parameters that are programmed to generate inventory plans for a significant percentage of stocked parts. These control parameters directly impact customer service performance and inventory investment. Effects of parameter changes are difficult to predict due to the nature and number of control parameters. This paper describes the situation and presents a simulation prototype as a tool to determine how control parameters affect inventory, performance, and time needed until effects are realized. The simulation predicts the effects of decisions (implemented through parameter changes) on performance, including service to airlines, inventory levels, and operating costs. Essential to achieving our objective was the interoperability of several unique software programs.

1 BACKGROUND

The Boeing Spares Department manages over 120,000 stocked part numbers for Boeing's worldwide fleet. Boeing has five international spare parts warehouses to increase customer service. The primary warehouse is in the Seattle area (Auburn), with four regional warehouses in Atlanta, Brussels, Singapore, and London. Regional warehouses stock between 19,000 and 25,000 part numbers.

Computerized inventory planning calculates monthly demand forecasts, reorder points (ROP), and reorder quantities (ROQ) for approximately 70,000 part numbers. Another program determines inventory allocation to the five warehouses when inventories fall below predetermined levels.

The following terms are defined for subsequent discussion.

ROLT: Re-Order Lead Time is the time between the date an inventory replenishment order is triggered and the arrival date of this replenishment quantity.

ROP: Reorder point is the inventory level that triggers an inventory replenishment order.

ROQ: Reorder quantity is the amount of inventory ordered when an inventory replenishment order is triggered.

Customer order class: Each customer order contains an attribute called customer order class that indicates a desired level of service for that order. The four customer order classes are: routine (RTN), expedite (EXP), critical (CRT), or airplane on ground (AOG). These are listed in ascending order of criticality, with greater attention to service given to more critical orders.

Release: A replenishment order, originating from the main warehouse, is called a release. Releases of size ROQ are generated when the inventory level for a part reaches its ROP. There are two classes for a release, routine and expedite. (These are different from customer order classes.) Routine releases arrive at the main warehouse once the ROLT has elapsed. Expedite releases have a reduced ROLT and are triggered under "stock out" conditions or when other special handling is necessary.

Stock status: A spare part can be in one of three mutually exclusive states called stock status. These states are stock ('S'), no-stock ('T'), or recommend for stock ('R'). Stock status 'S' items are expected to be delivered to the customer within a 10 day period. No-stock or stock status 'T' items typically have low sales activity and do not have the same service guarantees as stock status 'S' parts. Stock status 'R' items are in transition from stock status 'T' to 'S'; as the first inventory has not yet arrived. Stock status 'R' could represent a new part for a new airplane model or a no-stock item recommended for stock due to increase in the part's sales activity.

2 INTRODUCTION

A significant percentage of Boeing's spare parts' inventory is managed through a set of control parameters that affect customer service and inventory investment. The Control Parameter file is complex, with the possibility of an enormous number of options and combinations. There are approximately 20 groups of control parameters. Within each of these groups, parameters are usually classified into a number of classes. The exact effects of many of these control parameters are not well understood by management and are, therefore, seldom intuitively and sometimes arbitrarily.

One class of control parameters is performance level, a theoretical value that represents a desired level of service to customers. For example, a value of 90% for the performance level control parameter theoretically implies that 90% of the time a customer's order will be fully satisfied from stock in inventory within 10 days from the order date. Use of this control parameter for comparative analysis is detailed in section 5.0, Results.

Two key questions arise regarding inventory management decisions:

1. What affect will changing a control parameter have on service to customers and on inventory management costs?
2. When a change to a control parameter is made, how long will it take before that change is fully realized?

Many parameters interact with each other so that simultaneous change to any of these parameters may result in unpredictable effects.

3 STATISTICAL ISSUES

The simulation's statistical issues were addressed as an integral part of this project. Primary issues included:

1. Selecting an appropriate representation of parts from some population of interest.
2. Determining a sampling strategy that allows drawing valid inferences about the whole part population.
3. Creating an experimental design that analyzes the effects and interactions caused by control parameter changes.

3.1 Sample Selection and Size

Due to the diversity of the part population, stratified random sampling was selected as the appropriate method. The part population is divided into sub-populations, that historically demonstrated relatively homogeneous behavior patterns, and random samples are drawn from each one.

The stratified random sampling approach has two main advantages:

1. Statistical inferences can be drawn from each sub-population or stratum, independent of the other strata.
2. Stratified sampling may result in more precise estimates of the characteristics of the entire population.

Estimating precision for the whole population depends on the sample size and on selecting strata that include parts within each stratum that are homogeneous with respect to the characteristic of interest. For example, if performance was a characteristic of interest, then the population could be stratified by unit cost and average monthly usage, since these classifications are used for setting performance level parameters in the Inventory Planning program.

The results of the simulation prototype presented in section 5.0, Results, are based on a random sample of parts (with no stratification) selected from a target population of items with high sales. A sample size of 301 parts was randomly selected from a target population of just under 10,000 items. The entire sales history for each part in the sample was extracted from actual sales history archives to generate the Sales History file for input into the simulation.

3.2 Experimental Design

A statistical experimental design methodology was developed to accurately determine the effects of the control parameters on the measures of performance with a minimum number of simulation runs. Three experimental design methodologies were investigated and documented (Bier, Tjelle, 1994) for this project:

1. Box-Behnken.
2. Central composite.
3. Optimal.

The Box-Behnken design was not chosen due to automation difficulties. The other two designs are potential candidates. Implementation of these procedures will enforce statistical rigor in evaluating the interaction occurring between control parameters. Statistical details for these designs are beyond the scope of this paper.

The results of these simulation prototype experiments do not include the benefits of implementing these statistical techniques.

4 THE MODEL

A prototype simulation model of the inventory planning process was developed. Critical operational requirements include:

1. The simulation language must dynamically interface with existing production software.

2. The simulation language must interface with statistical analysis software.
3. The simulation language must handle the size and complexity of this problem.
4. The simulation must execute in a mainframe computing environment.
5. Portability to the PC environment is important to future developments.

To successfully analyze the influence of various control parameters on inventory, satisfying the interoperability requirement described in 1. and 2. above is mandatory. GPSS/H simulation language (Henriksen, Crain, 1989) was selected because it satisfied all requirements.

4.1 General Architecture

Figure 1 is a simplified architecture of the simulation program's environment. The simulation model communicates via data files with the Inventory Planning program, coded in FORTRAN and the Allocation program, coded in COBOL.

The Control Parameter file contains the input data directly affecting inventory levels and customer service.

The Sales History file contains actual sales records for the spare parts' sample being simulated. It varies in size depending on the parts selected for the sample. For example, when a sample of 300 parts was chosen from a population of high sales, over 60,000 sales were found during 25 years of sales history.

The Initial Conditions file contains part data and the end date for the simulation warm up phase. As the simulation executes beyond the warm up phase, the performance is computed and recorded in a Results file, discussed in section 5.0, Results.

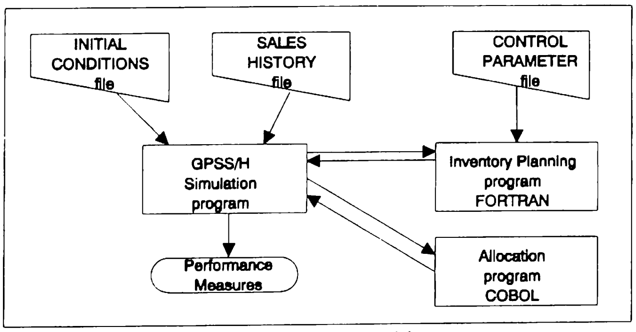

Figure 1: General Model Architecture

4.2 Components of the Simulation Model

The simulation process consists of three modules.

1. The simulation, which drives the whole process.
2. The Inventory Planning program, which is responsible for—
   - Analyzing sales patterns on an item by item basis.
   - Determining if a forecast can be made.
   - Adjusting forecasts.
   - Computing ROP and ROQ.
   - Making recommendations regarding changes in part status from stock to no-stock and from no-stock to stock.
   - Writing any changes to a file that is read by the simulation.
3. The stock Allocation program, which distributes inventory to the sub-stores.

4.3 Simulation Warm Up

To reduce statistical bias in the simulation, initial conditions are established by a preprocessing program and a simulation warm up phase is run without keeping track of performance. The initial conditions for inventory plans and bin levels are created prior to the execution of the warm up phase. Parts recommended for stock by the planning program within the first six months of recorded sales history are given the stock status 'S', an inventory plan, and a bin level as initial conditions for the simulation. Initial bin levels for these items are based on a random selection of stock around an expected stock of ROQ/2+ safety stock. For other parts recommended for stock during the warm up period, stocking dates and ROP/ROQ plans are determined. The inventory planning program is not called during execution of the warm up phase.

4.4 The Simulation

The simulation is executed on the sales history of a random sample representative of a parts' population targeted for analysis. Inferences are made about this population based on the simulation results.

The primary function of the simulation is to measure elements of inventory performance (service level to customers, investment, inventory turns, etc.). This is achieved by modeling critical aspects of inventory management, including rules that govern daily operations and by integrating inventory management programs directly into the simulation. It interfaces with inventory management programs and accurately measures various aspects of inventory performance over years of actual sales histories.

In its current form, the simulation model, being deterministic, is atypical for modeling an inventory system (Law, Kelton, 1991). Currently there are no stochastic events generated within the simulation. The current method available for generating replicates is to randomly select another sample of parts from the same part population. Stochastic elements can easily be introduced into the simulation when the need arises. Such elements are planned for future evolution of the program, when it will be used to evaluate decisions for future scenarios. This is discussed further in section 6.0, Future Direction.

The simulation program encompasses the processes involved in running an inventory system, including the processing of airline orders, the process for replenishing depleted inventory, the weekly process of reallocating stock to sub stores, and the monthly process of updating and implementing new inventory plans. Incorporated into the simulation are currently used decision rules that govern the processes and define their interrelationships. These rules were captured during extensive interviews with personnel from the Spares Department.

Historical sales data are the driver of the simulation. Each sale order is characterized by several attributes, such as customer order class (RTN, EXP, etc.), order quantity, and the preferred store from which it should be dispatched. The simulation processes each order chronologically according to the sale transaction date and attempts to fill the order initially from the preferred store. If the preferred store cannot satisfy the order, then secondary stores are queried for available stock for shipment. Depending on the customer order class, the search criteria can become more complex. For example, an AOG order is the highest priority with no location restrictions for filling the order. An RTN order only picks from the inventory of the store identified on the customer order as the primary source, and from the main store as a secondary source. A search sequence of the warehouses determines which store(s) can meet the order's requirement. Split shipments (part from preferred and part from secondary stores) are included in the simulation logic. As sales occur, inventory levels decline. When a sale causes inventory to fall to or below ROP, the inventory replenishment process is triggered, a replenishment quantity for ROQ is ordered, and the arrival time for that release is computed based upon the ROLT assigned to the part. An order release is classified as either routine or expedite, depending on various rules built into the simulation that consider the state of inventory, namely existence of a stock-out or potential stock-out.

Incorporating the inventory planning and allocation processes into the simulation was a relatively straight forward accomplishment. The simulation interacts with production programs through files, by writing files of system state variables for each part. These files serve as input to the Inventory Planning and Allocation programs.

The simulation subsequently modifies any system variables, such as ROP, ROQ, and stock status, as directed by output from the Inventory Planning program, and continues with the execution. The simulation similarly communicates with the Allocation program. State information (such as bin levels at each store, stock due in, stock due out, safety stock, ROP, and ROQ) is written on a file for input to the Allocation program. The Allocation program processes the data and returns the part quantities to be shipped from the main warehouse to each regional sub-store. This again illustrates the importance of programs dynamically communicating and interoperating with one another.

Performance information is computed and recorded during the execution of the simulation. The types of data currently captured are:

1. Dollar value of inventory, globally and by store.
2. Dollar value of plans (ROP + ROQ), expected inventory, and simulated inventory.
3. Dollar value of actual sales and of forecasts by month.
4. Time distributions of order date to ship date by store and by order class code.
5. Fill rates (customer service performance) by store and by order class code.
6. Counts of trans-shipment and other events.

4.5 Validation

Simulation validation is difficult for the following reasons:

1. The historical system data has not been recorded to enable comparison to the simulation's results.
2. The Inventory Planning program was not part of the inventory management process in earlier years.
3. The Inventory Planning program has periodically been enhanced, and it is not possible to determine the impact the changes had on the simulation.
4. Planners often override the Inventory Planning program recommendations but changes were not documented.

Regardless, preliminary subjective validation was performed using the sales history data. The part sample selected for prototype analysis was used. Sales history data for the part sample, including the purchase and ship dates for each order, were extracted from the sales history archives. Graphical comparisons were made between actual and simulated data, and summary statistics were computed. Comparisons of trends and values indicate a reasonable similarity between the actual and simulated data.

5 RESULTS

Two prototype simulation runs were performed that adjusted only the performance level control parameters. This class of parameters is a theoretical value for the desired level of performance that represents the relative frequency customers have their orders fully satisfied on the day that they placed the order. A low performance test was made for an inventory performance setting of 90%, while a high performance comparison run was made with performance set to 99.5%.

The following outputs and charts compare results for these experiments. Tables 1 and 2 provide output for low and high inventory performance settings, respectively.

Table 1: Low Performance (90% Theoretical Fill Rate)

	Average Stock Value ($)	Maximum Stock Value ($)	Average Holding Time (Days)	Percentage of Time Parts had Stock Status 'S'
Auburn	974668.32	1762858.00	169.2	80.1%
Atlanta	45232.57	167981.00	110.5	46.0%
Brussels	29198.62	101096.00	113.2	40.1%
Singapore	10355.49	28634.00	192.8	22.8%
London	17549.04	84436.00	152.8	31.8%
Global	1077004.04	2100310.00	160.7	N/A

Table 2: High Performance (99.5% Theoretical Fill Rate)

	Average Stock Value ($)	Maximum Stock Value ($)	Average Holding Time (Days)	Percentage of Time Parts had Stock Status 'S'
Auburn	1815934.94	3515890.00	289.0	80.1%
Atlanta	54865.70	187484.00	116.8	46.3%
Brussels	36146.13	120842.00	124.8	40.5%
Singapore	12333.79	32601.00	199.8	23.1%
London	20570.24	86858.00	179.9	32.3%
Global	1939850.82	3902597.00	260.2	N/A

The outputs of Tables 1 and 2 are the average dollar values of stock, the maximum observed dollar values, the average holding times (days), and the percentages of time parts were stocked (stock status 'S'). The values in these figures are calculated using the following formulas.

Average stock value is defined as—

$$\sum_{i=1}^{n} \frac{(t_i - t_{i-1}) \times X_i}{t_n - t_0} \qquad (1)$$

where—

n = number of periods when inventory is stationary.

X_i = value of inventory during the i^{th} period of stationary inventory.

t_{i-1} and t_i = beginning and end times of the i^{th} period of stationary inventory.

t_0 = simulated clock time at the end of the warm up period.

t_n = clock time at the end of the simulation.

As expected, large increases are observed in average and maximum stock values between the low and high cases. It is especially noticeable at the main Auburn store where a significant percentage of the inventory is kept. This suggests that to achieve a theoretical increase in fill rate of 9.5%, approximately an 80% increase in inventory dollars is necessary.

The maximum stock value is reported in dollars for each store and globally. This is the highest single day dollar value of inventory and is rounded to the nearest dollar.

Average holding time, reported in days, is calculated as—

$$\frac{\sum_{i=1}^{n} (t_i - t_{i-1}) \times K_i}{\sum_{i=1}^{n} K_i} \qquad (2)$$

where—

n, t_i, and t_{i-1} = defined in Equation (1) above.

K_i = number of units of all part types in inventory during the i^{th} period of stationary inventory.

Also, as expected, the average holding time increases significantly in the main Auburn warehouse at the higher performance and increases slightly at each sub-store. This clearly indicates that to achieve a higher fill rate, a very significant increase in inventory is required, which also results in a large increase of the average inventory holding time.

The last column of output, the percentage of time that all parts had stock status 'S', is defined as—

$$\frac{100 \times \sum_{i=1}^{m} D_i}{m \times T} \qquad (3)$$

where—

D_i = number of days that part i had stock status 'S'.

m = number of part types.

T = simulation duration since statistical reset.

Figure 2 is a histogram comparison of time between sale date and ship date for items with stock status 'S' for low (90%) and high (99.5%) performance. Frequency classes are in 10 day increments, with the first frequency class representing 0 days, or equivalently, the order is immediately satisfied from stock in bin. The time between sale and ship dates is recorded only when the order becomes fully satisfied, i.e., split shipments are counted only when the last part that completes the order is shipped.

Each plot is subdivided into the four order classes (RTN, EXP, CRT, AOG). In the low performance case, RTN and EXP orders are immediately satisfied from bin approximately 73% of the time, while the high priority orders, CRT and AOG, are higher at approximately 82%. In the high performance case, a significant increase in fill rate is observed. For RTN and EXP orders, an increase of approximately 13%, to 86%, is achieved, and for CRT and AOG orders the increase is approximately 8%, to 90%. Note that the theoretical performance levels are not attained. One major factor is the conservative nature of the forecast evident in the time series plot in Figure 3, where the forecast is below actual sales most of the time.

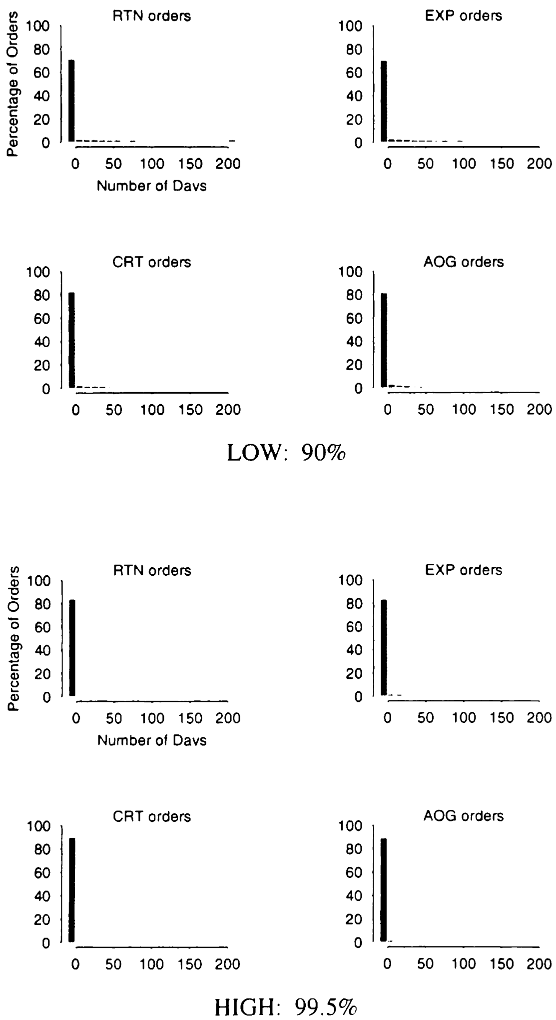

Figure 2: Inventory Fill Rate - Low vs. High Performance

Figure 3 plots actual dollar value sales, recorded monthly, against the value of the monthly forecast for the part sample. This chart shows the forecast lagging actual sales. Reasons for this phenomenon include:

1) Certain airline orders are excluded from the forecasts.
2) Unusually high orders are partly excluded from the forecast.
3) Conservative parameters are used for the exponential smoothing forecast method.
4) When trends are observed, a damping procedure is used, under the assumption that trends do not last forever.

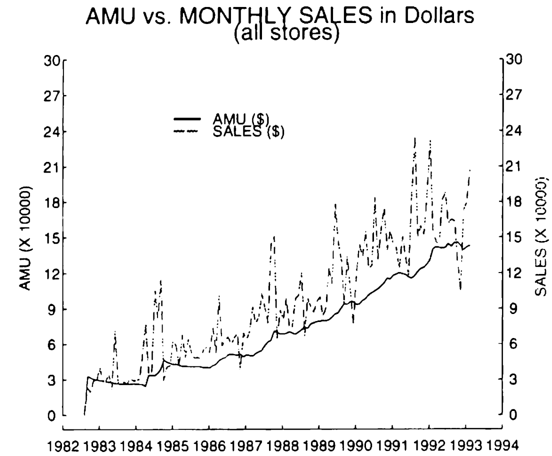

Figure 3: Actual Sales vs. Forecast

6 FUTURE DIRECTION

The following are recommendations resulting from the conclusion of the prototype phase of this project:

1. Train the customer in the use of the simulation in its current form.
2. Simplify the process of setting up an experimental run, executing the simulation, and displaying the results.
3. Program the statistical procedures for sample selection and experimental design.
4. Program statistical methods that generate future sales patterns based upon past sales.
5. Enhance the simulation by incorporating decision processes of inventory planners and by adding variation to the re-order lead times.

The first three recommendations are for immediate follow on work. Implementing recommendation 4 would enable determination of the effects of management decisions on various aspects of performance for future sales scenarios, prior to implementation of those decisions.

The rationale for recommendation 5 follows: Inventory planners make (necessary) daily decisions that affect inventory. These decisions often override the inventory plans and recommendations made by the Inventory Planning program. For example, customer demand for a part may increase unexpectedly, and planners may be privy to the reasons for this increase, whereas the Inventory Planning program cannot absorb and process this specific part information. The simulation currently does not account for these manual planning processes. The model accepts all inventory plan recommendations from the Inventory Planning program without exception. If the manual decision processes of inventory planners can be defined and quantified, it is desirable to include them in the model.

ROLTs are currently modeled deterministically, but they do vary. Data on delivery times for inventory replenishment must be analyzed so that statistical distributions can be developed to represent this variability and be programmed into the simulation.

7 CONCLUSION

The simulation prototype has provided a powerful platform for gaining insight into operation and control of inventory managed by the Spares Department. This was demonstrated by changing a control parameter and comparing the effects of the change on inventory. Future experiments and analysis will, hopefully, allow greater understanding of the other control parameters and their effects on inventory, thus achieving our ultimate objective.

This project has shown that the interoperability of simulation with existing production software does provide a powerful decision analysis environment. Without this interoperability, the analysis would not be economically feasible. When other design elements (e.g., the statistical analysis programs) are implemented and integrated, Spares Department management will have a formidable analysis tool for managing the spares parts inventory of the Boeing Company.

A "lessons learned" from this project is the need to carefully consider the intra-language architectures in a legacy system environment. Calling COBOL and FORTRAN programs from GPSS/H in a mainframe environment, though feasible, was found to be much easier in a PC environment.

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REFERENCES

Bier, I. J. and J. P. Tjelle. 1994. Simulation of the Spares Inventory Planning Process. BCSTECH-94-005. Bellevue, Washington, Boeing Computer Services.

Henriksen, J. O. and R. C. Crain. 1989. GPSS/H Reference Manual. 3rd ed. Annandale, Virginia, Wolverine Software Corporation.

Law, Averill M. and D. W. Kelton. 1991. Simulation Modeling and Analysis. 2nd ed. New York, McGraw-Hill.

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