Improving Performance and Flexibility at Jeppesen: The World's Leading Aviation-Information Company

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Jeppesen Sanderson, Inc. maintains, manufactures, and distributes flight manuals containing safety information for over 300,000 pilots and 400 airlines worldwide. Its service deteriorated when a growing line of over 100,000 aviation charts overwhelmed its production system. We developed optimization-based decision support tools that improved production planning. Concurrently, we developed a method for evaluating investments in production technology. Our work reduced lateness and improved production processes, which led to a decrease in customer complaints, a reduction in costs of nearly 10 percent, an increase in profit of 24 percent, and the creation of a new OR group. Today, OR-based decision support systems are spreading to all areas of the company.

Jeppesen Sanderson, Inc., the world's leader in aviation information, maintains, manufactures, and distributes flight manuals containing critical safety information to over 300,000 pilots and 400 airlines worldwide from over 80 countries. Over 80 percent of pilots rely on Jeppesen charts. Jeppesen's customers include major airlines, such as American, Delta, Federal Express, Japan Airlines, Korean Airlines, Lufthansa, Northwest, Quantas, Southwest, United, UPS, US Airways, many smaller airlines, and many private and corporate pilots.

Historically Jeppesen has been very innovative, but in 1997, we found it in trou-

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ble. Jeppesen's growing product line overwhelmed what had been an efficient production system. It could not maintain its once stellar service and was threatened with losing a major customer. We developed a suite of optimization-based decision support tools that improved production planning and revealed the value of operations research to Jeppesen managers. Concurrently, we developed a novel and general method for evaluating investments in production technology. With this new method, we overcame some difficulties the firm experienced with previous techniques. Our work dramatically reduced lateness, which led to increased customer satisfaction, a reduction in production costs of nearly 10 percent, an increase in profit of 24 percent, and the creation of a new interdisciplinary 14-person OR group.

Some weeks, it revises over 1,500 charts.

Jeppesen's founder, Captain Elrey B. Jeppesen, was one of the aviation industry's early colorful pioneers. In 1927, he earned his pilot's license, which was signed by Orville Wright. In 1930, he became an airmail pilot with Varney Airlines, and later with Boeing Air Transport, flying the Salt Lake City-Cheyenne route, the most dangerous route at that time. With no aeronautical charts available, many pilots used road maps for navigation and often followed the railroad tracks. If weather conditions deteriorated too much, they made emergency landings in fields and waited out the storms. During the winters of 1930 and 1931, several of Jeppesen's fellow pilots were killed, and their deaths were partly attributed to the lack of aviation information. These tragic losses prompted Jeppesen to start making systematic notes on issues related to flight safety. He recorded field lengths, slopes, drainage patterns, and information on lights and obstacles, he made drawings that profiled terrain and airport layouts, and he even noted the phone numbers of local farmers who could provide weather reports. On his days off, Jeppesen climbed hills, smokestacks, and water towers, using an altimeter to record accurate elevations.

Pilots started asking Jeppesen for copies of his notes, and in 1934, the Jeppesen charting business was born. When Varney Airlines, Boeing Air Transport, and several other companies merged to form United Airlines, United became the first major air carrier to subscribe to Jeppesen's early Airway Manual Service. In 1961 Jeppesen became a part of Times Mirror, a major publisher (which publishes the *Los Angeles Times*, *The Baltimore Sun*, and a number of special interest magazines, such as *Popular Science* and *Field and Stream*). In 1995, in recognition of Captain Jeppesen, the Denver International Airport named its main terminal the Jeppesen Terminal, and it displays a statue of Captain Jeppesen there. In October 2000, Jeppesen became part of the Boeing Company team.

Today, Jeppesen Sanderson has about 1,400 employees (900 in Denver, Colorado, 300 in Frankfurt, Germany, and the rest in small offices around the world). Although over 80 percent of pilots worldwide use Jeppesen charts, the firm's competitors include the US and Canadian governments, several airlines, including Swiss Air, and

Richel, a European firm. Jeppesen is well aware that advances in technology are dismantling barriers to entry into the aviation-information market. In fact, this awareness was one motivation for our work. Jeppesen wanted to assure customers that its service and the quality of its products was still unsurpassed.

Problem Background: Products

Throughout our work, we concentrated on Jeppesen's charting products. Jeppesen also offers flight simulators, training packages, flight planning, and other aviation products. The basic building block of all Jeppesen's paper products is the *chart* or *flat* (Figure 1). These charts range from 5.5 by 8.5 inch black-and-white charts to large multicolored maps, also called *folds*. Twenty-five to 36 charts are collated into sections, which are assembled into *manuals*, or *coverages*. A manual is a large leather loose-leaf ring binder with replaceable charts and folds.

Jeppesen's primary products include weekly revisions to which customers subscribe and new manuals. The revisions go out to customers who already have Jeppesen manuals. A revision is a collection of folds and charts that have been changed or revised during the current production week. A pilot subscribing to this service receives updated information every week. A customer ordering a manual gets a binder containing all the current folds and charts for a geographical area.

The Processes: The Revision Assembly Process

Aviation information changes so often that about 75 percent of all charts are revised at least once every year, and a substantial number of charts must be revised even more often. Flight manuals are usually configured by geographical areas (for example, the Western United States, South America, or the Pacific Rim). Many pilots subscribe to these *standard coverages*. Jeppesen's large customers, such as major airlines, however, often order special sub-

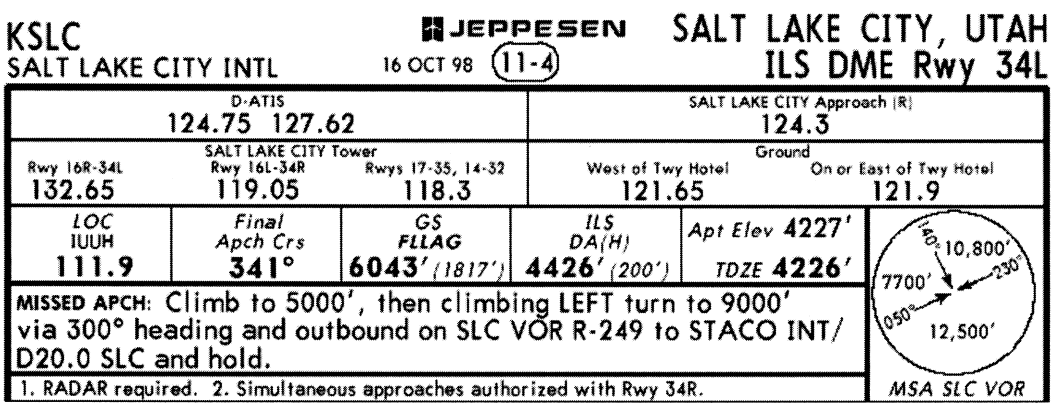

Figure 1: Jeppesen manuals, or coverages, usually contain a set of charts for a geographical area, such as the Western United States, Europe, or South America. An average manual contains about 700 charts. Charts contain safety information, such as approach routes, radio frequencies, and GPS coordinates. Some charts, called folds, are large and printed in color. Most charts, called flats (above), are 5.5 by 8.5 inches in size and are printed in black and white. Manuals are composed of numerous sections, with each section consisting of 25 to 36 flats.

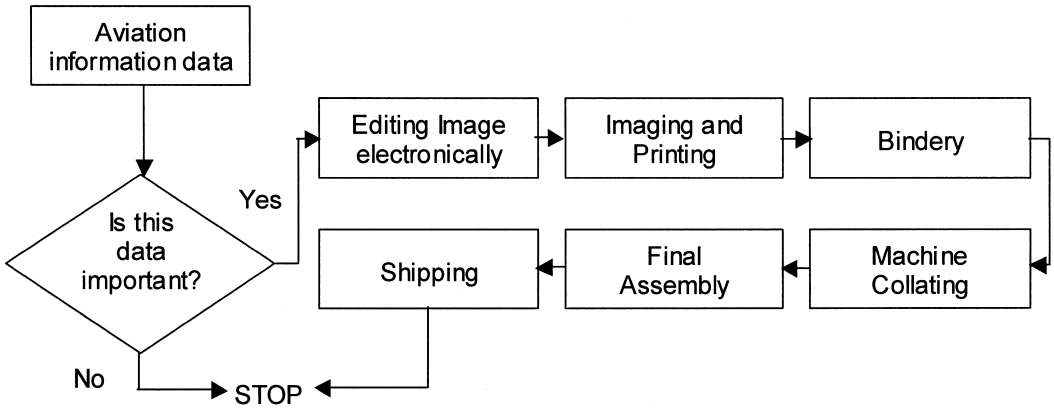

Figure 2: When Jeppesen gets information about a potential change it decides whether the change requires an alteration of a chart. If so, it edits the image file electronically, prints a new negative, which goes to imaging and printing, where it is stripped onto a plate containing 21 negatives. Jeppesen then prints the plate, cuts it into individual charts, and then rounds corners and punches holes in the charts in the bindery. After the bindery, the charts go into the machine collating department, where machines collate charts into sections. Each section contains up to 36 charts that will eventually go into the same coverage. These sections and large folded maps go to the final assembly department, where employees manually assemble these into coverages and stuff them into envelopes. Large boxes of envelopes then go to the shipping department. Quality control and verification is performed at each step of the process.

scription packages or *tailored coverages*.

Tailored coverages contain charts with customized information, pages specially configured, and other special features that customers request. Jeppesen maintains over 500 different standard coverages and 2,000 different tailored coverages drawn from over 100,000 distinct charts.

A critical change in aviation information (for example, an airport runway is closed or expanded) typically affects one standard chart and several tailored charts. Within one week of modifying a chart, Jeppesen must issue a new manual page and send it to all those subscribing to coverages containing this page. Every week Jeppesen mails between 5 and 30 million pages of chart revisions to over 200,000 customers worldwide. Some weeks, it revises over 1,500 charts, affecting over 1,000 coverages.

When Jeppesen obtains information about a possible change, it decides whether to alter based on whether the change is important or permanent. Some changes, such as a runway closing for 20 minutes on one day, do not need to be included on a chart. If changing a chart is necessary, the first step of the process is to edit the image file electronically (Figure 2). Simple changes take less than five minutes, while complex changes can take eight hours of redrafting. After Jeppesen edits an image file, it prints a new negative and sends it for imaging and printing, where it is stripped onto a plate containing 21 negatives. Jeppesen then prints the plate, cuts the printed sheets into individual charts, then rounds corners and drills holes into the charts (bindery). It sends the charts to the machine collating department, which collates them into sections.

Each section contains up to 36 charts that will eventually go into the same coverage. Large maps (folds) are not included in sections because collating machines cannot handle thick folded material. Sections and folds go to the final-assembly department, where employees manually assemble them into coverages and stuff them into envelopes. Single envelopes addressed to pilots and large boxes of envelopes for airlines then go to the shipping department, which ships by a standard method, if they are on schedule, or by express if they are not.

The Processes: Orders for New Manuals

Jeppesen's marketing department gets about 1,500 new orders per week, each for various quantities of various manuals (Figure 3). For example, an airline running a class for pilots might order 20 to 30 manuals to support this training.

When Jeppesen receives a new order for a manual, it can either ship precollated manuals from stock or hand-assemble manuals to order. About 60 percent of the manuals covered by new orders are precollated; the rest are hand-assembled. Orders for manuals in stock are shipped immediately. However, manuals that are usually precollated can be out of stock or some of their charts may need replacing because of recent revisions. Producing a new batch of the precollated manuals or hand-assembling a manual may take as long as a week. When Jeppesen has precollated manuals in stock that need revision, it must decide whether to manually insert updated charts or to discard the manuals and build new ones.

For low volume manuals, Jeppesen uses an inefficient build-to-order process. To build a flight manual, an employee must select charts from over 250,000 pigeonholes, arrange them in the correct order, and separate them with the appropriate tabs. Since an average manual has 700 charts, this process is extremely time consuming and prone to errors. To decrease errors, Jeppesen subjects each hand-assembled manual to a quality check, in which another employee checks each page against a content list and corrects any errors.

Service Problems

In recent years, the increasing volume and variety of aviation information threatened Jeppesen's ability to provide prompt customer service. By the fall of 1997, when we began our work at Jeppesen, the number of orders delivered late was growing at an alarming rate. In the early summer of 1998, the Air Transport Association (ATA), the international organization of

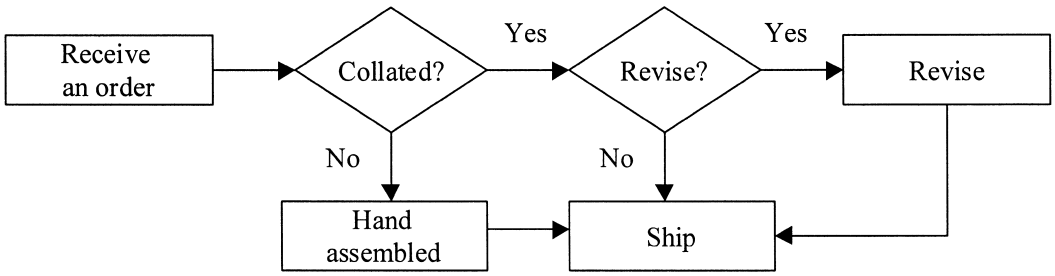

Figure 3: New-order manuals that are precollated and do not require revision are shipped immediately. Otherwise, manuals are hand-assembled or revised and then shipped.

airlines, wrote to Jeppesen's CEO complaining that the timeliness of Jeppesen's service "needed improvement and was not meeting its expanding expectations." The ATA demanded immediate and dramatic improvement in the timeliness of both of Jeppesen's modes of service: its weekly dissemination of updated aviation charts, and its shipment of orders for new flight manuals. It did not question the accuracy and clarity of Jeppesen's aviation information, upon which airline safety depends.

Jeppesen's customer service had deteriorated because its existing production and supporting systems could not keep up with changing customer demand. In the past, Jeppesen's product line had consisted primarily of standard manuals and a small number of customized manuals. Typically, standard manuals have high subscription quantities, and since standard manuals had historically accounted for the bulk of the demand, the production system was geared to using long production runs. Over the years, demand for customized manuals increased, while average subscription quantity decreased (Figure 4). While overall production volume increased slightly, the number of products grew rapidly and the average subscription quantity decreased rapidly. The production process, which relied on a combination of heavy machinery, manual labor, and paper-based planning tools, remained virtually unchanged. Jeppesen's managers realized the company was in danger of losing its competitive edge.

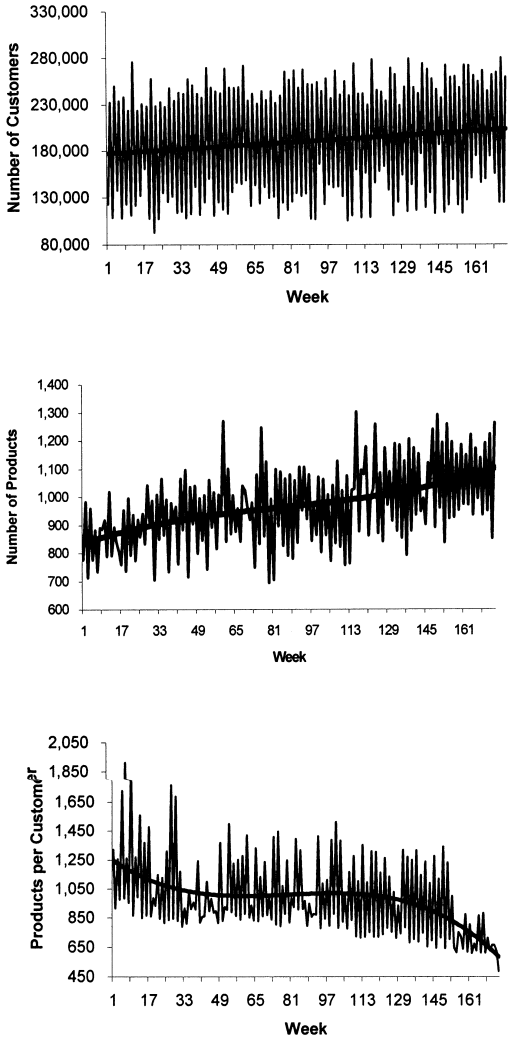

Figure 4: Between 1995 and 1997, Jeppesen's customer demands changed towards greater customization. The number of customers grew moderately; the number of individual products grew quickly, while the quantity per order fell rapidly.

Project Description and History

In December 1997, Alex Zakroff, a Jeppesen industrial engineer, asked Professor Gene Woolsey at the Colorado School of Mines for help at Jeppesen. Zakroff believed operations research could help Jeppesen solve some problems at its production facility. Woolsey took us (fellow professor Elena Katok and doctoral student Bill Tarantino) and several other stu-

dents to tour Jeppesen and found numerous opportunities to use OR tools to improve production planning. Tarantino decided to tackle Jeppesen's problems and use the analysis in his dissertation. Tarantino and Katok worked through the Jeppesen plant under Zakroff's and Ralph Tiedeman's guidance in all production areas per Woolsey's recommendation and developed ideas for the project. We were actively involved with Jeppesen for the next two years, developing analytical models for process improvement, and decision support tools for production planning and scheduling.

Our project included two parallel efforts (Figure 5). In the first, strategic economic analysis, we studied how to improve the production process by making strategic investments in alternative production technology. We developed a list of technology alternatives to increase throughput in the production areas and a method that combines simulation and optimization to analyze these alternatives and justify investments, and we recommended purchase of several pieces of capital equipment that cost over $9 million and improved performance during 1998 and 1999.

In the second effort, we created a suite of decision-support tools for production planning that used all available resources efficiently, including newfound capacity from additional equipment. We built several spreadsheet-based and database management tools, which became extremely popular among planners and have since permeated Jeppesen and several of its major customers, including Delta, United, and US Airways.

Our OR modeling efforts covered several aspects of production. First, we developed a large-scale linear program, called the scheduler, that optimizes production of the weekly revision. Second, we developed a mixed-integer-programming model

Strategic economic analysis			
Projects	**Analysis**	**Approval**	**Implementation**
folder collator	Dec 97-May 98	Jun-98	Jan-99
tower collators: machine collating	May - Dec 98	Jan-99	Mar-99
tower collators: orders	May - Dec 99	Jan-99	Apr-99
bindery	Sep 98-Feb 99	Mar-99	Jul-99
Print-On-Demand (POD)	Apr 98-Apr 99	May-99	Oct-99
Decision support tools for production planning			
Revision planning tool	Dec 97-Jan 98	Feb-98	Mar-98
Revision scheduling model	Dec 97-Jul 98	Aug 98-Oct98	Nov-98
Capacity planning tools	Feb 98-Apr 98	May-98	Jun-98
Production cost planning system	Apr 98-May 98	Jun-98	Jul-98
Inventory model	Jun 98 -Jul 98	Aug-98	Sep-98
Order fulfillment scheduling model	Nov 98-Dec 98	Jan-99	Jan-99
Interactive plater	Feb 99-Jul 99	Aug-99	Sep-99

Figure 5: Our project included two parallel efforts: strategic economic analysis and decision-support tools for production planning. Each project had an analysis period, an approval point, and an implementation period. The implementation month listed represents the first month of implementation; the implementation period can be as much as six to 12 months.

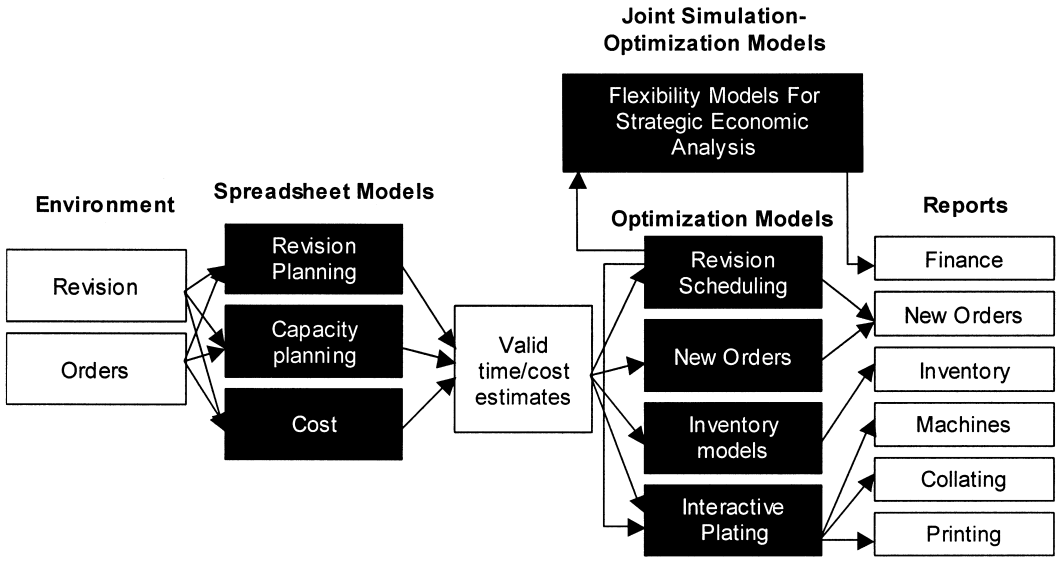

Figure 6: We used spreadsheet-based models to derive empirically valid time and cost estimates for all production areas. We then used these estimates in a variety of optimization models for production planning and strategic management.

that daily optimizes the completion of new orders. Third, we developed a stochastic dynamic inventory-management model that controls disposal of outdated charts that vendors typically print. Finally, we developed an interactive, knowledge-based heuristic based on the approximate solution of a large-scale nonlinear mixed-integer program to minimize scrap when making plates for offset printing.

Models Used in Decision-Support Tools

We used three types of interrelated models in our analysis: spreadsheet-based, optimization, and joint simulation-optimization models (Figure 6, Table 1).

Our first task was to develop accurate cost estimates for the various steps in the production process. Jeppesen planners provided us with standard rates for some processes and average values for performance data. We tested the data and quickly identified shortcomings, which we resolved by collecting additional data. What began as data collection to justify the firm investing in a print-on-demand (POD) digital printing system became a cost-planning tool used to make daily production decisions. To determine the cost of a particular production step, we collected empirical data on each process by working in the area and recording processing times and product characteristics. For example, to estimate the time it takes to collate a coverage on a tower collator, we recorded the number of charts in a coverage, the total quantity of the coverage demanded, the setup time for loading and unloading, and the processing times for different coverages. We then used regression analysis to fit equations for setup and processing times as a function of the number of charts in a coverage and the quantity demanded. At times, as in the case of tower processing times, we observed nonlinear relation-

Model	Type/Solution	Size	Implementation	Impact
Revision scheduler	Linear model combined with heuristic	250,000 variables; 40,000–100,000 constraints	GAMS with OSL solver; data and user interface in Access	Decreased tardiness in revision by 60%; aided strategic planning
New-orders scheduler	Mixed-integer model	1,500 variables; 1,000 constraints	GAMS with OSL solver; data and user interface in Access	Automated the scheduling process; eliminated backlog and tardiness in new orders
Plater	Nonlinear mixed-integer problem, solved using a knowledge-based heuristic	10,000 variables; 1,500 constraints	Algorithm written in Perl; data and user interface in Access	Automated and shortened scheduling process; decreased scrap
Inventory-management tool	Stochastic dynamic programming model solved using a heuristic	Used for almost 1,000 charts	Heuristic solution implemented in Excel; data and user interface in Access	Automated an ordering process; reduced costs of scrap and reorders

Table 1: We developed four optimization models, each of which improved a different area in Jeppesen's production operations.

ships. We later used these empirically derived and validated equations as inputs to optimization models (Appendix).

Jeppesen's production group consists of six distinctive areas with different processes, labor requirements, and final products. The capacity-planning tools are a suite of spreadsheet and database models that provide these areas with explanatory reports and daily updates to manage their weekly and daily workloads.

An important capacity-planning tool that we developed is the revision-planning tool, a capacity-planning system that determines labor and equipment requirements for the weekly revision. All Jeppesen managers use this system to allocate the work they have for the week. In the past, the production areas had no way to predict their weekly requirements. As a result, they could not plan for temporary help or vendor assistance, nor could they tell employees what work to expect. The resulting lack of efficient planning led to late revisions, high overtime, and high employee turnover. The revision-planning tool gave planners flexibility early in the week to make staffing and outsourcing decisions and gave employees forecasts of their weekly workloads. In developing these and other tools, we developed the data building blocks and equations needed for other, more sophisticated optimization-based decision-support systems at Jeppesen.

The scheduler is a linear-programming model that minimizes the cost (regular and overtime labor, outsourcing, lateness) of producing the weekly revision subject to capacity constraints and numerous in-

ternal business rules (Appendix). The scheduler also determines the optimal way to produce coverages (POD, offset, or outsourcing for printing, different types of machines or manual processes in machine collating and assembly areas). The basic scheduler model has over 250,000 variables and between 40,000 and 100,000 constraints.

To be practical, this model must obtain solutions in minutes on Jeppesen computers. When we first formulated this problem, it took several hours to solve. To improve solution times, we took advantage of the problem's structure and used decomposition to reduce the problem. We solve the parts of the problem individually and then combine the solutions to construct the solution to the whole problem. We implemented this model and the postprocessing module in GAMS [Brooke, Kendrick, and Meeraus 1999] and did preprocessing decomposition in Microsoft Access [Viescas 1999].

The data requirements for the scheduler are formidable, primarily because each revision has its own special business rules. We implemented the scheduler's data interface in Access, which reads a flat file with all revision requirements, generates data-input files for GAMS, initiates GAMS with a macro button, and reads back the GAMS solution. Afterwards, the scheduler generates reports for all six production areas. Jeppesen uses this system twice a week and has used it to identify data errors and inefficiencies in past scheduling practices to improve use of resources and hence to reduce costs. Immediately after we introduced this tool, Jeppesen established a new record for the number of consecutive weeks with 100 percent on-time revisions. The scheduler decreased tardiness of revisions from almost nine percent to three percent, a 60 percent improvement, avoided expedited-shipping costs, and dramatically improved customer satisfaction. However, our main purpose in developing the scheduler was to develop a valid optimization model of the system for Jeppesen to use in strategic economic analysis.

By working in the plant, we obtained first-hand understanding.

One output of the scheduler model is the schedule for printing charts. The scheduler establishes the timing and incorporates Jeppesen's business rules, so the information on when to print each chart can go to the interactive plating tool (the plater). Planners use this tool in assigning charts to printing plates for offset printing. Each plate consists of 21, 16, or eight images of charts with 800 to 1,500 charts printed each week in quantities of 100 to over 200,000. When one plate contains multiple charts, the number of prints made from the plate determines the number of copies of each chart. A chart can go on a plate multiple times (one to 21), however, and a chart can go on multiple plates. The machine operations area prefers to receive charts in close to complete coverages, but printing likes to print each chart only once. These objectives conflict, which necessitates a systems approach in the scheduler.

Although we can represent the plating problem as a nonlinear integer model

(Appendix), we suspect that the resulting optimization model cannot be solved for real-scaled problems in anything like reasonable time. Therefore, we created an algorithm for the plater based on the plating rules used by the Jeppesen scheduler. We implemented this algorithm in the Perl programming language [Schwartz, Olson, and Christiansen 1997] with an Access interface that allows users to change inputs and the solution. Jeppesen is using the plater twice a week (Mondays and Thursdays) to automate scheduling and reduce excess printing.

The plater solution has a module for scheduling machine collating that determines the first day a coverage can be completed by machine operations. The problem is a mixed integer program with about 40,000 variables, 30,000 constraints, and about 4,800 binary variables that change weekly based on demand and solves in a few minutes on a Jeppesen PC.

We developed the new orders model as a result of a five-day executive-training class in quantitative methods that we conducted at Jeppesen during the fall of 1998. As part of the class, we introduced GAMS and realized that we could use an optimization model to improve the on-time rate for new orders. Before we developed this model, Jeppesen's on-time rate for 1996 through 1998 had averaged 61 percent, and new orders had had a moving-average backlog of about 600 late volumes a week (a volume is 700 charts). We implemented the model in the first week of January 1999. By the end of January, new orders was performing 95 percent on time, and the backlog had nearly disappeared. The new orders on-time rate for the first-quarter of 2000 was 100 percent.

The new-orders group runs the model every day. The model considers about 1,000 outstanding orders, a two-week planning horizon, the time required to complete an order (empirically estimated using a planning tool), production capacity, shipping requirements, and different types of lateness. The model minimizes cost and penalty functions for lateness that implicitly minimize shipping costs. The greatest benefits included increased customer satisfaction, which led to an increase in new orders (higher sales); decreased shipping costs because of a decline in late orders; and decreased production costs with reduced overtime.

The new-orders model is a linear program, and we take advantage of the network structure of the formulation to get a nearly integral solution (Appendix). This problem is small (about 14,000 variables and 2,000 constraints) and solves in less than a minute on a PC.

After several test runs, we found that the new-orders formulation resulted in an integer solution for approximately 95 percent of the orders. Postprocessing similar to the scheduler's assigns multiple day orders to the day in which most of the order is produced. We enhanced the model's solution with an Access database and user interfaces. The system provides a daily schedule that lists the time of day an order must arrive at the shipping department to go out that day by the prescribed method.

When Jeppesen prints a chart, total quantity printed is composed of the revision quantity and the bin-stock quantity. The revision quantity goes to current sub-

scribers as a part of the revision service. The bin-stock quantity is held in anticipation of new orders. Jeppesen uses the inventory tool we developed to compute bin-stock quantities for the most expensive charts (enroute, area, and airport qualification charts).

Since Jeppesen must revise charts at unpredictable times (weeks to months after the current version), it cannot use standard inventory-management models. Uncertainties about distribution of demand and the probabilities of revisions affect decisions about bin-stock quantity. If Jeppesen planners order too few charts, they may later incur large fixed costs for new orders, but if they order too many, they risk scrapping the bin stock if the chart must be revised early. We model this problem as a periodic-review inventory system with random deadline [Katok et al. 2000].

The time we invested in working on the line saved us countless hours in data collection.

The new system includes an Access-based interface that makes it easy for users to update demand and revision-history data, to place orders, and to track savings. The system determines savings by calculating the difference in costs between the results of the old ordering process and the solutions produced by the new system. In addition, we determined reorder costs from past invoices and compared them to recent reorder costs. Beginning in August 1998, Jeppesen has used the system to control the ordering process for almost 1,000 charts. Between August 1998 and August 1999, the system saved over $800,000 in reduced scrap and reduced reorders.

The Sampling Algorithm for Flexibility Planning

This project's most innovative technical contribution is a new method for determining the value of equipment that provides manufacturing flexibility, the sampling algorithm for flexibility planning.

An investment in new equipment can produce value in three possible ways. The new equipment may be more efficient than the old equipment—faster, or require fewer operators—and the added efficiency can decrease production costs. The new equipment may add capacity at a bottleneck, increasing the extra capacity throughput of the entire system and lowering inventory costs, decreasing lead times, and possibly avoiding lost sales. The third way new equipment could capture value is by increasing decision flexibility—by allowing managers to postpone production decisions until they acquire more information.

For Jeppesen, decision flexibility is very important. Aviation information changes constantly, so Jeppesen often receives revision or new order information after it has started production. Since the offset process may take longer than a week, production must start well in advance of a due date, usually when demand information is not complete. The ability to postpone production decisions has value.

We can use standard deterministic optimization models to capture value from efficiency and capacity, but to capture value from decision flexibility, we must model uncertainty, which necessitates flexibility.

The ability to model uncertainty efficiently extends our method over prior work. We modeled uncertainty by combining the optimization model of the system with a model that simulates uncertain parameters in the environment. At each step of the algorithm, we simulated a realization of uncertain parameters and optimized the system given all prior decisions. We then computed the new equipment's value by comparing the average performance of the system with and without the new equipment [Katok, Tarantino, and Harrison 2000]. This flexibility-planning method is general and can be applied beyond Jeppesen. We used this method to justify investments in a new automated collator for the assembly department, in five tower collators for machine-collating and new-order departments, in a new bindery system, and in several presses (Table 2). In the analysis that had the most revolutionary impact on production, we examined the print-on-demand digital printing system (POD)—a $6.9 million investment that augments the traditional offset process at Jeppesen. This system compresses the production process of assembling revisions into a single operation, shortening lead times to hours, and planners can postpone production until they have complete information on demand. Digital images of charts are sent to the POD, which produces a collated coverage. IBM custom-built this equipment, overcoming the main technical challenge of supporting the thin paper Jeppesen uses for charts. Increasing its thickness by even a small amount would increase the weight and size of manuals, which would be unacceptable to Jeppesen customers.

Approach: Active Decision Support

We were not the first analysts at Jeppesen to attempt changes in production planning or to justify investments in new technology, but our effort was the first

Equipment	Impact
Two automated collators for the final assembly area	Fewer employees needed to collate folded material. Reduced use of temporary employees and of vendors for outsourcing folded materials. Decreased costs to complete fold requirements by over $800,000 in 1999.
Two tower collators for machine collating	Improved ability to collate small coverage runs.
Three tower collators for precollating new orders	Improved ability to precollate various coverage types and to precollate for additional demand.
Bindery	Simplified and enhanced bindery operations.
Two new printing presses	Improves ability to do work in house that was formerly done by vendors.
A print-on-demand (POD) digital printing system	Reduced lead times, improved responsiveness, increased productivity, and decreased errors.

Table 2: Based on our analysis using the joint simulation-optimization algorithm for flexibility planning (and in the case of new printing presses, Jeppesen's analysis), Jeppesen bought additional equipment, which greatly improved its production operations.

successful one in many years. In large part, we attribute our success to a set of guiding principles for OR implementation that we call active decision support. During our work at Jeppesen, we found that these four guiding principles helped us gain acceptance for OR methods and with successful implementation:

(1) Be personally involved throughout the entire process,
(2) Use a systems approach to modeling,
(3) Start small and build on past success, and
(4) Understand and identify explicit risks associated with change.

We found personal involvement to be the most important of the four principles. When describing the process of building decision-support systems, most textbook authors (for example, Turbam and Aronson [1998]) talk about a "needs assessment" and "identifying basic requirements" as the first step in constructing a DSS. We often had the most difficulty eliciting from users precisely what they wanted their system to accomplish. Most users are unfamiliar with this concept and therefore view identifying requirements as an abstract theoretical exercise until they see a working prototype. After a prototype has been completed, however, substantial changes are usually difficult. For this reason, we recommend that OR analysts spend time working along side plant employees to fully comprehend all processes before starting to build tools to improve performance [Woolsey 1998]. Many professionals never work in the areas they are trying to improve and don't see doing so as a useful expenditure of their time. However, we found that investing this time is essential to thorough understanding and to accurate definition of system requirements. By working in the plant, we obtained first-hand understanding of the production processes, we simplified data collection, and most important, we developed long-lasting personal relationships and trust. In the end, the time we invested working on the line saved us countless hours in data collection and modeling and was crucial in the implementation stages. When it came to implementing the decision-support tools for production planning, we were considered part of the production team, because we had taken the time to participate in the original process before trying to build tools to improve it. Personal involvement should continue through the system-development cycle until full acceptance. We found that educating users and passing ownership of solutions to users was key to our success.

"I didn't start this company to make money; I started it to stay alive."

The second guiding principle is to use a systems approach to all modeling and improvement efforts. At Jeppesen, each production area had traditionally operated autonomously, seeking to maximize its own productivity and not always considering the effect on other production areas. We demonstrated the benefit of seeking to optimize the entire production process. Using the systems approach triggered a shift in managers' thinking about their production processes and methods.

The third principle is to start small and

build upon past success. For example, the first time we analyzed an investment in equipment, we justified the purchase of an assembly collator, which we thought would quickly improve one of Jeppesen's production bottlenecks. The analysis was straightforward because it affected one production area, final assembly, and the collator was inexpensive given its benefits. Efficient use of the collator started to dissipate bottlenecks and reduce costs, our credibility increased, and we gained acceptance for several other pieces of production equipment, each of which improved the system's performance.

The fourth principle is to understand and articulate the risks associated with change. Whenever a firm embraces a new technology, it takes risks. Jeppesen was no exception. These risks fall into four major areas: technological, financial, implementational, and managerial. Technological risk, whether a system will perform as expected, is always a concern. Financial risks stem from uncertainties about technological risks, project costs, and benefits. Implementational risks have their roots within technical and financial risks, and within people's natural resistance to change; therefore, any OR tool that requires change will face resistance during implementation. Finally, managerial risk arises as managers oversee the project and mitigate other risks. By understanding the risks and communicating them clearly to management, we controlled their expectations and improved the probability of project success.

Impact on Jeppesen and the Airline Industry

Alex Zakroff, the head of planning at Jeppesen, compared using OR tools to "turning on the light." Before the introduction of these tools, Jeppesen was unable to predict future demands, which forced production to scramble to fill orders on time. Planning tools helped Jeppesen to see further into the future and to plan accordingly. Also, the planning tools helped managers to use resources efficiently, including the capacity the new equipment added (Table 3).

Our work at Jeppesen dramatically decreased lateness in both new orders and revision assembly (Figure 7). In 1998, more than a third of new orders were late. This was unacceptable, because airlines depend on Jeppesen's products for safe operation of their flights. Through May 2000, new orders were running at 100 percent on

	1998	Jan–May 2000
New orders	35% late	0% late
Revisions	8.8% late	3.3% late
Customer complaints	Increasing	Decreasing
Threat of lost customers	Yes	No
Production cost (1998 to 1999, 1999 to 2000)	+7%	−10%
Gross profits	—	+24%
OR group	No	Yes
New equipment (1999 and 2000)	None	$9 million

Table 3: OR had a significant impact on the performance of Jeppesen's production and distribution division that controls the revision and new-orders processes between 1998 and May 2000.

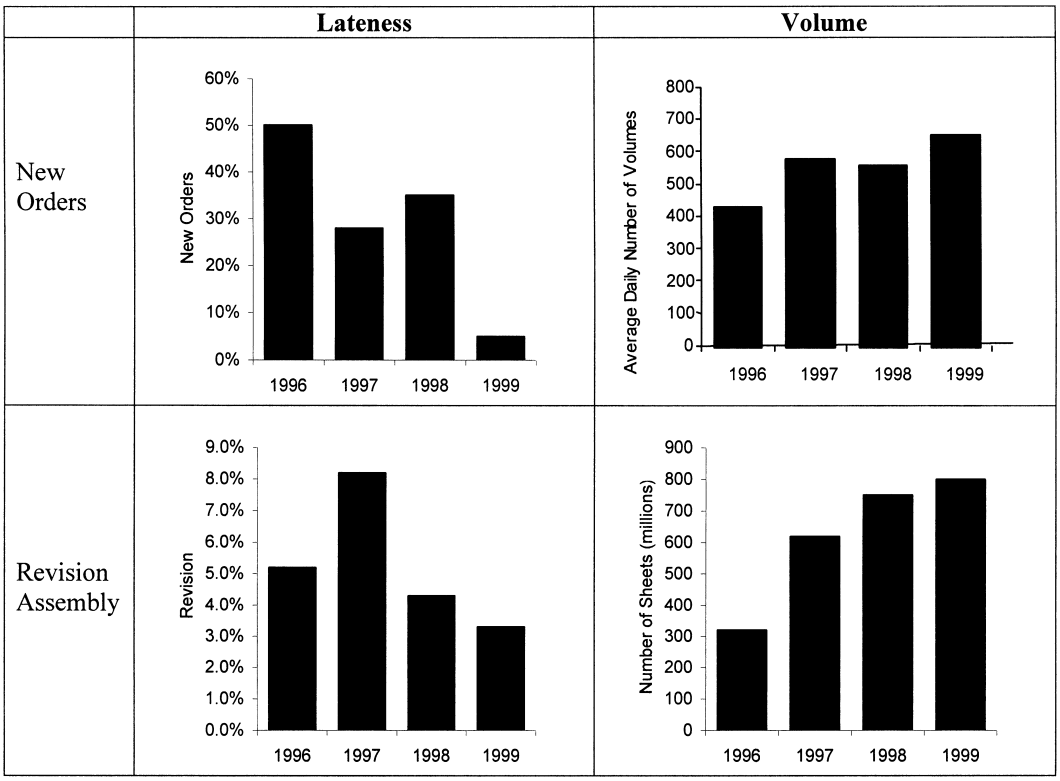

Figure 7: As a result of using OR methods, Jeppesen's performance has improved. Between 1996 and 1999, it nearly eliminated lateness in new orders, while average daily demand in volumes (one volume is 700 sheets) grew by 65 percent. In revision assembly, lateness decreased by 60 percent while total yearly volume increased by 25 percent.

time, even as demand grew. Revisions' lateness has decreased by 60 percent while the volume of revisions has increased by 30 percent, or a quarter of a billion charts. With improved performance, Jeppesen reported that customer complaints and the threat of losing major customers had decreased.

Using Jeppesen's financial records, which include all costs for producing flight manuals, we calculated that production costs decreased by almost 10 percent (Figure 8) and profits increased by 24 percent, as demand increased. The new equipment provided additional production capacity, and the planning tools and models enabled Jeppesen to improve its use of all resources.

The OR methods we introduced to Jeppesen served as catalysts for new ideas and encouraged out-of-the-box thinking. Most important, by increasing on-time deliveries to Jeppesen's customers, our work has improved safety in the airline industry. We made improvements in four areas:

—We isolated and analyzed six technologies that when used efficiently in production increased the flexibility of Jeppesen's production system enough that it could provide acceptable customer service. Based on our analysis and recommendations, Jeppesen bought $9 million worth of

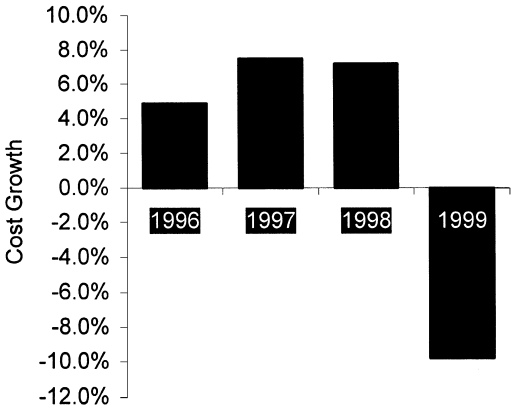

Figure 8: As a result of introducing OR, the growth trend in production costs was reversed. While in 1997 and 1998 costs grew by almost seven percent, in 1999 costs decreased by almost 10 percent.

new equipment.

—We developed a suite of decision-support tools for planning and scheduling revisions that improved Jeppesen's production performance. The decision-support system (DSS) combines a relational database model of the revision-assembly process with a flexible large-scale optimization model. This model determines resource requirements for assembling the week's revisions and provides information needed to optimize the week's revision process. After we developed the first module of the DSS, we implemented the revision-planning tool in the summer of 1998, and from then until the spring of 1999, Jeppesen delivered only two revisions late. It made similar improvements in new orders increasing on-time orders from a low of 65 percent in 1998, the year prior to our work, to 100 percent in 2000.

—We introduced OR to Jeppesen and, during two years, substantially changed its operations.

—We believe we succeeded because we used active decision support, starting by physically working through the production process from start to finish. By doing this, we gained understanding of the process and credibility with employees and managers on the production floor, without whose support change would not have taken place.

—Our work introduced Jeppesen to operations research methods, highlighting the usefulness of applied OR for manufacturing and technology management. Now OR-based decision support systems are spreading throughout the company, and in its 1999 organizational restructuring, Jeppesen created an autonomous, interdisciplinary operations research and planning group at the director level. This group of 14 people consists of OR analysts, industrial engineers, production planners, and management-information-systems professionals, who are charged with using OR approaches to improve efficiency throughout the company.

—We improved the safety of the airline industry. Jeppesen products are essential to the airlines and their safe operation. Although the benefits are difficult to quantify, the reliable, on-time delivery avoids disruption to airline services (with possible losses in revenue and even in terms of loss of human life). Many customer testimonials concerning Jeppesen's charts' impact on the safe operation of various airlines and private pilots are on file at the marketing department. As Captain Elrey Jeppesen said, "I didn't start this company to make money; I started it to stay alive" [Opening ceremonies at Denver International Airport, February 21, 1995].

Contributions to Operations Research Profession

Our work at Jeppesen demonstrated the value of OR analysis in a company that influences the safety of millions of airline passengers and pilots every week. It also changed every facet of Jeppesen's production process. Indeed, Jeppesen demonstrated that it realized the value of this work by creating its OR group. Jeppesen's then parent company, Times Mirror, awarded Jeppesen the 2000 Times Mirror Innovation Prize in recognition of its revitalization.

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APPENDIX

We used the following mathematical models at Jeppesen Sanderson, Inc.

The Production Scheduling Model (Scheduler)

Indices

t days of the week, e.g., Monday.

r production resources, e.g. machine tower, ditte collator, and inserter collators.

s production stages, e.g. printing (PR), machine collating (MC), assembly (FA).

c, c' coverages.

p charts, or pages in a coverage.

Coverage and Chart Index Sets

C all coverages.

P all charts.

$C_{AW} \subseteq C$ airway coverages.

$C_{AC} \subseteq C$ air-carrier coverages.

$P_{AW} \subseteq P$ airway charts.

$P_{AC} \subseteq P$ air-carrier charts.

The two groups of charts and coverages, airway and air carrier, are mostly produced separately, although one group of air-carrier coverages contains only airway charts. Airway coverages never contain any air-carrier charts and are shipped to all categories of customers. Air-carrier coverages are generally shipped to airline customers.

Time Index Sets

T all days of the week.

$T_{AW} \subseteq T$ days for producing airway coverages, beginning of the week.

$T_{AC} \subseteq T$ days for producing air-carrier coverages, end of the week.

Resources Index Sets

R all production resources.

R_{PR} printing resources.

R_{MC} machine-collating resources.

R_{FA} final-assembly resources.

Given Data on Coverages

$demand_c$ subscription quantity of coverage c.

$fold_c$ number of folds in coverage c.

$flat_c$ number of flats in coverage c.

maxdist maximum difference in content of two coverages to be produced simultaneously in machine collating.

Given Data on Charts

$totq_p$ total print quantity for chart p.

$bstock_p$ bin stock quantity for chart p.

Given Capacity and Production Data

$regprint_{tr}$ number of hours of capacity available in printing area on day t on resource $r \in R_{PR}$.

$regcollate_{rt}$ number of hours in machine collating available on day t on resource $r \in R_{MC}$.

$regassem_{rt}$ number of hours in assembly available on day t on resource $r \in R_{FA}$.

$otpint_t$ number of overtime hours of capacity available in printing area on day t.

$otcollate_t$ number of overtime hours in machine collating available on day t.

$otassem_t$ number of overtime hours in assembly available on day t.

sec_r number of charts in a section built using resource r.

$opers_r$ number of operators needed to run resource r.

$tempcap_t$ maximum number of temporary hours available on day t.

Given Revision Characteristics

$content_{cp}$ 1 if coverage c contains chart p and 0 otherwise.

$ucovbound_{ct}$ the upper bound on production of coverage c on day t. Generally $ucovbound_{ct} = demand_c \; \forall \; c \in C_{AW}, t \in T_{AW}$ or $c \in C_{AC}, t \in T_{AC}$ and 0 otherwise, but there are some exceptions.

$uchartbound_{pt}$ the upper bound on production of chart p on day t. Generally $uchartbound_{pt} = totq_p \; \forall \; p \in P_{AW}, t \in T_{AW}$ or $p \in P_{AC}, t \in T_{AC}$ and 0 otherwise but there are some exceptions.

Given Cost Data

$reginwage_s$ regular hourly wage in production stage $s = \{PR, MC, FA\}$.

$otinwage_s$ overtime hourly wage in production stage $s = \{PR, MC, FA\}$.

outprcost cost to print one chart using an outside vendor.

outassemcost hourly cost for outside assembly vendor.

$lcost_c$ penalty cost if coverage c is late.

invpenalty small inventory penalty to prevent unnecessary inventory.

tempcost hourly cost for temporary employee in assembly.

Derived Data

$dist_{c,c'} = \Sigma_p \; |content_{cp} - content_{c'p}|$ the difference between coverage c and c'.

$sections_{cr} = [flat_c/sec_r]$ if $flat_c > 0$, 0 otherwise; number of sections in coverage c if it is collated using tower.

$sqty_p = \Sigma_c \; content_{pc} \times demand_c$ amount of chart p needed to produce the entire subscription quantity of all coverages that contain it.

$sfactor_p = 1 + totq_p - sqty_p/sqty_p$ scrap factor for charts printed.

Empirically Derived Data

$msetup_{cr}$ time (in minutes) it takes to set up coverage c in machine collating area to be processed on resource $r \in R_{MC}$.

$mprocess_{cr}$ time (in minutes) it takes to process one unit of coverage c in machine collating area on resource $r \in R_{MC}$.

$asetup_{cr}$ time (in minutes) it takes to set up coverage c in final assembly area to be processed on resource $r \in R_{FA}$.

$aprocess_{cr}$ time (in minutes) it takes to process one unit of coverage c in final assembly area on resource $r \in R_{FA}$.

pprocess time (in minutes) to print one chart, approximated by allocating the fixed setup time over the average run quantity for a plate of 21 charts.

$tprocess_{cr}$ time (in minutes) for a tempo-

rary worker to process one unit of coverage c in the final-assembly area on resource $r \in R_{FA}$.

We empirically derived setup and processing times for using different resources at different production stages by collecting this data and then fitting regression equations.

Decision Variables for Production/Flow

$PAPERPROD_{prt}$ number of charts p produced in printing using resource $r \in R_{RP}$ on day t.

$COVERPROD_{crt}$ number of coverages c produced in machine collating using resource $r \in R_{MC}$ on day t.

$ASSEMPROD_{crt}$ number of coverages c produced in final assembly using resource $r \in R_{FA}$ on day t.

$SHIP_{ct}$ number of coverages c shipped on day t.

$LATE_c$ number of coverages c late.

Decision Variables for Inventory

$PAPERINV_{pt}$ number of charts p available at the end of day t.

$COVERINV_{ct}$ number of coverages c that passed machine collating available at the end of day t.

$ASSEMINV_{ct}$ number of coverages c that passed final assembly available at the end of day t.

Decision Variables for Overtime, Temporary Employees, and Outsourcing

$OUTPRN_{pt}$ quantity of charts p outsourced for printing on day t.

$OUTASSEM_{ct}$ quantity of coverages c outsourced for assembly on day t.

$OTPRN_{tr}$ number of overtime hours used in printing on day t on resource $r \in R_{PR}$.

$OTMC_{tr}$ number of overtime hours used in machine collating on day t on resource $r \in R_{MC}$.

$OTFA_{tr}$ number of overtime hours used in final assembly on day t on resource $r \in R_{FA}$.

$TEMPASSEM_{tr}$ number of temporary hours used in final assembly on day t on resource $r \in R_{FA}$.

Objective

Minimize

$\Sigma_c\,(lcost_c \times LATE_c + outassemcost \times OUTASSEM_c) + outprcost \times \Sigma_p\, OUTPRN_p + \Sigma_{rt}\,(otinwage_{PR} \times OTPRN_{tr} + otinwage_{MC} \times OTMC_{rt} + otinwage_{FA} \times OTASSEM_{tr}) + \Sigma_{prt}\,(reginwage_{PR} \times pprocess \times opers_r \times PAPERPROD_{prt})\, \Sigma_{cr \in R_{mc}t}\,(reginwage_{MC} \times opers_r \times msetup_{cr}/demand_c\, mprocess_{cr}\, COVERPROD_{crt}) + \Sigma_{cr \in R_{FA}t}\,(reginwage_{FA} \times opers_r \times asetup_{cr}/demand_c\, aprocess_{cr}\, ASSEMPROD_{crt}) + invpenalty\, \Sigma_{ct}\,(COVERINV_{ct} + ASSEMINV_{ct}) + invpenalty\, \Sigma_{pt}\, PAPERINV_{ct} + tempcost\, \Sigma_{cr \in R_{FA}t}\,(opers_r \times tsetup_{cr}/demand_c\, tprocess_{cr}\, TEMPASSEM_{rt})$.

The objective function minimizes the total weighted sum of lateness penalty, outsourcing cost, overtime-labor cost, and regular-labor cost. We approximate the impact of setup costs in the machine-collating and assembly areas by calculating the per-unit setup costs by dividing the total setup cost by the demand (lines 4 and 5). This approach has been shown to work well in a wide variety of lot-sizing problems [Katok, Lewis, and Harrison 1998].

Production Flow Constraints

Flow constraint for printing

$$PAPERINV_{p(t-1)} + \sum_{r \in R_{PR}} PAPERPROD_{prt} + OUTPRN_{pt} - \sum_c content_{pc} \sum_{r \in R_{MC}} COVERPROD_{crt} - PAPERINV_{pt} = 0 \quad \forall p, t. \tag{1.1}$$

Flow constraint for machine collating

$$COVERINV_{c(t-1)} + \sum_{r \in R_{PR}} COVERROD_{crt} - \sum_{r \in R_{FA}} ASSEMPROD_{crt} - OUTASSEM_{ct} - COVERINV_{ct} = 0 \quad \forall\, c,t. \tag{1.2}$$

Flow constraint for final assembly

$$ASSEMINV_{c(t-1)} + \sum_{r \in R_{FA}} ASSEMROD_{crt} + OUTASSEM_{ct} - SHIP_{ct} - ASSEMINV_{ct} = 0 \quad \forall\, c, t. \tag{1.3}$$

Every coverage demanded is either shipped or is late

$$\sum_t SHIP_{ct} + LATE_c = demand_c \quad \forall c. \tag{1.4}$$

Capacity Constraints

Capacity in printing

$$\sum_p pprocess \times sfactor_p \times PAPERPROD_{prt} \le regprint_{rt} + OTPRN_{rt} \quad \forall\, t, r \in R_{PR}. \tag{1.5}$$

Capacity in machine collating

We approximate the impact of setups on capacity by allocating the setup time on a per-unit basis.

$$\sum_c ((msetup_{cr}/demand_c + mprocess_{cr}) \times (COVERPROD_{crt}) \le regcollate_{rt} + OTMC_{rt} \quad \forall\, t, r \in R_{MC}. \tag{1.6}$$

Capacity in final assembly

Note that since setups in assembly are external, they do not affect capacity.

$$\sum_c aprocess_{cr} \times ASSEMPROD_{crt} \le regassem_{rt} + OTFA_{rt} + TEMPASSEM_{rt} \quad \forall\, t, r \in R_{FA}. \tag{1.7}$$

Overtime capacity in printing

$$\sum_{r \in R_{PR}} ORPRN_{rt} \le otprint_t \quad \forall\, t. \tag{1.8}$$

Overtime capacity in machine collating

$$\sum_{r \in R_{MC}} OTMC_{rt} \le otcollate_t \quad \forall\, t. \tag{1.9}$$

Overtime capacity in final assembly

$$\sum_{r \in R_{FA}} OTFA_{rt} \le otassem_t \quad \forall\, t. \tag{1.10}$$

Temporary employee hours capacity

$$\sum_{r \in R_{FA}} TEMPASSEM_{rt} \le maxtemp_t \quad \forall\, t. \tag{1.11}$$

Business Rules Constraints

This constraint insures that similar coverages are produced at the same time on the same resource in machine collating. Note that this constraint fulfills its intent when coverages c and c' are each produced on a single day using a single resource. This is the case with over 95 percent of coverages. For the other five percent, we use a postprocessing module to move production to the resource and day where the largest quantity is produced.

$$\frac{COVERPROD_{crt}}{demand_c} = \frac{COVERPROD_{c'rt}}{demand_c} \quad \forall\, r \text{ and } c, c' \text{ where } dist_{cc'} \le maxdist. \tag{1.12}$$

Insures that business rules on chart production are respected

$$\sum_{r \in P_{PR}} PAPERPROD_{prt} \le unchartbound_{pt} \quad \forall p, t. \tag{1.13}$$

Insures that business rules on coverage production are respected.

$$\sum_{r \in R_{MC}} COVERPROD_{crt} \le ucovbound_{ct} \quad \forall c, t. \tag{1.14}$$

New-Orders Model

Indices

t the next 14 work days.

p order number.

c coverage.

r resources (30-bin tower, 60-bin tower, by hand).

Index Sets

$C_p \subseteq C$ coverages in order p.

Given Data

$capacity_t$ available hours for a day t.

otval overtime limit for any week (usu-

ally 20 percent).

capval limit on the amount of available time that can be used for orders.

$flat_c$ number of flats in coverage c.

$infold_c$ number of folds that must be placed inside coverage c.

$endfold_c$ number of folds that go on the bottom of coverage c.

$sections_{cr}$ number of resource r sections in coverage c.

wage hourly regular-time wage.

otwage hourly overtime wage.

Empirically Derived Data

$ptime_p$ time required to complete an order.

$due_{p,t}$ penalty cost if order p is shipped on date t. (Penalty factors are based on the number of days an order is late and whether the order is late in shipping or late to the customer. An order late to shipping can reach the customer on time by premium shipping method. The highest penalty is lateness to the customer.)

$capreal_t$ the real capacity for any day t, where $capreal_t = capacity_t(1 - capval)$.

$msetup_{cr}$ time (in minutes) to set up coverage c in order p in the new-orders area to be processed on resource r.

$mprocess_{cr}$ time (in minutes) to process coverage c in order p in the new-orders area on resource r.

$asetup_{cr}$ time (in minutes) to set up a coverage c in order p in the new-orders area to be assembled on resource r.

$aprocess_{cr}$ time (in minutes) to assemble coverage c in order p in new orders on resource r.

We empirically derived setup and processing times for each coverage in an order using different resources at different production stages by collecting required data and then fitting regression equations.

Derived Data

$ptime_{pr}$ total time to complete order p using resource r.

$ptime_{pr} = \Sigma_{c \in C_{pr}} (msetup_{cr} + mprocess_{cr} + asetup_{cr} + aprocess_{cr})$.

Decision Variables

X_{prt} production of order p on resource r day t.

$OTIME_t$ overtime on day t.

Objective Function

Minimize $\Sigma_{prt}\, due_{pt} X_{prt} + wage\, \Sigma_{prt}\, ptime_{pr} X_{prt} + otwage\, \Sigma_t\, OTIME_t$.

Minimizes the sum of total labor cost and total late penalty cost associated with producing all the orders.

Constraints

Capacity constraint

$$\sum_{pr} ptime_{pr} X_{prt} \le capreal_t + OTIME_t \quad \forall\, t. \tag{1.15}$$

Ensures that the entire order is processed on one day t

$$\sum_{rt} X_{prt} = 1 \quad \forall\, p. \tag{1.16}$$

$0 \le X_{prt} \le 1 \quad \forall\, p, r, t.$

$OTIME_t \ge 0 \quad \forall\, t.$

Interactive Plating Model

Indices

c all charts in the revision.

p all plates in the revision.

Given Data

$fcost_p$ the fixed cost of using plate p.

$vcost_p$ the variable cost pf printing one copy of plate p.

$demand_c$ number of copies of chart c needed in the revision.

$csize_c$ the size of chart c.

$psize_p$ the size of plate p in terms of the number of size-1 charts it can hold.

Decision Variables

X_{cp} the number of times chart c is put on plate p.

Y_p is 1 if plate p is used and 0 otherwise.

Q_p the number of impressions of plate p printed.

For each plate p, we can compute the upper bound on print quantity $\bar{Q}_p$ as a function of what is on the plate:

$$\bar{Q}_p = \max_c \left\{ \frac{demand_c}{X_{cp}} \right\}.$$

Objective Function

Minimize $\Sigma_p\ vcost_p Q_p + fcost_p Y_p$. Minimizes the total plating and printing cost.

Constraints

Ensures that we print sufficient number of each chart c

$$\sum_p X_{cp} Q_p \geq demand_c \quad \forall\ c. \tag{1.17}$$

Links the Q_p and the Y_p variables

$$Q_p \leq \bar{Q}_p Y_p \quad \forall\ p. \tag{1.18}$$

Ensures that we do not put more charts c on a plate p than the room on the plate allows

$$\sum_c csize_c X_{cp} \leq psize_p. \tag{1.19}$$

$Y_p \in (0, 1) \quad \forall\ p$, X_{cp} integer $\forall\ c, p$, $Q_p \geq 0\ \forall\ p$.

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