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Pulling a Job Shop into Supply Chain Management

by

Daniel H. Wheeler

Bachelor of Science in Electrical Engineering, University of Missouri, 1983
Master of Business Administration, Wichita State University, 1996

Submitted to the Sloan School of Management and the Department of Electrical Engineering and Computer Science in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management

and

Master of Science in Electrical Engineering and Computer Science

June 2000

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ABSTRACT

The Instron Corporation in Canton, MA, manufactures material testing systems. These systems are used to evaluate the tensile strength of metals, plastics, composites, textiles, and other materials by holding a test sample at each end with a mechanical "grip," pulling in opposite directions, and measuring the applied forces. This thesis describes the efforts of a project improvement team chartered to dramatically reduce inventory for a variety of mechanical grips without increasing cycle time or component fabrication costs. The author developed optimization techniques, queuing theory models, and simulation tools to guide the improvement efforts.

The project team achieved a thirty-percent reduction in grip inventory in six months by consolidating redundant supply chains, changing from a make-to-stock to a make-to-order process, and changing from material resource planning to pull production. The inventory reduction increased the inventory turns from less than two to over four turns per year. Strategic inventory placement models suggested the problem could be split into two separate approaches: (1) managing the capacity of the job shop to meet the increased demand from supply chain consolidation; and (2) developing a control system for component and raw material inventories.

The analysis of the capacity of the grip assembly job shop uses optimization techniques to specify the assembly lot sizes for the various grips and queuing theory to estimate the reserve capacity required to maintain cycle times under probabilistic demand. Simulations of the job shop assembly process validate the analysis and resource management plan. The continuous review control system specifies reorder points and order quantities for the hundreds of detail components and raw materials.

The team's efforts are expected to reduce inventory by a similar amount in the coming months as excessive stocks are consumed. Recommendations for further reductions include improved component outsourcing, disposition of slow-moving inventory, and optimization of safety stock levels. Implementation of these recommendations will lead to inventory reductions of similar magnitude.

Thesis Supervisor: Donald B. Rosenfield
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The project improvement team at the Instron Corporation deserves the credit for reducing inventory in the electromagnetic grip work cell. Members of the core team include Kerry Rosado, Paul Carmichael, Norm Houle, Scott MacEwen, Jim Cooney, and Bill Gates. Led by the project manager, Mark Lind, the team also implemented many improvements to the assembly process with the help of the lead grip mechanic, Mark Frangiosa.

The grip rationalization team, led by Jon Wyman, provided exceptional support in its parallel effort to reduce grip product offerings and standardize connectors. Team members include Paul Blasi, Frank DaSilva, Amy Pietrzak, Tom Keegan, and Mark Lind. Additional outstanding support was provided by Phil Hood, Jan Heffernan, Barbara Cabral, Jan Masterson, Nancy DeSario, Lorraine Carnie, Joe Kearney, and Bob Angus.

As the key sponsor of the project, Bill Milliken was directly involved in setting project goals, authorizing resources, and monitoring performance. His leadership provided the drive to achieve the project's objectives within the constrained time. Three other members of the Instron management team, Brad Munro, Marc Montlack, and Jud Broome, in particular, offered constant encouragement, support, and improvement ideas throughout the life of the project.

The MIT project advisors, Don Rosenfield and Al Drake, led the effort to integrate academic and industry interests and deliver a worthwhile product from both perspectives. Through several on-site visits and advisory meetings and continuing correspondence, they have guided the project along the path of maximum return. Don's suggestions and derivations of capacity models and queuing theory founded much of the project's analysis and recommendations. Steve Graves of MIT also provided useful comments on the use of inventory models. The 1999 LFM intern at Instron, Maria Alvarez, deserves academic mention for her outstanding work preparing the grip work cell for further improvement efforts.

The final words of thanks must go to Mary, Will, Elizabeth, and Julia, who provide the reasons and rewards for all the efforts herein.

Biographical Note

The author, Dan Wheeler, is a Leaders for Manufacturing Fellow of the Class of 2000 at MIT. He is a candidate for dual master of science degrees, in Management and Electrical Engineering and Computer Science. Previous education includes a Masters in Business Administration from Wichita State University in 1996 and a Bachelor of Science Degree in Electrical Engineering from the University of Missouri in 1983.

Dan's participation in the LFM program at MIT is sponsored by The Boeing Company, where he has worked since 1987 in Wichita, Kansas. His most recent assignment there was as principal engineer for Manufacturing Research and Development, working to improve assembly processes for 737 and 777 Struts and Nacelles.

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The Challenge at Instron

The Setting: Instron Corporation and EM Grips

Instron Corporation of Canton, MA, supplies instruments, systems, software, and accessories used to evaluate the mechanical properties and performance of metals, plastics, composites, textiles, ceramics, rubber materials, biomedical materials, and adhesives. Specific properties tested include tensile strength, fatigue, response to impact, and hardness. Tensile strength testing is performed by holding the test sample at each end with a mechanical "grip," pulling in opposite directions, and measuring the resulting forces. A variety of grips accommodate different test sample features, including flat bar stock, round bar stock, cord and yarn, fiber, and elastic. The grips are components of two main types of systems: servo-hydraulic (S/H) and electromechanical (EM). The systems are primarily used for fatigue and tensile testing, respectively, although cross-functional applications are common.

The thesis shows how supply chain rationalization, optimization techniques, queuing theory, and simulation models can be applied to significantly reduce inventory while maintaining required customer service levels.

The Project: Consolidate Operations and Reduce Inventory

Instron maintains two distinct supply chains for the marketing, design, manufacture, and service of electromechanical grips. One chain is based at the company's global headquarters in Canton, MA, with a major internal supplier of machined components in Binghamton, NY. The other chain is based at the company's European regional headquarters in High Wycombe, England, which houses a second internal machine shop. Instron has adopted a "Center of Excellence" strategy: all electromechanical systems and accessories (such as EM grips) will be designed and built at the Canton plant. As an additional motivation, executive management has identified inventory management as a primary method to achieve cost reduction goals, targeting the EM grip inventory for immediate attention through the efforts of an ad hoc improvement team.

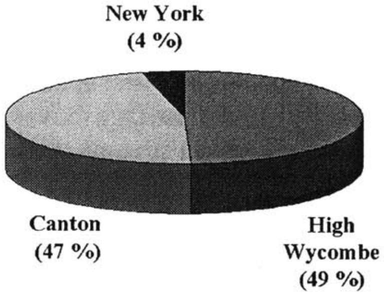

Figure 1. June Inventory

Figure 1 shows the total grip inventory at the project outset in June, 1999. The material is valued at its standard cost and includes all raw materials, components, work-in-process, and finished goods throughout the company. Instron turns this inventory less than twice each year. Note that the inventory is equally divided between the two supply chains.

The Product Line: A Grip for Every Application

Instron manufactures a wide range of EM systems for testing tensile strength. A typical double-column system is shown in Figure 2. The main components are the base, vertical columns, carriage with load cell, grips, control panel, and computer. The base contains the motor, the control panel interface electronics, and the computer interface; it also supports a connector to which the lower grip is attached. The vertical columns house ball screws driven by the motor. The carriage rides the ball screws and a load cell is connected to the carriage to provide measurements of the applied forces. Finally, the upper grip is connected to the load cell.

A previous Instron internship project[1] resulted in a rationalization of the EM grip product line, reducing the number of grips offered from ninety to fifty-six. This number grew slightly over 1999 as new products were introduced, but a concurrent engineering team is scaling back product offerings by standardizing connectors.

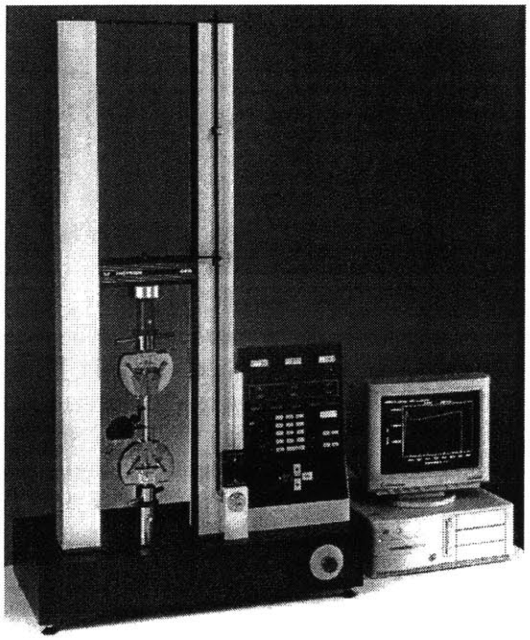

Figure 2. EM Tensile Testing Systems

The fifty-six grips are categorized into families by the mechanical feature or technology by which the gripping action is accomplished - wedge, pneumatic, screw, and miscellaneous. Secondary groupings are based on grip applications, such as cord and yarn grips, fiber grips, and thin film grips. Within each family of grips exists a range of force capacities; the wedge grip family, for example, ranges from a capacity of 1 kilo-newton (kN) for the smallest grip to 300 kN for the largest. A 5 kN wedge-action grip is shown mounted to the carriage / load cell and base on the system in Figure 2; the grip itself is shown in Figure 3.

The wedge grip is loaded by placing a test sample between two faces located in the wedge-shaped opening in the body of the grip. The handles of the adjusting nut are turned about the central spindle until the sample is secured. When the carriage moves upward to test the sample's tensile strength, the wedge action forces the two faces to clamp the sample more tightly.

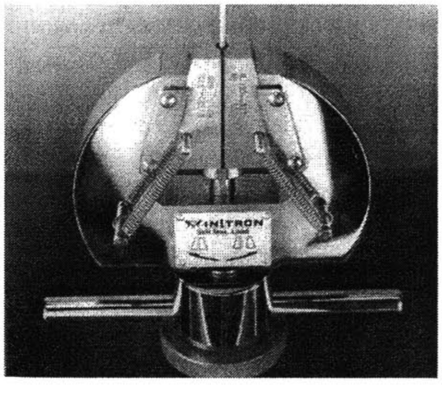

Figure 3. Wedge Grip

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[1] Alvarez, M. J., "Analysis of the Accessory Business: Focus on ElectroMechanical Grips," Masters Thesis, MIT Leaders for Manufacturing Program, May 1999.

The grip set consists of an upper and lower grip and each grip is assembled from 15 to 20 component parts. In the Canton supply chain, half of these component parts (springs, dowel pins, fastening hardware, etc.) are purchased from suppliers as standard items. The other half of the components are metal parts fabricated at the internal machine shop in Binghamton, NY or at outside machine shops near Canton. Most of the 5 kN components are fabricated in Binghamton. At the outset of the project, the High Wycombe supply chain also produced this grip, with redundant processes of in-house fabrication and assembly.

Typical pneumatic side-action and screw grips are shown in Figures 4 and 5, respectively. The pneumatic grip operates by applying air pressure through a nozzle into the bellows at the base of each grip. The bellows is a precision machine component which has a wedge shape at its upper end. As the bellows expand, the wedge shape moves upward and separates two horizontal links at the base of the grip's "arms." The horizontal links are mechanically coupled to vertical multiplying links, which pivot and drive the faces in the opening toward each other, thereby providing a gripping action from each side of the test sample.

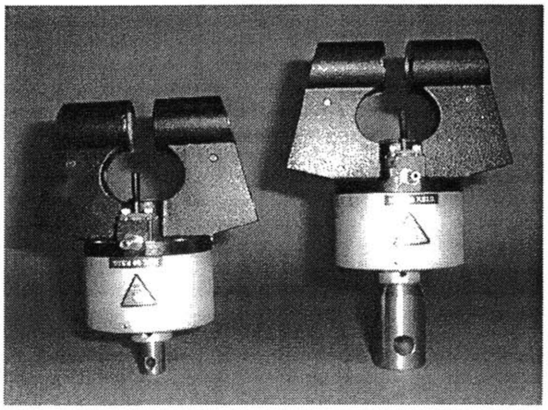

Figure 4. Pneumatic Grips

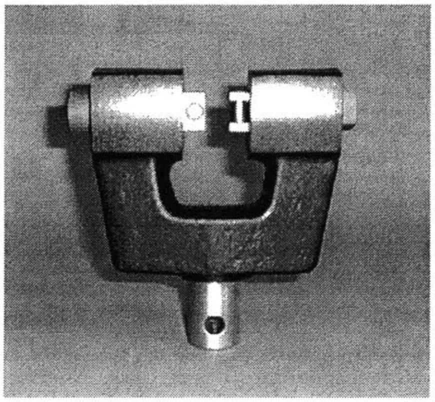

Figure 5. Screw Grip

The operation of the screw grip is straightforward. Each face is driven inward by manually turning the horizontal screw to which it is attached. The pneumatic and screw grip designs are somewhat older than the wedge grip design - their detail parts are often machined from castings and forgings with relatively long lead times. The wedge grip shown in Figure 3, in contrast, is designed so that its detail parts are machined from round bar stock with relatively short lead times. The longer lead times for castings and forgings have important consequences for inventory levels.

The Outcome: Success!

During the second half of 1999, the improvement team reduced EM grip inventory by thirty percent. Figure 6 shows the monthly measurement of inventory, including raw materials, components, WIP, and finished goods at all three major locations: High Wycombe (HW), Canton (CA), and Binghamton (NY).

There are several important points to note from Figure 6. First, the overall level of inventory dropped thirty percent from the end of June to the end of December. Second, the Canton inventory did not change much over the six-month period, although output increased thirty percent. High Wycombe inventory, on the other hand, dropped fifty percent as component inventories were shipped to Canton.

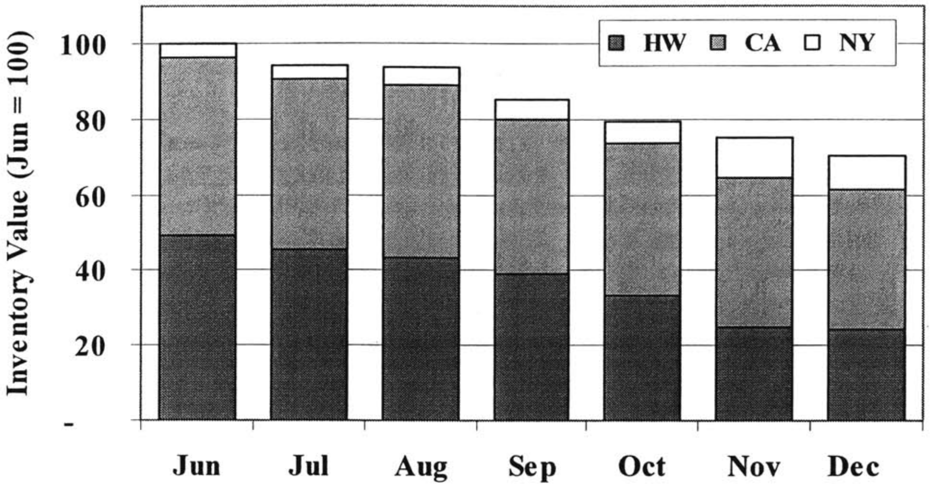

Figure 6. EM Grip Inventory Reduced by 30%

As a final note, inventories in the New York machine shop more than doubled over the six-month period. The increase is due to a change in policy, described more fully in Chapter 4, intended to place the machine shop on an equal footing with external suppliers.

The Analysis Approach: Divide and Conquer

Interactions between inventory policies at different stages of an assembly supply chain can present an intractable problem for analysis[1]. Breaking the problem into smaller segments allows decisive analysis but also imposes the risk of a sub-optimal solution. The project team accepted this risk for two reasons. First, Instron management directed the team to implement dramatic short-term improvements, advocating a limited time for analysis and declaring, "The enemy of better is best."

The second reason for accepting the possibility of suboptimization was suggested by the application of the Strategic Inventory Placement Model[2]. This model determines the placement and levels of safety stock that minimize the total inventory costs across the supply chain. Calculations are based directly on replenishment lead times and the probability of stockouts due to time-varying demand (see Appendix A). For example, the model shows that safety stocks are minimized by placing them entirely at the component stage.

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[1] Graves, S. C., "Safety Stocks in Manufacturing Systems," *Journal of Manufacturing and Operations Management*, 1 (1988), pp. 67-101.

[2] Graves, S. C., "Strategic Inventory Placement Model Assignment," in-class assignment, 15.762 Operations Management Models and Applications, March 1999.

In our case, the replenishment lead time for the assembly job shop averages around two hours while the required order cycle time is typically two to three weeks. In other words, the grip cell mechanic has two weeks in which to perform a job that takes two hours. So the assembly process can be completely decoupled from the component fabrication process with little risk of suboptimization of inventory levels.

Figure 7 shows the overall approach to the problem. The major elements of the analysis (supply chain consolidation, job shop capacity, and pull production) are introduced in the following sections. The pull production section introduces the distribution by value (DBV) technique for prioritizing attention and improvement efforts.

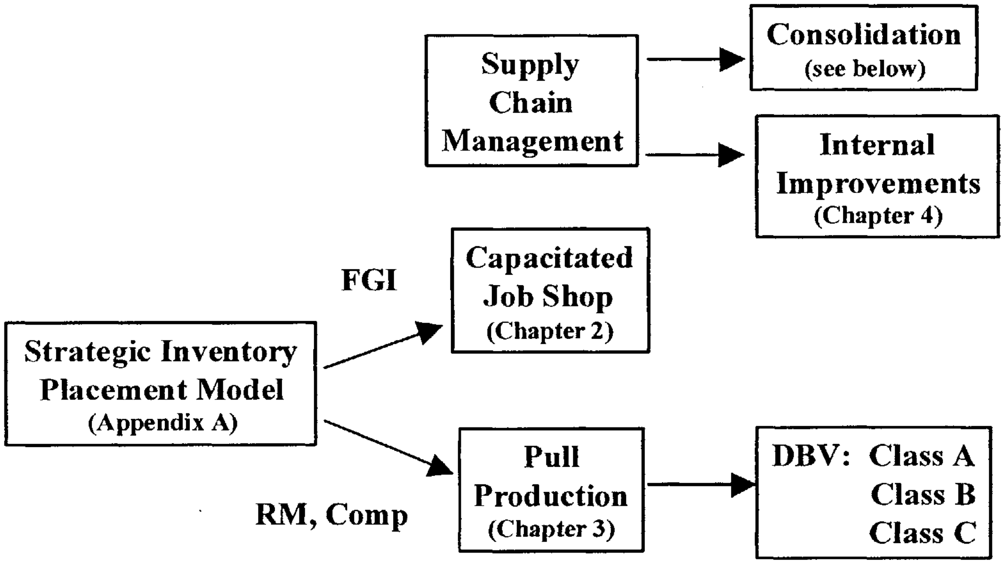

Figure 7. Overall Approach

The First Approach: Consolidate Supply Chains

The US-based supply chain is diagrammed in Figure 8. The different stages of inventory are shown as triangles and labeled as raw material (RM), component (Comp), work-in-process (WIP) or finished goods inventory (FGI). The NY machine shop outsources heat-treating and chemical processing to nearby suppliers. Additional component parts are purchased by the Canton organization for the work cell in Canton to assemble for shipment to customers.

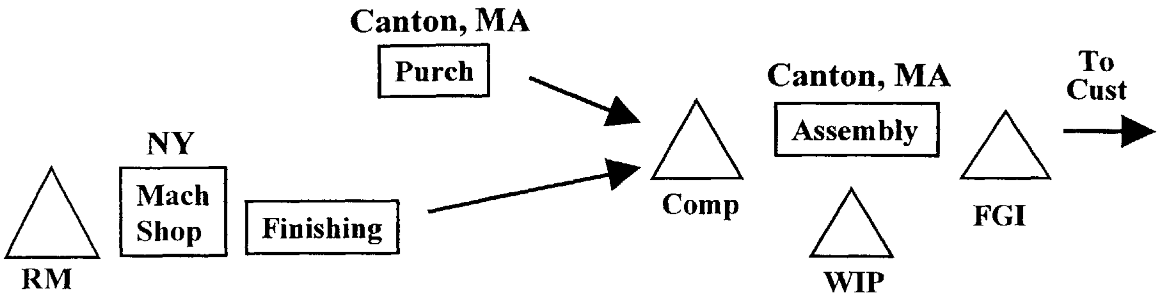

Figure 8. US-Based Supply Chain

The UK-based supply chain is identical in structure, as shown in Figure 9, with identical stockpiles of inventory. The major difference between the two diagrams is the location of the machine shop within the High Wycombe plant. Thermal and chemical processes are largely subcontracted as in the US.

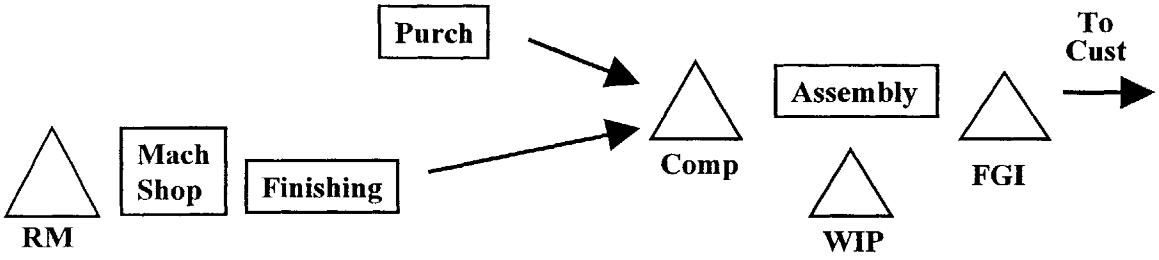

Figure 9. UK-Based Supply Chain

Most noteworthy is the similarity of inventories in the two diagrams. The consolidation of these eight segregated holdings presents the opportunity for significant savings. As the two supply chains are combined, the inventory in the US manufacturing flow path naturally increases; however, the combined safety stock levels are lower than the sums of the individual safety stocks before consolidation. This desirable result is described in more detail in Appendix B.

The Second Approach: Make to Order

The determination of batch or lot sizes for the assembly jobs in the grip work cell is a central problem. Traditional operations at Instron specified batch sizes of twenty to forty sets of grips; however, customer orders typically include grip quantities of only one or two sets. As shown in Figure 10, this make-to-stock process caused a sizable buildup of finished goods inventory.

Figure 10. 5kN/30kN FGI Before Project

Given the assembly lead times (two hours) and order cycle times (two weeks), a natural question is: can the job shop make grips as they are ordered? If so, then finished goods might be completely eliminated. However, the job shop capacity is constrained. The demand for grips varies over time in a random fashion, so a peak in demand may overload the job shop and delay the assembly of an order beyond the required two-week cycle time.

The job shop capacity is governed primarily by limited available labor (the shop has adequate space, assembly jigs, tools, and miscellaneous supplies to support any foreseeable increase in demand). The model presented in Chapter 2 allocates this available labor to the different jobs to minimize finished goods by specifying appropriate assembly lot sizes. There is some variance in the recommended lot sizes depending on demand - grips that are ordered frequently are built in larger lots than those ordered infrequently. Overall, the application of this model slashed lot sizes for every grip model, resulting in significantly reduced finished goods inventory (see Figure 11).

The Third Approach: Pull Production

The traditional assembly process at Instron is based on material requirements planning (MRP). The manufacturing planner initiates jobs to meet forecast demand, usually in fairly large lot sizes, as noted above. Through MRP, the Instron production system explodes the end item order into its bill of materials and issues pull orders to the stockroom (where all inventory is stored).

A fundamental problem with MRP at Instron is its reliance on forecast demand. If the forecast is wrong, then stocking levels are either too high (causing high inventory holding costs) or too low (causing stockouts and delayed orders). Pull production attempts to solve this problem by allowing production only when finished goods are physically "consumed." MRP *schedules* releases, while pull production *authorizes* releases[1].

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[1] Hopp, W. J., and M. L. Spearman, "Factory Physics," (1996), Irwin McGraw-Hill, Boston, p. 317.

Figure 11. 5kN/30kN FGI After Project

The improvement team implemented pull production in the job shop by setting up stock shelves for finished goods and components within the shop. Orders for grips are filled by removing finished goods from the shelves; when the level of finished goods drops below some specified quantity (the reorder point), the mechanic is signalled to replenish it (using the lot sizes determined above). To build a set of grips, components are drawn from bins on the shelves; when the levels of any of these components drop below the reorder point, the mechanic signals the planner to place a replenishment order.

Determination of the reorder points and order quantities under probabilistic demand is one of the main results of the project. Chapter 3 describes how these values are provided by the economic order quantity (EOQ) and the continuous review (Q,r) models. Also described in Chapter 3 (with detail in Appendix C) is the distribution by value (DBV) analysis tool, which helps prioritize attention and improvement efforts for the hundreds of individual items in component inventory.

Pilot Project Validates the Approaches

The team implemented these approaches in stages, applying them first to the 5 kN / 30 kN wedge grip product line as a pilot project. This product line is relatively high volume, allowing a short cycle for observing the outcomes of improvement actions and evaluating their effectiveness. The wedge grips are also newly designed - the modern component fabrication methods support the inventory reduction efforts. Chapter 4 describes the product line supply chain in detail and Chapter 5 presents the pilot project results.

Team and Author Contributions

The project results reported herein are often attributed to the improvement team. This section clarifies the relative contributions of Instron management, the improvement team, and the author. Instron management specified that the European and U.S. supply chains were to be consolidated in the U.S. and that the grip work cell would implement pull production. The improvement team developed and executed the consoldation tactics, set up the work cell with kanbans, physically moved the inventory from the stockroom to the work cell, streamlined the work cell processes, and developed and implemented improvements to the New York machine shop processes.

The author participated in these activities as a full-time team member. Many of the tasks required to implement pull production were also performed solely by the author, most notably setting up the individual kanbans, counting parts for reserve bins, and creating order cards.

The author conceived the overall approach of dividing the problem into tractable sub-problems. In addition, the author analyzed demand, constructed the capacity model (with advice from the internship advisors), determined assembly lot sizes, calculated kanban order quantities and reorder points, created all simulations, developed the queuing models for the Instron application, and maintained all measurements.

Overview of Chapters and Appendices

This chapter provides an introduction to the project and its setting. The description of the top-level approach to the inventory reduction problem highlights the division of the problem into manageable units and three corresponding approaches for solution.

Chapter 2 presents the model of the capacitated job shop. One section is devoted to the analysis of grip demand, its probabilistic nature, and its component streams. The capacity model is briefly described and analysis results are presented.

Chapter 3 describes the details of designing and implementing a pull production system within the job shop. The chapter introduces the distribution by value concept and discusses material flow process improvements.

Chapter 4 provides the analysis of the supply chain for the 5 kN / 30 kN wedge grip product line. The internal machine shop and its interaction with the assembly job shop receives focused coverage. Also described is an application of the SIP model to high-value components and finished goods.

Chapter 5 presents the results and conclusions from the improvement project team's efforts. Recommendations for further improvements are developed and summarized.

Appendix A describes the Strategic Inventory Placement Model (SIPM) and demonstrates the validity of dividing the problem into several standalone sub-problems.

Appendix B provides calculations demonstrating how consolidation of safety stocks for two similar supply chains reduces overall inventory levels.

Appendic C presents the distibution by value model for inventory classification, along with sample calculations and results for Instron grips.

Appendix D describes the capacitated job shop model in depth.

Appendix E develops the application of queuing theory to the job shop to determine waiting time distributions for assembly jobs.

Appendix F presents the details of a simulation of the job shop under probabilistic demand, using lot sizes developed in the capacity model.

Appendix G describes an approach for disposal of slow-moving inventory.

Appendix H presents a method for setting component safety stock levels to minimize holding costs while maintaining the capability to assemble finished goods with a specified probability.

Appendix I concludes the thesis with a step-by-step guide to reducing inventory at Instron.

Proprietary data throughout this document has been disguised.

2

The Job Shop at Capacity

This chapter focuses on the job shop capacity problem, addressing the following questions:

> How will the shop meet the increased demand from the consolidated supply chain?
> Is the current headcount adequate?
> Will each order be completed within two weeks?

The first question is answered by direct application of the capacity model. The model requires a thorough understanding of the increased demand as an input and the next section presents this information. The model determines assembly lot sizes for each of the fifty-six grips by budgeting available labor across the product line.

The current headcount of 1.5 (one full-time mechanic and two backups who fill in as needed) will increase to about 1.8 to best meet the increased demand. There is a tradeoff between headcount and inventory: if headcount is high, then assembly lot sizes can be reduced and inventory is relatively low; if headcount is tightly constrained, then assembly lot sizes and inventories grow.

The last question is answered by applying queuing theory to the model. A waiting time distribution is developed with the key result that 95 percent of all orders will be completed within two weeks of arrival. A reserve capacity is specified to meet peaks in demand, presenting another tradeoff, this time between headcount and order cycle time - if headcount is increased, more orders are completed on time.

Demand has Two Components: CM and OTC

Instron's EM grip customers include material testing service providers as well as large manufacturing firms with in-house test capabilities. Some customers purchase total systems (as shown in Figure 2) with various grips included as accessories and others purchase individual grips for new applications using existing machines. The total system orders are also known as custom machine (CM) orders and comprise about sixty percent of all grip orders by both number and value; the individual grip orders are referred to as over-the-counter (OTC) orders and make up the other forty percent. Grips are almost always ordered one pair at a time.

Figure 12 shows total demand for EM grips in each month of the last five years. Several features of this data are noteworthy. First, the demand ranges from a low of 59 units in January 1995 to a high of 266 units in December 1997 with an average monthly demand of about 130 units.

Second, a quarterly hockey-stick pattern is evident, with low demand in the first month of each quarter and high demand in the third month of each quarter. This pattern is caused by the consumption of grips as quarterly sales goals are met. Third, orders also exhibit an annual pattern, also caused by sales goals: the first quarter levels are nominal, the second quarter is slightly lower, the third quarter is higher than both, and the fourth quarter is the highest of any. Finally, demand for any one month remains fairly constant year-to-year.

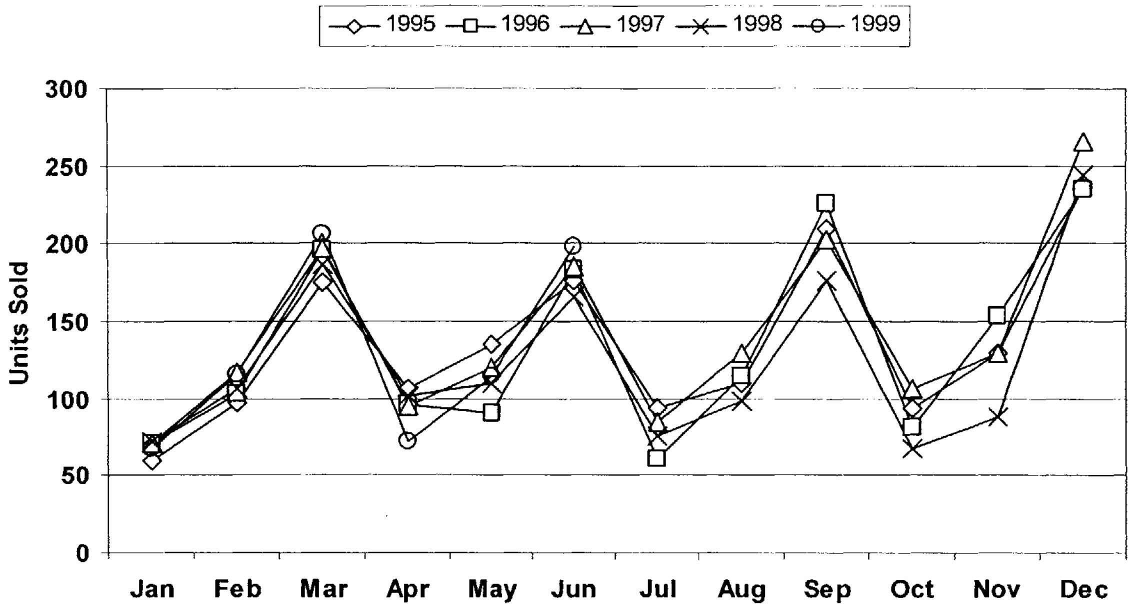

Figure 12. Composite Grip Demand

The data in Figure 12 is based on shipped goods; that is, grip usage is formally counted when the grips are actually shipped. This measurement does not accurately reflect job shop loading, however. Cycle times for custom machines range from four to twelve weeks and finished grips are delivered to the CM final assembly and test area about two weeks before system delivery. So sixty percent of the demand placed on the job shop exhibits the same quarterly and annual patterns, offset two weeks to the left.

Daily demand for OTC grips, on the other hand, is highly random. Customers place orders for these grips when new applications arise, which can happen any time during the quarter or year. The typical cycle time required by customers is on the order of two weeks, so the two demand streams can be combined with a reasonable fit to actual loading.

The combined daily demand is shown in Figure 13 for the first six months of 1998. The CM orders are shifted two weeks to the left of machine shipping dates while OTC orders remain at actual shipping dates. Note that the peak demand for any one day is 24 grips while on a few days there are no orders. A ten-day moving average is superimposed on the daily orders.

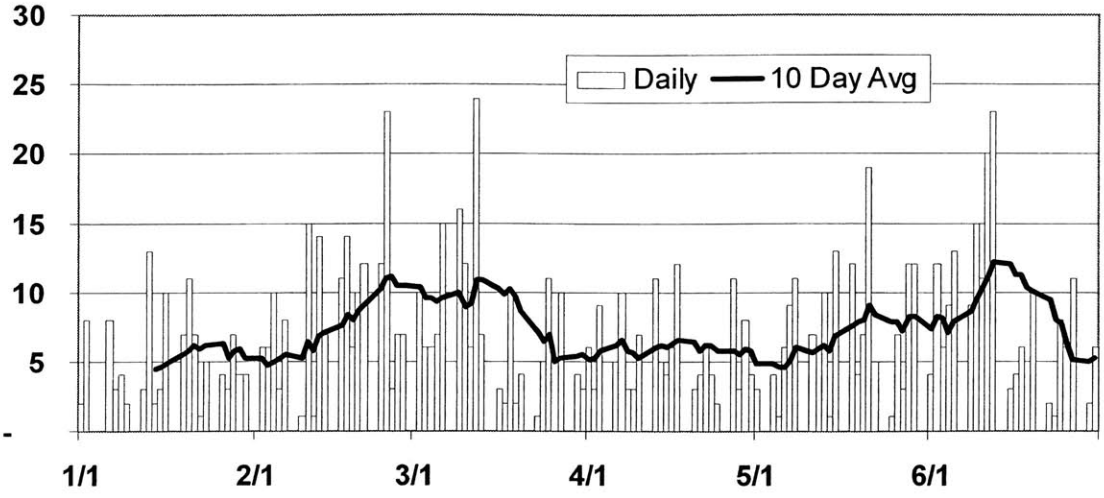

Figure 13. Daily Grip Demand

A rough idea of job shop loading after supply chain consolidation can be derived from this data. The average load is about eight grips each day; using an estimate of 1.5 hours assembly time per grip, the average daily load will be about twelve hours, somewhat less than two heads. The ten day moving average provides an estimate of quarterly peak loading. At its mid-June peak, the job shop must assemble twelve grips, requiring over 18 labor hours; in practice this will be accomplished by two mechanics working overtime during this one- or two-week period.

These estimates are useful for a first approximation of required staffing for the job shop, but two issues deserve further review: (1) the distribution of assembly times, and (2) the possibility of congestion and excessive cycle times. The capacity model explores both of these issues.

Capacity Model Provides Assembly Lot Sizes

The capacity model helps answer the question, "How many units of each grip should be assembled at one time?" As shown in Figure 14, traditional processes at Instron produce grips in lot sizes of twenty or more. Are significant reductions possible, especially with increased demand from the consolidated supply chain? The answer is "yes."

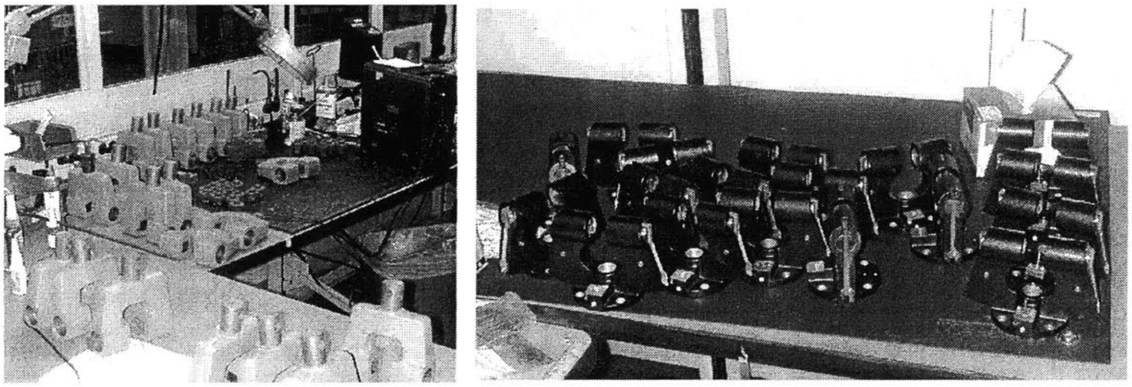

Figure 14. Batch Production in the Job Shop

To build the capacity model, values for several variables are needed for each grip model, including preparation and assembly times, annual demand, and standard cost. Two global variables must also be specified: holding cost as a percent of item value and the available labor in hours.

Each grip has a standard preparation time (setup time) for lots of any size and a standard assembly time per grip (run time). The preparation tasks include picking component parts from the stock shelves in the work cell, setting up assembly jigs, and gathering tools and consumables. Setup times are typically around fifteen to thirty minutes, although some of the higher capacity grips have setup times measured in hours.

The assembly tasks are straightforward: the mechanics assemble the components in several steps, completing all units in the batch for each step before progressing to the next step. Most steps involve manual placement of parts, pressing, fastening, and applying lubricants; some drilling is required for older designs. The run times range from half an hour to over fifteen hours. Figure 15 shows the distribution of these run times for the 1700 grips that are produced in the shop each year. The mean assembly time is 1.5 hours.

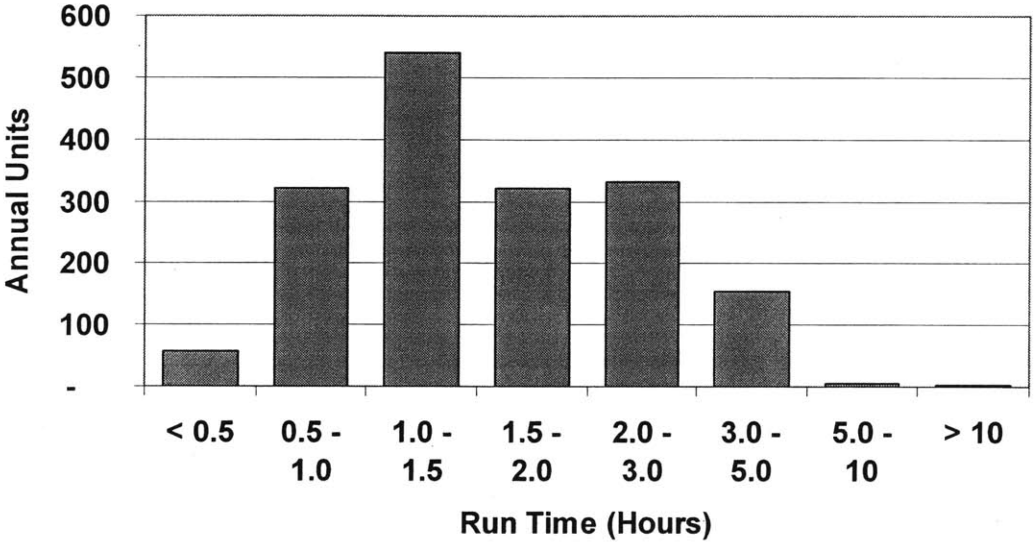

Figure 15. Annual Usage Assembly Time Distribution

The number of labor hours available to perform the work is one of the key variables in the model. As noted above, the job shop employs one full-time mechanic and has access to two others as needed, for an equivalent headcount of 1.7. Using a value of 1,880 hours per year, a total of 3,200 hours are available to build the 1700 grips. The total run time is about 2700 hours, leaving 500 labor hours for setup time throughout the year. Our task is to budget these 500 hours across the fifty-six models.

For any one grip, the optimum lot size can be derived from the economic order quantity (EOQ) model[1]. The EOQ is also known as the economic lot size, a more appropriate name in this

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[1] Hopp, W. J., and M. L. Spearman, "Factory Physics," (1996), Irwin McGraw-Hill, Boston, p. 58.

setting. The optimum lot size (Q) balances setup or ordering costs (A) with holding costs (h) based on demand (D).

$$\textbf{Economic Lot Size } Q = \sqrt{(2 * A * D / h)}$$

However, this formula applies to just one grip model. We can extend the model to multiple grips by converting the assembly times, demands, and holding costs to arrays and then inserting a variable, λ, common to all grips as a multiplier of the setup times (this variable, known as a Lagrangian multiplier, can be thought of as the value of the setup time).

$$Q_i = \sqrt{(2 * \lambda * A_i * D_i / h_i)}$$

In this equation, the subscript *i* identifies the individual grip models. By adding the sum of all the setup times to the sum of all the assembly times and setting the result equal to the total available labor, we can calculate the value of lambda and then all of the lot sizes[1]. Appendix D provides the details of this development.

Figure 16 presents the a sample of the key information resulting from the analysis, given 1.7 heads. Assembly lot sizes are shown for each of the fifty-six models. The available setup time is

Model	Annual Demand	Setup Time	Run Time	Std Cost	Assy Lot Size	Lots/Year
	units	hrs/lot	hrs/unit	$	units/lot	
A100-1	16	0.50	1.00	628	1	16
A100-2	32	0.50	0.60	554	2	16
A100-3	71	0.50	0.50	89	6	12
A100-4	24	0.50	0.50	584	1	24
A100-5	23	0.50	1.32	52	5	5
A200-1	7	0.50	1.32	85	2	3
A200-2	16	0.50	0.33	69	3	5
A200-5	15	0.25	1.30	129	2	7
A200-6	263	0.50	1.25	451	5	53
A200-7	171	0.50	1.75	155	7	24
A200-8	84	0.50	1.75	169	5	17
A200-9	20	0.50	2.00	358	2	10
A240-1	12	0.50	1.30	110	2	6
A240-2	76	0.50	1.40	449	3	25
A240-3	28	0.50	2.00	204	3	9
A240-4	10	0.50	2.00	412	1	10
A240-4	22	0.50	2.00	883	1	22
A240-5	30	0.50	0.65	364	2	15

Figure 16. Sample Assembly Lot Sizes

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[1] Rosenfield, D. B., and A. W. Drake, advisors to the internship, June-Dec. 1999.

budgeted across the models with preference given to those with high usages and those with medium usages coupled with long setup times.

The capacity model is useful for what-if analyses. If the headcount is increased, the available setup time increases as well and lot sizes decrease. The reverse case is also true - decreasing the headcount increases the lot size and inventory holdings, but there is a lower limit of 2784 hours (total run time plus one setup time for each grip model) or about 1.5 heads. Below this limit the job shop is overloaded and cannot complete its annual workload.

The effect of reducing setup time also affects the lot sizes. Many of the grips in Figure 16 have setup times of thirty minutes. If this baseline setup time can be reduced to fifteen minutes, the lot sizes decrease significantly, as shown in Figure 17. The total number of lots per year increases from 650 to 1000, symbolizing a leaner, faster flow of production. Appendix D includes more detailed discussions of these extensions to the basic model.

Model	Annual Demand	Setup Time	Run Time	Std Cost	Assy Lot Size	Lots/Year
	units	hrs/lot	hrs/unit	$	units/lot	
A100-1	16	0.25	1.00	628	1	16
A100-2	32	0.25	0.60	554	1	32
A100-3	71	0.25	0.50	89	3	24
A100-4	24	0.25	0.50	584	1	24
A100-5	23	0.25	1.32	52	3	8
A200-1	7	0.25	1.32	85	1	7
A200-2	16	0.25	0.33	69	2	8
A200-5	15	0.25	1.30	129	1	15
A200-6	263	0.25	1.25	451	3	88
A200-7	171	0.25	1.75	155	4	43
A200-8	84	0.25	1.75	169	3	28
A200-9	20	0.25	2.00	358	1	20
A240-1	12	0.25	1.30	110	1	12
A240-2	76	0.25	1.40	449	2	38
A240-3	28	0.25	2.00	204	1	28
A240-4	10	0.25	2.00	412	1	10
A240-4	22	0.25	2.00	883	1	22
A240-5	30	0.25	0.65	364	1	30

Figure 17. Assembly Lot Sizes with Reduced Setup Times

Job Queues Meet Cycle Time Requirements

The baseline model described above works well when assuming a constant flow of work. When demand varies with time, however, a modification is required. The problem with the baseline model occurs when operating near the optimal headcount - the model tends to allocate all available setup time. This prescription also raises worker utilization to high levels (98% of the available 1.7 heads in the above case), which can be desirable when demand is deterministic but can cause problems when demand is probabilistic[1]. High levels of utilization bring the potential for congestion and inordinate delays. Queuing theory can measure the waiting time performance of the job shop under random demand and indicate an appropriate level of reserve capacity.

Appendix E develops the application of the theory to the EM grip job shop. The development begins with the simple case of a single mechanic (or server), Poisson arrivals of job orders, and assembly times fitting an exponential distribution; in other words, the M/M/1 queuing system. This simple case illustrates how the baseline capacity model maximizes worker utilization and minimizes finished goods inventory but also causes congestion to the extent that the average cycle time for a job is 113 hours, well beyond the 75 hours available in two weeks with one mechanic.

Adding reserve capacity to the model improves the performance. The reserve is added in the form of reduced hours available from the single mechanic. The capacity model recalculates the lot sizes, increasing most of them and decreasing worker utilization from 98% to 93%. As a result, the average cycle time for a job drops to 21 hours and more than 95% of all jobs are completed within the two week requirement.

The simple M/M/1 case illustrates the effectiveness of the approach as a starting point. The appendix extends the analysis progressively, applying first the M/M/c model for multiple servers and then the M/G/1 model for assembly times with a general distribution. The end result from this analysis provides an operational rule similar to that for the simple M/M/1 case: reserve about seven percent of the available capacity for peak loads and the jobs will be completed within two weeks most of the time. In actual practice, management discretion places higher priority on high-value and important customer orders; these special conditions are fairly rare and are handled as exceptions on a case-by-case basis, falling outside the scope of the capacity model.

Simulation Validates Model Results

Application of queuing theory to the job shop work flow requires a number of simplifications and assumptions. One way to check the results of the model is through computer simulation. Appendix F describes a simulation of the job shop under probabilistic demand and supports the above results.

The simulation has five main sections: input, demand, stock, build, and output. The input section collects all information required to run the simulation: the number of heads, hours per day, assembly SKUs, setup and run times, lot sizes, demand probabilities for each month in the quarter, initial inventory quantities on hand, and finished goods reorder points. The demand section generates daily random demand, based on the input probabilities.

The stock section and the build section are the main engines of the simulation. The stock section begins by logging the amount of stock at the beginning of each day as equal to the stock at the end of the previous day. If the daily demand can be filled by this "sunrise" stock, then it is, and the stock level is reduced accordingly. If this reduction causes the level to drop below the reorder point or if the daily demand cannot be filled by the sunrise stock, then a pull signal is triggered and the lot size for the item is added to the daily build plan. The sunrise stock minus the daily demand plus any built units yields the end-of-day or "sunset" stock.

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[1] Rosenfield, D. B., and A. W. Drake, advisors to the internship, June-Dec. 1999.

There is a provision in the simulation model for peak demand - if demand depletes the stock beyond what can be replenished as specified by the build plan, then the unmet demand is carried forward each day until it is finally satisfied.

The output section calculates the total setup and run times based on the daily build plan and predicts the total labor hours required each day. The daily load and ten-day moving average are then charted; one example is shown in Figure 18.

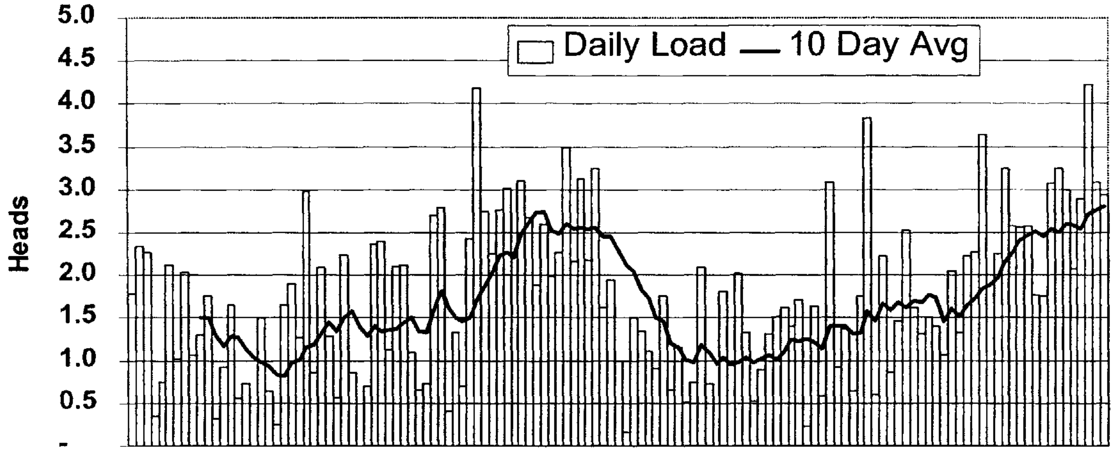

Figure 18. Simulated Six-Month Job Shop Loading

The job shop loading estimated from the data of Figure 13 can now be refined. It appears that staffing at about 1.7 heads will cover foreseeable demand for grips. As noted above, overtime may be needed for the two- or three-week period at the end of each quarter; this is normal practice at Instron.

3

Pull Production and Inventory Control

This chapter describes the inventory control system implemented by the improvement team. The control system works hand-in-hand with the implementation of pull production in the job shop. As finished goods are pulled from the shop to fill orders, the mechanics are signaled to build additional units whose components are then pulled from component stores. The stocking levels of the components in the work cell are the primary subject of this chapter.

The order quantity, order point (Q,r) model is presented first. The distribution by value technique is then described as a tool to classify items by importance. Treatment of each classification is then covered, with modifications to the basic (Q,r) model noted. The chapter closes by describing the qualitative improvements made in the work cell by the project team.

Order Quantity, Order Point (Q, r) Model

Inventory management seeks to answer three questions: (1) how often to review inventory levels, (2) when to place an order, and (3) how much to order[1]. The order quantity, order point (Q,r) model provides answers to the first two questions, while economic order quantity (EOQ) theory answers the third. The (Q,r) model is appropriate for a continuous review system with fixed order quantities[2].

Inventory Review Frequency. The grip assembly cell at Instron operates on a continuous review basis. Component parts are stored in bins with reserve quantities segregated (bagged) within each bin. As grips are assembled, the mechanics pick components from each bin; when the reserve bag is opened, an order card within or attached to the bag is delivered to the production planner as a signal to place a replenishment order. This process constitutes a continuous review policy, answering the first question.

The main reason for choosing a continuous review policy is that it requires less safety stock and lower inventory carrying costs than a periodic review system[3].

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[1] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, p 28.

[2] *Ibid*, p. 237.

[3] *Ibid*, p. 237.

Order Placement Criterion. The second question can be reworded to ask how many parts are in the reserve bag. This reorder point (ROP) is the sum of two parts: the average demand over the lead time (DOLT) and the safety stock (SS) level.

$$\mathbf{ROP} = \mathbf{DOLT} + \mathbf{SS}$$

Calculating average demand over the lead time is straightforward; it is equal to the average demand per time unit (μ) multiplied times the lead time (LT).

$$\mathbf{DOLT} = \mu * \mathbf{LT}$$

Determining the appropriate safety stock level is more involved, requiring management judgment as one input. The purpose for the safety stock is to provide a buffer against the variability of demand, more specifically during periods of peak demand. But setting the level to cover the maximum conceivable peak demand may be prohibitively expensive. Instron management agrees that 95% coverage of demand is reasonable, with stockouts occurring once for every twenty orders, on average. The safety stock level is then determined from the variance of the demand over the lead time ($LT * \sigma^2$) as some number (z) of standard deviations of lead-time demand (assuming independent time increments):

$$\mathbf{SS} = \mathbf{z} * \sigma * \sqrt{\mathbf{LT}}$$

With normally distributed demand data, the 95% coverage dictates a z-value of 1.64. More detailed developments of this model may be found in the references[1, 2].

Order Quantity. The final question of how much to order is answered by EOQ theory, balancing holding costs with ordering costs:

$$\mathbf{EOQ} = \sqrt{(2 * A * D / h)}$$

Here, A is the order cost (estimated at $45 for Instron), D is annual demand, and h is the holding cost, equal to the standard cost of the item times an estimate of the cost of tying up that value in inventory, expressed as a percentage. The holding cost for Instron is estimated at 30% annually, made up of 15% as capital costs, 10% taxes, insurance, and storage, and 5% disposition costs.

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[1] Graves, S. C., "Strategic Inventory Placement Model Assignment," in-class assignment, 15.762 Operations Management Models and Applications, March 1999.

[2] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, pp. 237-238 and 247-252.

The application of this model varies with the classification of the inventory. The next section discusses how inventory is classified and the following sections apply the above model.

Distribution by Value Allows ABC Classification

The EM grip product line consists of fifty-six models. The bills of materials for these models explode into a list of over 1700 item numbers, of which about half are actually kept as stock (SKUs). Determining the appropriate inventory control policy for the hundreds of SKUs can be tedious and time-consuming; by applying the distribution by value (DBV) technique, the control efforts can be focused on the most significant inventory items[1].

The method starts by listing all SKUs of concern, in our case, the components stored in the Canton grip work cell. Finished goods inventory policies are described in Chapter 2 and are excluded from the DBV analysis; raw materials and components stored in Binghamton, NY, are discussed in Chapter 4 and are also excluded.

For each SKU, the method requires the standard cost and the annual usage as inputs. The cost is multiplied times the annual usage to arrive at the annual cost-volume of the item. The list of SKUs is then sorted by the annual cost-volume in descending order. Appendix C provides the details of this process for the grip work cell and the key result shown in Figure 19.

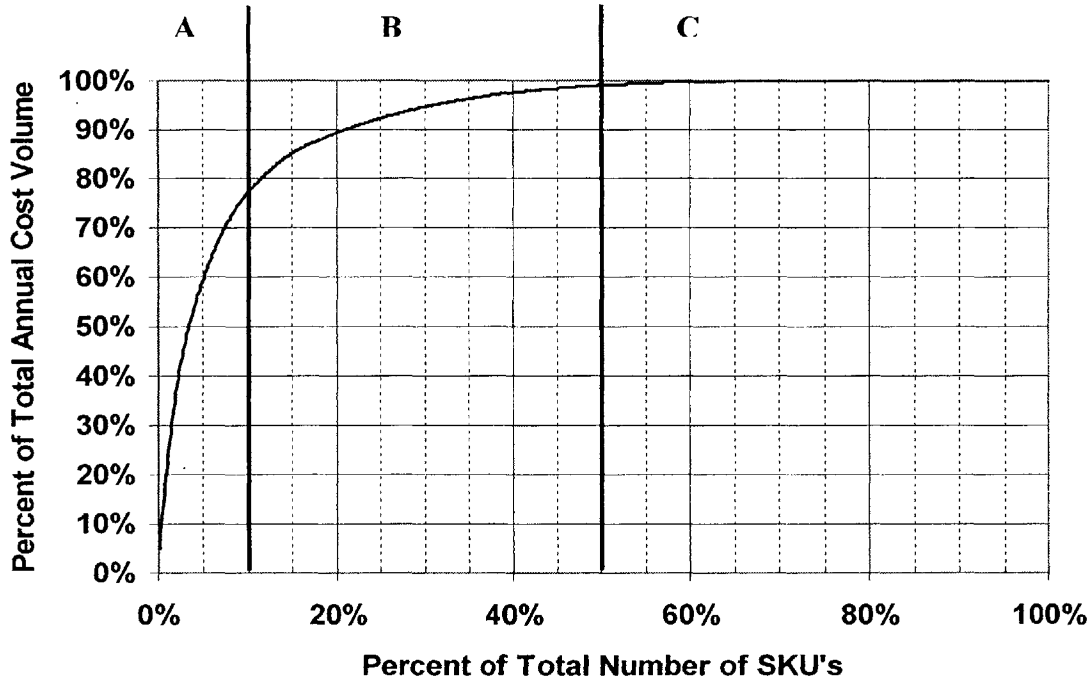

Figure 19. Distribution of Value by SKUs

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[1] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, p. 33.

Ten percent of the total number of SKUs account for almost eighty percent of the total cost-volume. These SKUs are labeled "Class A" and receive special attention as described below. On the right half of the figure, fifty percent of the SKUs represent a very small portion of the total cost-volume. These SKUs (typically fasteners, springs, inserts, etc.) are labeled "Class C" and are covered by a straightforward inventory policy needing little attention. The middle class of SKUs, Class B, constitute the remainder of the items - too valuable to assign to a Class C policy, but not valuable enough to receive special attention.

Class A Items Require Special Attention

The 5 kN wedge grip seen initially in Figure 3 is exploded in Figure 20, demonstrating the contribution of the Class A items to the overall value of the finished goods. Eighty percent of the total value of the grip comes from only three of the thirty-five detail parts - the body, the spindle, and the adjusting nut.

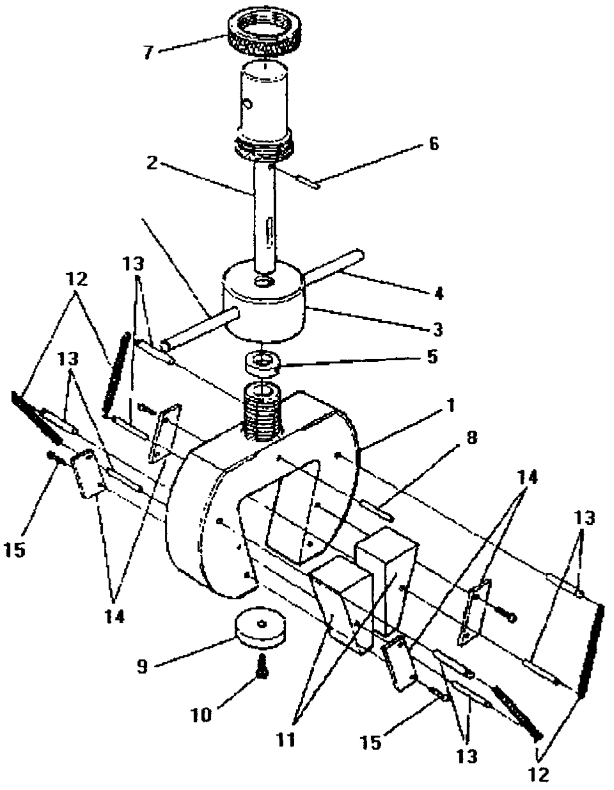

Figure 20. Exploded View of 5kN Wedge Grip

The body, labeled part number 1 in the figure, is identified at Instron as item number M211-1. Its standard cost is $613.

The spindle, labeled part number 2 in the figure, is item number M211-2. Its standard cost is $66.

The adjusting nut, labeled part number 3, is item number M211-3. It costs $46.

All three parts are machined from cylindrical steel bar stock at the company's internal machine shop in Binghamton, NY.

The application of the (Q,r) model to these three parts begins with a review of each item's monthly usage over the last one or two years.

Usage data for the M211-1 body during 1998 and the first nine months of 1999 is graphed in Figure 21. Each data point measures the number of parts consumed for the particular month. The negative forty units in Oct 1998 reflects a restocking adjustment from a cancelled order. Also shown on the graph are three horizontal lines: a dashed line at the mean monthly usage of 18.0 units and two heavy solid lines at the mean plus and minus two standard deviations. The standard deviation of the monthly data is 15.1 units after excluding the data point of -40 units in October.

The restocking adjustment represents an assignable cause of variation and can be removed from the calculation of the standard deviation[1].

This usage data, along with a stated replenishment lead time of 40 days, allows the calculation of the reorder point. The demand over the lead time is equal to the monthly mean times the lead time in months, or 18.0 times 1.3 = 24 units. The 95% safety stock level is equal to 1.64 times the standard deviation times the square root of the lead time in months, or $1.64 * 15.1 * \sqrt{1.3} = 28.6$ units. The reorder point is the sum of these two values, or 52.6 units. So whenever the stock level of these grip bodies goes below 53 units, we place a replenishment order. We expect about 24 units to be consumed while we wait for the order to arrive; the other 29 units are our insurance against a spike in demand.

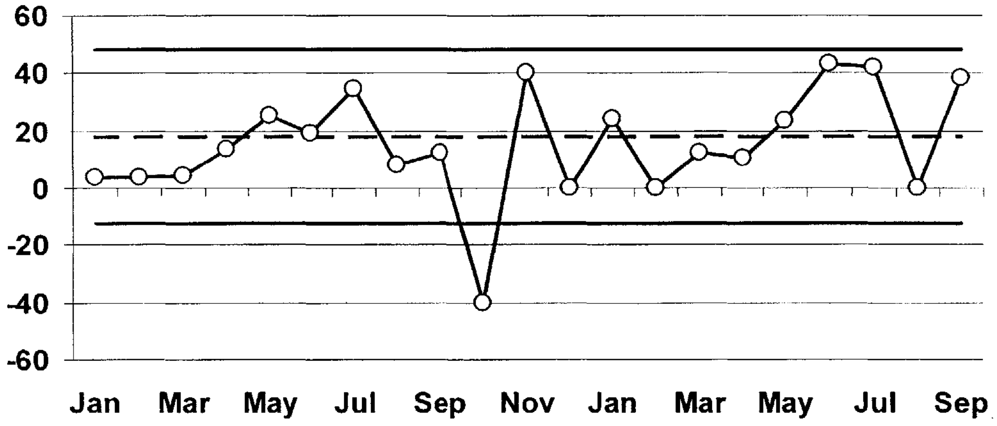

Figure 21. M211-1 Monthly Usage

How many units are ordered? Assuming an order cost of $75 and a holding cost of 30%, the EOQ model suggests an order size of thirteen units. This is somewhat counterintuitive in that the lot size does not appear to fully replenish the bin. But there are multiple lots in the pipeline so that the on-hand quantity plus the on-order quantity exceeds the reorder point. Thus, it is important that work cell personnel look at the total quantity on-hand *and* on-order before placing additional orders.

Another way to deal with this difficulty is to look again at the reorder point, particularly the lead time. The M211-1 is supplied internally, from Binghamton, NY. The stated lead time is a worst-case scenario and assumes the part must be fabricated from scratch. Since the part is a Class A item, the project team negotiated its delivery from NY on demand, with a maximum lead time of five days. This new value for the lead time reduces the DOLT from 24 units to three units and the safety stock from 29 units to ten units. The new reorder point is thirteen units. Now the order quantity of thirteen units is less counterintuitive.

This example illustrates the effort that goes into establishing order quantities and reorder points. For Class A items, this effort is certainly justified. The team is also pursuing the reduction of the

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[1] DeVor, R. E., T. Chang, and J. W. Sutherland, "Statistical Quality Design and Control," (1992), Macmillan Publishing Company, New York, p. 167.

cost of the item itself as well as reduction of the order cost; these pursuits may have offsetting effects in the EOQ calculation.

Silver provides the following list of additional guidelines for the control of Class A items[1].

1. Maintain inventory records on a perpetual basis.
2. Keep top management informed with monthly reports.
3. Estimate and influence demand:
    a. Contact customers for advance order planning.
    b. Improve forecasting and the predictability of demand.
    c. Manipulate demand by altering price structures.
4. Estimate and influence supply.
5. Keep initial stocks low.
6. Review the order quantity and reorder point values frequently.
7. Determine precise values for order quantity and reorder points.
8. Be proactive with shortages.

Choosing the right scope of products for these guidelines is a central concern. When considering the operation of the EM grip job shop in isolation, about eighty items fall into the Class A category. When the scope is widened to include EM machines or even the entire Instron product line, the number of items increases beyond a reasonable number for monthly review by top management. The best approach for Instron is probably for mid-level managers to review the Class A items in their respective product lines on a monthly basis and provide rollup statistics and special cases to top management.

Class B Items in (Q,r) Model Balance Holding Costs and Stockouts

The Class B inventory items receive the same basic treatment as that applied to the Class A. The main exception is that Class B items do not receive the same degree of individual attention. Usage data is imported from the company's information system into a spreadsheet model, which then carries out the EOQ and ROP calculations. A brief review of the recommended order quantities and reorder points provides a cross-check against the introduction of outliers and anomalies into the calculated decision variables.

Class C Items Covered by Straightforward Policy

The calculations and cross-checking for Class A and Class B items is not warranted for Class C items. These items are the trivial many, with very low value. However, they are required for assembly, so it makes sense to maintain relatively high levels of stock with sizable order quantities and long periods between orders. The inventory control system specifies an order quantity of one year's supply for each item, with reorder points set at six months' supply.

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[1] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, pp. 317-318.

Many Class C items have extremely low usages and some even show zero use in the last two years. Methods for managing slow-moving stock at Instron are described briefly in Chapter 5 as a recommendation for future improvements and Appendix G covers some of the technical details. A distribution by value chart sorted in descending order by weeks of future coverage identifies the dead and dying stock[1] and a decision rule balances the value of the excess stock against its storage and holding costs[2].

Silver also suggests establishing a Stock / No Stock rule to answer whether to make a special purchase from the item's supplier for each customer demand transaction or to purchase to stock. The basic rule is to not stock an item if its holding cost exceeds its order cost over the expected time period between demand events, or if the individual orders are large[3].

Project Team Improves Job Shop Processes

The project team implemented a number of process improvements within the shop. Chief among these were the modifications to the material flow to allow visual control of the pull production process. The work cell was relocated to an adjacent bay to make room for the inventory required by the grip assembly processes. The new location also provides an overhead crane to improve the ergonomics associated with the higher capacity and heavier grip models.

Stocking shelves were purchased and placed at one end of the work cell and filled with low-volume inventory. Team members grouped components for high-volume end items together and placed them on mobile racks so that the entire inventory could be moved to the mechanic's workbench for assembly.

Tools and jigs specific to the end item assembly were also placed on the mobile racks to reduce setup times. Figure 22 shows the mobile rack for the 5 kN and 30 kN wedge grips.

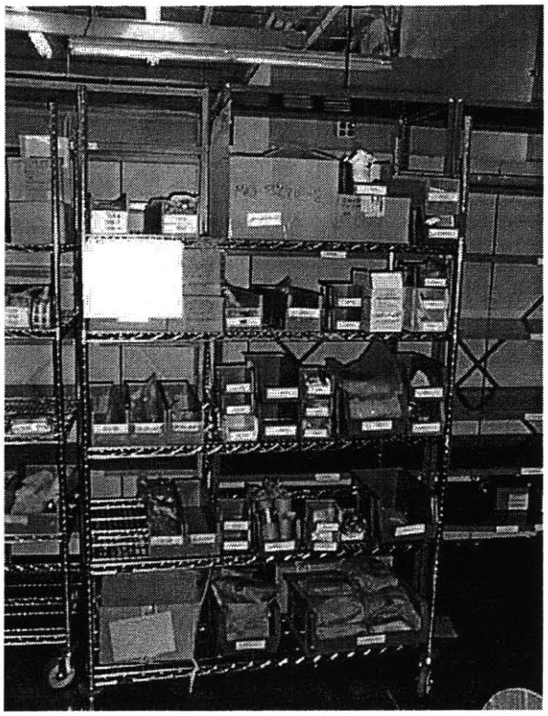

Figure 22. Mobile Rack

The team procured various low-cost tools to speed up the assembly process, including a modern variable-speed drill press, a bench-mounted Arbor press, and assorted small battery operated

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[1] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, pp. 367-369.

[2] Rosenfield, D. B., "Disposal of Excess Inventory," *Operations Research,* Vol. 37, no. 3 (1989), pp. 404-409.

[3] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, pp. 372-375.

tools. Akro-bin containers, visible in Figures 22 and 23, are key elements of the pull production system, and are standard items throughout the Instron factory. Process improvement purchases totaled about $9,200.

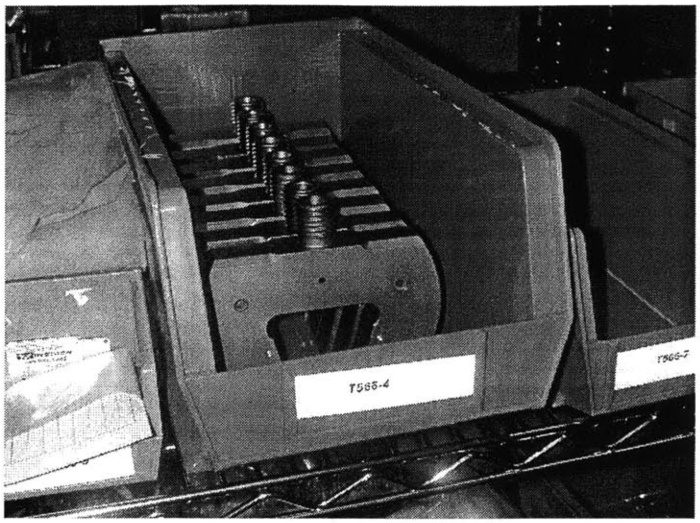

Figure 23. Kanban Bin for Grip Bodies

As a final note on factory floor process improvements, the relatively simple act of moving the inventory from the stock room to the work cell immediately demonstrated the excessive inventory holdings. The springs shown in Figure 24, for example, will supply the shop's needs for the next ten years. Such visual reminders of the excesses of MRP serve to convince team members of the need to change.

Figure 24. Ten Year Supply of Springs

4

Managing Instron's Supply Chain

Supply chain management describes the management of materials and information across the entire supply chain, from the procurement of raw materials through fabrication, assembly, and distribution to the consumer[1]. Chapter 1 describes the consolidation of the European and American supply chains. This chapter discusses two other aspects of supply chain management applied to the Instron grip inventory reduction project.

First, mapping the supply chain for the 5 kN / 30 kN wedge grips provides insights into the application of appropriate models. The component fabrication processes and operation of the Binghamton, NY, machine shop are important elements of this analysis. One of the project's critical success factors was the establishment and maintenance of a functional, heuristic process for pull production between Canton and Binghamton. Replacing the heuristic approach with an application of the SIP model as described in Appendix A will provide additional insights into appropriate inventory policies throughout the upstream supply chain and is recommended for future action.

The second topic of this chapter identifies the highest-value Class A inventory items, drawn from both finished goods and component inventories, and explores their supply chain topologies. Simple and straightforward cases allow brief treatment as noted in Chapter 1. Several items, however, present more complicated topologies with multistage or cross-connected links, warranting special attention.

The 5 kN / 30 kN Wedge Grip Supply Chain

Figure 25 maps the supply chain of the 5 kN / 30 kN wedge grips. Component parts are fabricated in Binghamton, NY, and stored there as well as in the assembly work cell in Canton. Components are also provided by external suppliers and stored in Canton. In most cases for this product line, the suppliers maintain adequate inventories to keep reasonably short lead times. Raw materials are not shown because of their relatively low value.

Final assembly takes place at the work cell in Canton and a few sets of assembled grips are stored locally. One or two sets of finished goods are also maintained in High Wycombe, England, to provide quick delivery to over-the-counter customers.

The map is a useful tool to develop inventory strategies. The project's prime directive to reduce inventory leads to the question, "Why are component inventories held in both Binghamton and

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[1] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), p. 471.

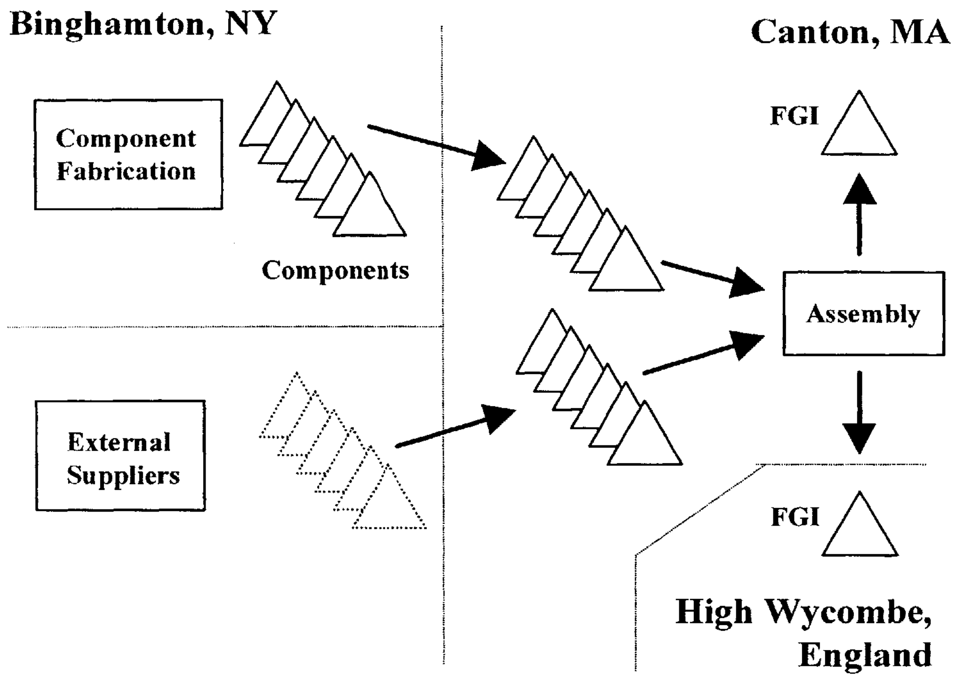

Figure 25. 5 kN / 30 kN Supply Chain

Canton?" These two locations can be considered separate stages in the supply chain with the transportation from Binghamton to Canton acting as the value-added step between them. In such simple serial supply chains, the optimal solution is "all or nothing" - either the stage has no safety stock or it has enough safety stock to decouple it from its downstream stage and the downstream stage can draw from the upstream stage as required[1]. So why store components in both places?

The answer lies in a management decision to place the Binghamton shop on more of an equal footing with external suppliers, particularly in the areas of blanket orders and shared inventories. Instron planners and buyers have established many blanket order arrangements with suppliers. At the end of each year, the buyers agree in writing to purchase the next full year's supply of each component in exchange for biweekly or monthly deliveries and billings.

The suppliers enter into these arrangements because they can secure advance orders and plan production accordingly. Instron benefits because lead times are reduced to the negotiated time period and the supplier shares the burden of holding inventories. The suppliers' inventories also serve as an incentive for the suppliers to reduce setup times and lot sizes, thereby further reducing lead times. Even if Instron maintains component inventories in both locations (Canton and NY), their sum can be smaller than the current excessive holdings in the Canton stockroom.

The NY machine shop accepted the challenge to maintain component inventories and deliver small lots on demand. In return, project team members worked with the shop to set up the pull

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[1] Simpson, K. F., "In-Process Inventories," *Operations Research,* 6 (1958), pp. 863-873.

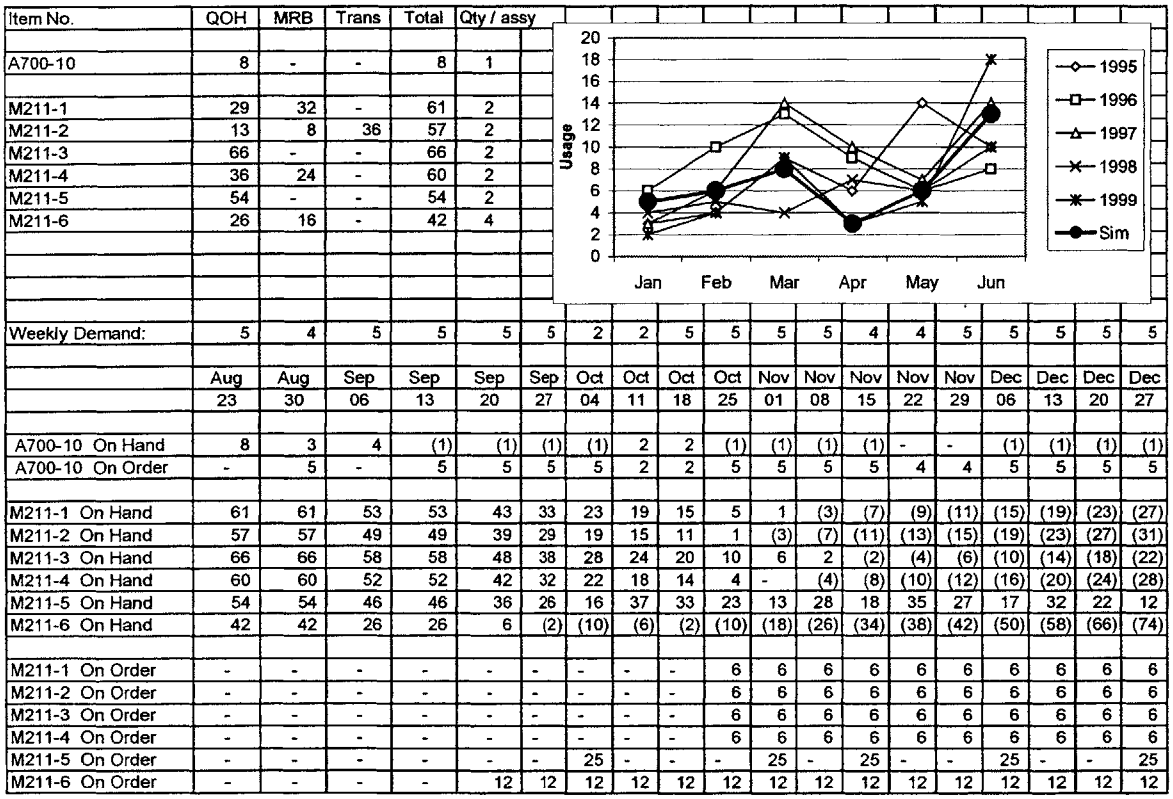
production system, review the component fabrication processes, and implement improvements. The next section describes these efforts.

Working Upstream – Kanban Bins in Binghamton

The pull production system implemented in the assembly work cell in Canton specifies order quantities and reorder points for all of the 5 kN / 30 kN wedge grips. Many of the machined detail parts are supplied by Binghamton and the blanket order concept applies. Parts are shipped by truck from Binghamton to Instron two or three times each week, so team members chose a lead time of five days. Order quantities vary depending on the part cost and on the quantity of details required for assembly; for example, two grip bodies are needed for one set of grips but the same set requires four handles. Binghamton agreed to supply grip bodies in lots of six and handles in lots of twelve.

At the time of implementation, a large quantity of parts were already on hand in Canton and an equal number of parts were shipped from High Wycombe. To kick off the program, Binghamton asked for three weeks' notice before delivery of the first lot of each component under the new system. Simulation of demand and component consumption provided reasonable estimates for production preparation. An example of the simulation spreadsheet is shown in Figure 26.

In the upper left portion of the spreadsheet, the quantity of on hand inventory is displayed for the finished grip set (A700-10) as well as six details fabricated in New York (M211-1 through M211-



Item No.	QOH	MRB	Trans	Total	Qty / assy
A700-10	8	-	-	8	1
M211-1	29	32	-	61	2
M211-2	13	8	36	57	2
M211-3	66	-	-	66	2
M211-4	36	24	-	60	2
M211-5	54	-	-	54	2
M211-6	26	16	-	42	4

Weekly Demand:	5	4	5	5	5	5	2	2	5	5	5	5	4	4	5	5	5	5	5
	Aug	Aug	Sep	Sep	Sep	Sep	Oct	Oct	Oct	Oct	Nov	Nov	Nov	Nov	Nov	Dec	Dec	Dec	Dec
	23	30	06	13	20	27	04	11	18	25	01	08	15	22	29	06	13	20	27
A700-10 On Hand	8	3	4	(1)	(1)	(1)	(1)	2	2	(1)	(1)	(1)	(1)	-	-	(1)	(1)	(1)	(1)
A700-10 On Order	-	5	-	5	5	5	5	2	2	5	5	5	5	4	4	5	5	5	5
M211-1 On Hand	61	61	53	53	43	33	23	19	15	5	1	(3)	(7)	(9)	(11)	(15)	(19)	(23)	(27)
M211-2 On Hand	57	57	49	49	39	29	19	15	11	1	(3)	(7)	(11)	(13)	(15)	(19)	(23)	(27)	(31)
M211-3 On Hand	66	66	58	58	48	38	28	24	20	10	6	2	(2)	(4)	(6)	(10)	(14)	(18)	(22)
M211-4 On Hand	60	60	52	52	42	32	22	18	14	4	-	(4)	(8)	(10)	(12)	(16)	(20)	(24)	(28)
M211-5 On Hand	54	54	46	46	36	26	16	37	33	23	13	28	18	35	27	17	32	22	12
M211-6 On Hand	42	42	26	26	6	(2)	(10)	(6)	(2)	(10)	(18)	(26)	(34)	(38)	(42)	(50)	(58)	(66)	(74)
M211-1 On Order	-	-	-	-	-	-	-	-	-	6	6	6	6	6	6	6	6	6	6
M211-2 On Order	-	-	-	-	-	-	-	-	-	6	6	6	6	6	6	6	6	6	6
M211-3 On Order	-	-	-	-	-	-	-	-	-	6	6	6	6	6	6	6	6	6	6
M211-4 On Order	-	-	-	-	-	-	-	-	-	6	6	6	6	6	6	6	6	6	6
M211-5 On Order	-	-	-	-	-	-	25	-	-	-	25	-	25	-	-	25	-	-	25
M211-6 On Order	-	-	-	-	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12

Figure 26. Simulation of Need Dates for 5kN Parts

6). Random number generators provide the weekly demand, which falls within the historical patterns in the graph in the upper right section of the figure. These weekly demands are subtracted from the on hand inventory each week from left to right across the middle of the sheet and when the on hand levels finally drop below the reorder point, orders are generated in the bottom rows. By repeatedly exercising this simulation, the most-likely and worst-case need dates for each part were determined and communicated to the machine shop.

The NY team members set up output kanban bins for each of the detail parts, as shown in Figure 27. Under the new process, when Canton places an order via email, the NY workers pull the order quantity and include it with the next shipment to Canton. The reorder points for the output kanban bins are based on the lead time for fabricating the detail parts. The next section describes this process for the M211-1 grip body.

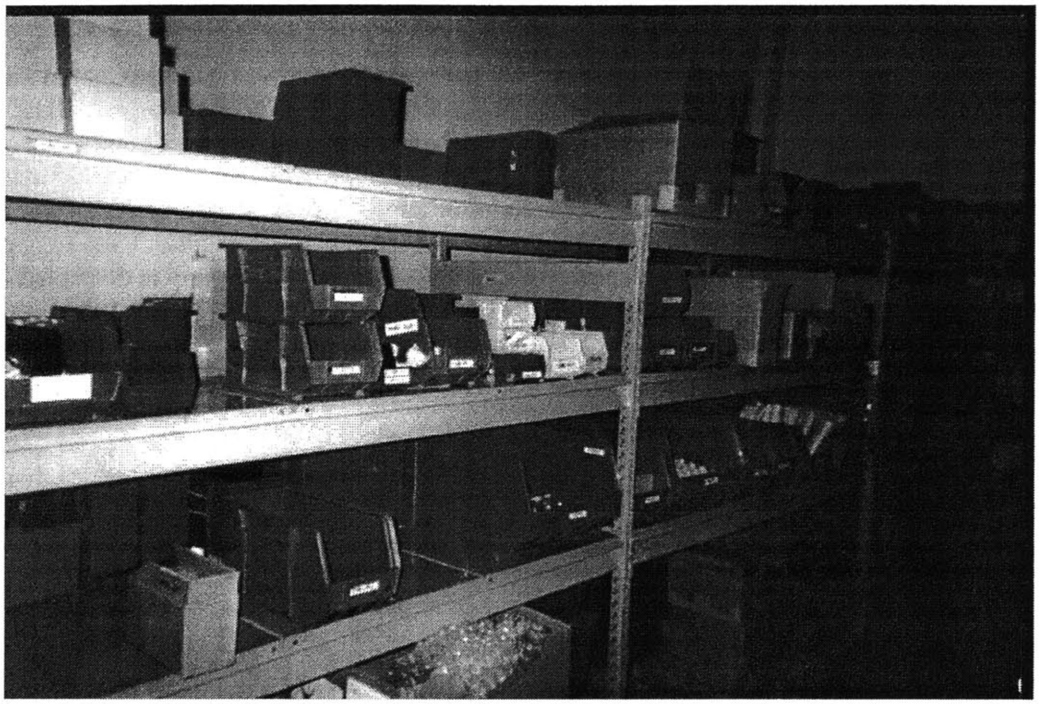


Figure 27. Binghamton Output Kanban Bins

The M211-1 Fabrication Process

The M211-1 grip body is made from stainless steel round bar stock. Figure 28 maps the process from raw material procurement through rough cut, heat treat, machining, and finishing steps until the parts are placed in the output kanban bin.The last three process steps add by far the most value to the item; just before the turning process, the piece is in an unfinished disk shape, known as a "slug" and measuring two inches thick and eight inches in diameter (see Figure 29). Slugs are worth about eight dollars; in comparison, grip bodies in the output kanban bin are worth several hundred dollars. Also, the lead time for the first three steps is twice as long as for the last three steps. So it makes sense to never run out of slugs.

The Canton order form specifies an order quantity of six units. The team chose to set the upstream order quantities and lot sizes in multiples of six to preclude mismatched batches as much as possible. The setup times required for the turning and milling machines drove a lot size of 24 and the team established this level as the reorder point for the output kanban bin as well.

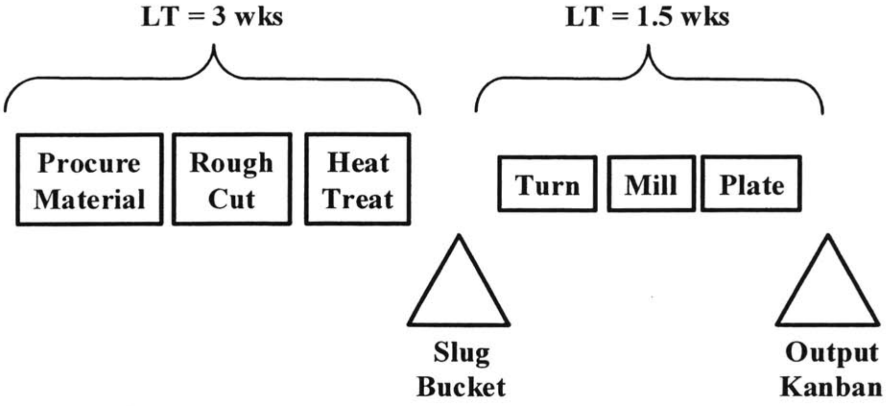


Figure 28. M211-1 Fabrication Process

The "slug bucket," a wooden shipping container used to store slugs midway through the fabrication process, was set up to hold a maximum of 48 slugs with a reorder point at 24.

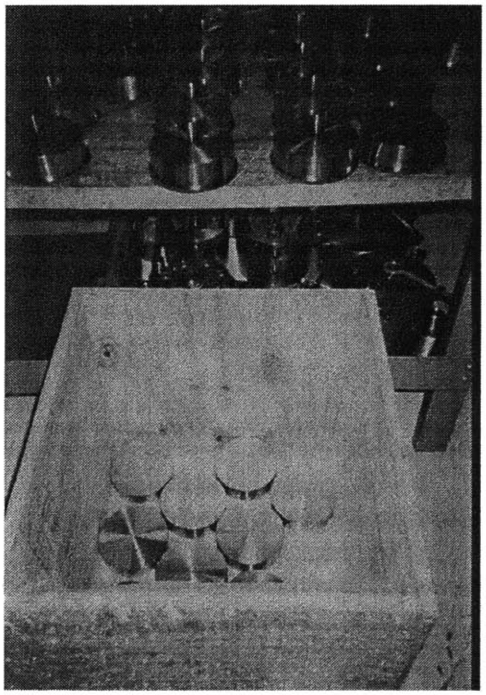


Figure 29. M211-1 Work In Process

A finished M211-1 grip body is shown in Figure 30, next to the tooling fixture required for the milling step in the fabrication process.

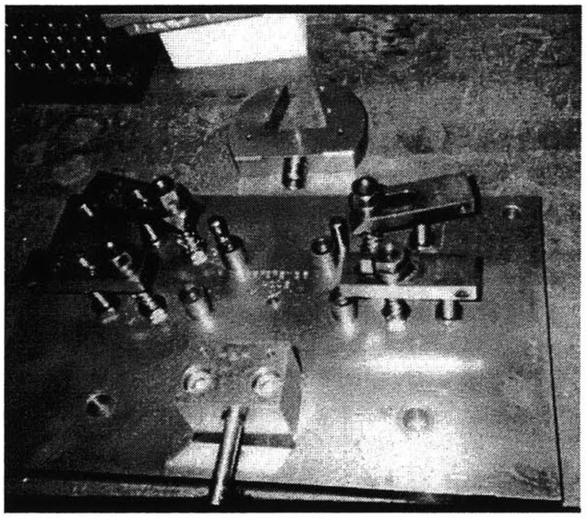


Figure 30. Finished M211-1 Grip Body

While this heuristic allocation of inventory through the fabrication supply chain may not be the optimal solution, it offers practicality for implementation and maintenance. Improvements to these inventory policies for components are included in the recommendations for future actions.

High-Value Supply Chain Topologies

As noted earlier, many of the high-value components and finished goods in the various bills of materials have simple network topologies that can be categorized as either serial, assembly, or distributive. For example, the M211-1 grip body, M211-2 spindle, and M211-3 adjusting nut all feed directly into the A700-10 wedge grip, representing an assembly topology.

Selection of the forty highest value SKUs allows the mapping of the sixteen most important supply chains. Of these sixteen, nine are simple serial, three are assembly, and one is distributive. The other three consist of a three-stage compound serial assembly network and two cross-linked two-stage networks. Given the long cycle times and short assembly times for finished goods, the SIP model recommends stocking only at the component level for all of the simple network topologies.

The three-stage compound serial assembly network is shown in Figure 31. In this SIP model diagram, the circles represent processes that add value and the triangles represent inventory placements. The model recommends stocking the M101-1C and M631-2 details, which both have relatively long lead times (several weeks). The discussion of inventory holding locations for the M211-1 fabrication process in the previous section applies to this case as well.

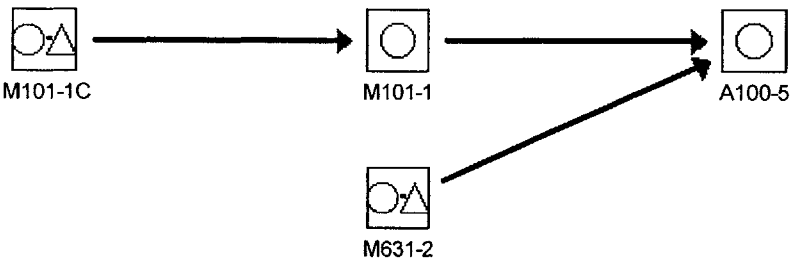


Figure 31. Screw Grip Supply Chain

The two cross-linked supply chains are beyond the scope of the SIP model. However, the same long cycle time and short assembly time argument applies. Inventory can be stocked at the component level only and finished goods made to order. The proper stocking levels of the components are thus completely decoupled from the downstream stages and the demand, lead time, and cost data for the individual components determines the appropriate stocking levels for setting up kanban bins.

5

Results and Recommendations

The internship successfully wedded the academic interests of MIT with those of its industrial partner, the Instron Corporation. This chapter presents the results on both fronts, first describing how the project developed the author's understanding of capacity management, inventory management, and the interplay and tradeoffs between them. New insights and intuition were gained by the application of several analysis tools, including the strategic inventory placement model, capacity modeling, queuing theory, simulation, and the continuous review inventory model, among others.

The chapter then presents the project results by quantifying the inventory reductions from several different perspectives. The contributions of the three different approaches (supply chain consolidation, make-to-order assembly processes, and pull production implementation) are split out to show roughly equal gains. The results of the 5 kN / 30 kN pilot project demonstrate the effectiveness of the reduction techniques, particularly for newly designed products.

The thesis closes with several recommendations: to improve component outsourcing, to dispose of slow-moving inventory, and to optimize levels of safety stocks. The most important recommendation is to extend the methodology to a broader range of product lines and thereby gain commensurate benefits.

Academic Results

Analyzing the work load in the job shop has provided several new insights for the author. The capacity model presents an analytical framework for thinking about capacity and how to specify appropriate assembly lot sizes. The use of a Lagrangian multiplier to budget the labor hours available for setup time yields an optimal solution by assigning larger lot sizes to items with longer setup times or with higher demand volumes.

Capacity management is further explored by considering customer lead time requirements. Applying queuing theory to the capacity model allows analysis of expected waiting and processing times for the work cell jobs; better yet, with simple queuing models, the waiting time distributions are revealed so that we can understand what percentage of jobs will be finished within the required window. This analysis allows us to reserve the right amount of labor capacity in the work cell to meet customer requirements with some desired regularity, say 19 out of 20 times.

It's important to understand the limitations of queuing theory in this application. The assumption of exponential service times does not fit well with the available data, suggesting the application of a general service time distribution queuing model, such as M/G/1. However, the closed form solution for the waiting time distribution for this system is intractable, let alone the extension to modeling more than one server. So the value of simulation is well demonstrated; its development and the iterated checking of its results with those of queuing theory provide a great deal of insight into capacity management and the tradeoffs between labor and inventory.

A second broad area of new understanding for the author resulted from the analysis and application of inventory management techniques. While continuous review inventory policies are familiar, their application to an actual production setting for hundreds of individual components built significant facility and intuition. The distribution by value technique to classify inventory for priority treatment is also important, especially when employing a cost volume product (rather than cost alone) as the driving variable. Exploring the disposition of slow-moving items based on ultimate sales value and salvage values provides additional understanding of inventory and customer service tradeoffs..

Perhaps most interesting among the inventory management techniques is the optimization of safety stock levels of the components of an assembly. Developing a linear programming model to minimize total inventory cost by varying the component safety stock levels subject to the requirement that all components be available for final assembly with a certain probability is an appealing and useful application of optimization theory.

Finally, the interaction between capacity management and inventory management provides a broader understanding of total plant management. Being able to separate the application of these two different sets of tools for the grip work cell enabled the project to move forward quickly. An extension of the analysis to more tightly bind the fabrication and assembly processes will present a worthwhile opportunity to explore more fully the interactions of the various models.

The Bottom Line: Inventory Reduced by Thirty Percent

Figure 6 in Chapter 1 summarizes the project results. Extending the time frame beyond the life of the project in both directions results in Figure 32. The high stock levels at the end of 1998

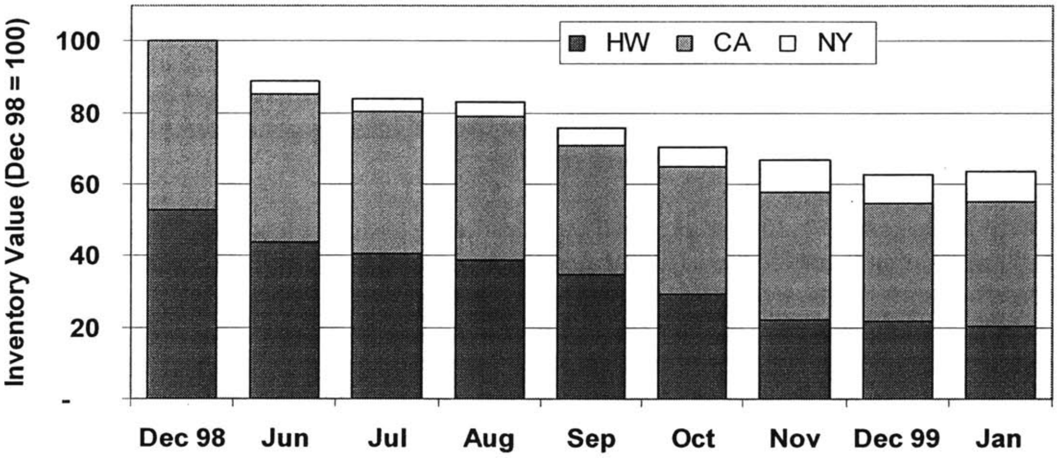


Figure 32. EM Grip Inventory

probably reflect a build-up to satisfy year-end demand. Available data does not indicate whether or not the Dec. 98 Canton inventory value includes NY inventory.

Beginning in June, 1999, measurements in Figure 32 reflect month-end values. The primary claim of a thirty percent reduction in inventory is the most conservative interpretation of the following data (inventory values are indexed to December 1998 values to disguise proprietary information).

Date	**Total Inventory**	**Excluding NY**
Dec 98	100	
Jun 99	89	85
Dec 99	63	55

The column titled "Excluding NY" is presented to estimate the additional inventory reduction that can result from outsourcing the machine shop link of the EM grip supply chain. Relating the two values for December, 1999, to the values at the beginning of the project (June, 1999) and at the end of the prior year yields the following measures of success:

Reduction during project, including NY	29.4 %
Reduction in 1999, including NY	37.3 %
Reduction during project, excluding NY	38.5%
Reduction in 1999, excluding NY	45.4 %

The most liberal interpretation of the data is that the EM grip inventory was nearly cut in half during the 1999 calendar year.

The Methods: Each Approach Is Effective

Contributions to inventory reduction from the three main approaches (supply chain consolidation, make-to-order assembly processes, and pull production implementation) are difficult to separate. The collection of measurement data is complicated by its "snapshot" nature - inventory value is measured at a point in time; once that time is passed, so has the opportunity for measurement.

Data is available at two discrete times, however, that allow an estimate of the effectiveness of the different approaches. Measurement of finished goods, components, assembly and component work-in-process (WIP), and raw materials is shown in the table at the top of the next page.

From mid-July to late November, inventory decreased about 22 percent. The switch from a make-to-stock (MTS) process to a make-to-order (MTO) process accounts for eight percent of the decrease. The effects from consolidating the two supply chains and implementing pull production are hard to distill; together they account for thirteen percent of the reduction. Team members believe it is reasonable to assume roughly equal contributions from these two methods, especially with respect to WIP - the MTO process reduces the size of the assembly batches and the consolidation of the two assembly shops reduces the number of assembly batches per year.

Miscellaneous effects comprise the remaining amount; these reductions include scrapping a small portion of the detail parts from High Wycombe, which failed incoming inspection in Canton.

		Total	US	UK
	Mid July (index = 100)	100.0	50.0	50.0
From MTS to MTO (FGI)		(8.2)	(3.8)	(4.4)
From MRP to Pull (WIP)		(7.3)	(3.6)	
Consolidated Assembly (WIP)				(3.7)
From MRP to Pull (RM & Comp)		(4.9)	9.8	(14.6)
Consolidated Safety Stocks				
Miscellaneous Effects		(1.7)		(1.7)
	Late Nov	78.0	52.4	25.6

The Pilot Project: A Standard for Design and Manufacturing

The pilot project targeted inventory for the 5 kN and 30 kN wedge grips and provided an early success for the team. An important reason for choosing this product line as a pilot is its excellent design for manufacturing (DFM) features. DFM is a methodology that seeks to minimize manufacturing costs while improving product quality[1].

The 5 kN and 30 kN wedge grips were designed together, replacing an older design composed of cast and forged detail parts with long lead times; the new design uses readily available bar stock as the raw material. The older design was stylish, with conical and multi-faceted prismatic geometry, while the new design is made entirely of cylinders, disks, and flat plates. The new design's short component lead times and straightforward machining operations allow smaller batch sizes and smaller inventories.

Figure 33 shows the pilot inventory value over the project's duration. The consolidation of the two supply chains began in July. High Wycombe maintained 54 percent of the total inventory and most of it was shipped by boat to Canton in July and August. At the outset of the project, the team decided to keep one or two sets of each of these grips in High Wycombe to serve the European over-the-counter market.

When the High Wycombe inventory arrived in Canton, it was inspected for compliance with engineering requirements. Unfortunately, a significant portion (designated MRB in Figure 33) of the incoming shipment failed the inspection for a variety of reasons, mostly related to the finishing processes. The Canton team sent the parts out to a local processing facility and reworked the bulk of the material by October; only about ten percent was scrapped.

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[1] Ulrich, K. T., and S. D. Eppinger, "Product Design and Development," (1995), McGraw-Hill, Inc., New York, p. 181.

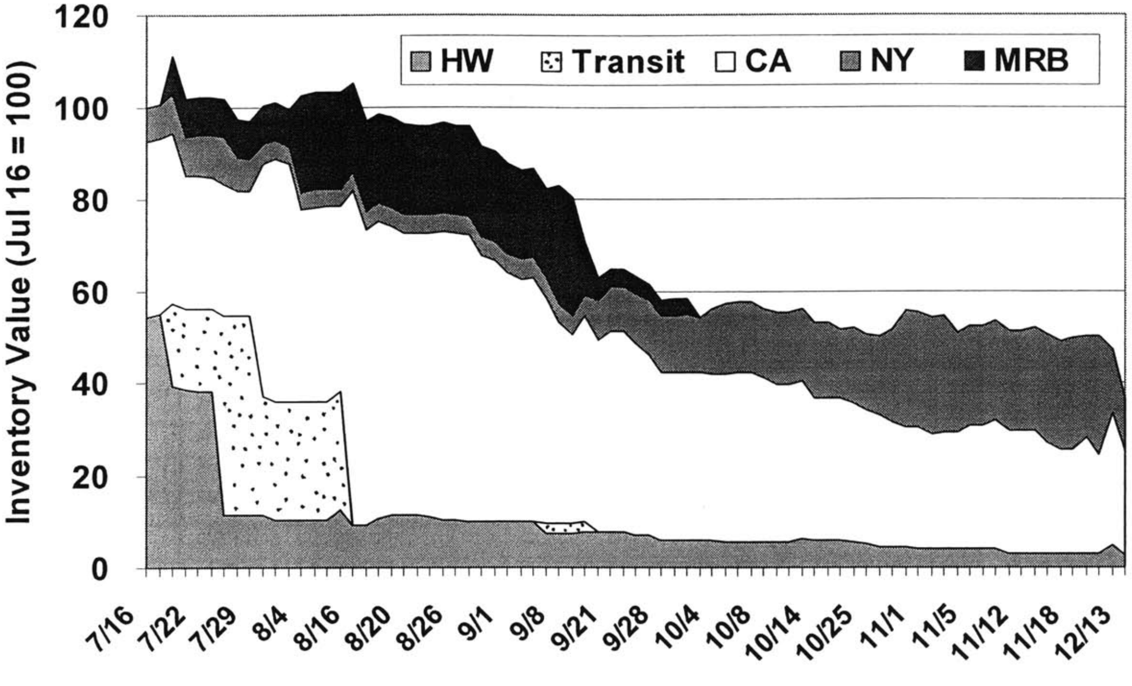

Figure 33. 5kN / 30kN Wedge Grip Inventory

The combined inventory was worked off during August and September. Over this period, the NY machine shop stopped production and waited for individual signals to restart. Those signals occurred sequentially through September and October, and the growth in NY inventory during this time reflects the implementation of kanban bins in NY.

The Canton job shop continued to work off the consolidated stores, aided by a strong fourth quarter, reducing its on-hand inventory by at least 25% while increasing production to cover global demand. The team improved performance from less than two to more than four turns per year, even including the NY inventory. Optimizing the inventory placement within the NY fabrication process will reduce this level further. Completely *outsourcing* the machining operation will double the turns again.

The Future, Step 1: Improve Component Sourcing

Focusing improvement efforts on the Class A, high-value, high-volume detail parts will yield significant benefits. Over half of the total dollar value of inventory flowing through the shop each year is finished goods. The remaining amount is raw materials and components, made up of 750 SKUs. The twenty highest value and volume parts among the 750 account for almost half of the total value and provide the opportunity for a highly focused effort. The twenty parts are shown in Figure 34; although the cost and usage data is disguised, the overall Pareto patterns are retained.

New York supplies twelve of the twenty parts, making up the bulk of the annual value. The benefits of outsourcing these parts center around production costs. Competing machine shops have quoted prices for supplying these parts at dramatically lower levels than the internal standard costs. Shifting the work outside will not only lower Instron's cost of goods sold, but also its inventory holding costs. Furthermore, the competing suppliers are willing to arrange periodic shipments of small lot sizes and hold some finished component inventories at their sites, off Instron's balance sheet. Such an arrangement serves as a powerful incentive for the suppliers to invest in machining capabilities to decrease setup times, lot sizes, and lead times. Instron's strategy for capital support of its internal machine shop must be clearly defined to respond to this compelling case for outsourcing.

No.	Item Number	Item Description	Std Cost	98 Use	$ Val
1	M255-60	Jaw Frame 20000 Lb	697.72	247	172,483
2	M693-8	Body	777.39	121	93,949
3	M709-69	Jaw Frame	50.60	1,125	56,928
4	M676-35	Carrier	657.38	76	49,920
5	M49-28	20 000 Jaw Frame	305.70	145	44,466
6	M399-89	Seal Metal Bellows	161.12	275	44,262
7	M550-4	Body	467.46	92	43,209
8	M60-74	Jaw Frame	238.59	171	40,840
9	M168-63	Spindle	110.03	295	32,477
10	M502-31	Plunger Housing	29.43	1,081	31,800
11	M552-45	Body	112.38	263	29,611
12	M208-68	Cord Tire Frame	117.94	212	24,999
13	M666-98	Jaw Frame	259.80	75	19,495
14	M59-51	Frame Pneumatic C	46.62	390	18,162
15	M61-46	Jaw Frame	56.73	283	16,075
16	M554-28	Check Nut	8.25	1,713	14,123
17	M767-40	Upper & Lower Frame	191.17	73	13,885
18	M85-37	Upper & Lower Frame	266.92	50	13,375
19	M470-80	Block Stationary	53.15	176	9,351
20	M91-61	Rubber Face Screw	44.63	154	6,854
Total					776,261

Figure 34. Top Twenty Detail Parts

The Future, Step 2: Dispose of Slow Movers

The difficulty of forecasting demand for EM grips is underscored by analyzing slow-moving inventory. Sales of several of the grip models were expected to take off but failed to do so. Component and finished goods inventories of these models contribute significantly to the overall grip inventory value, and their disposition will improve the work cell's performance.

Based on usage data for 1998 and 1999, about ten percent of Instron's total grip inventory will keep the production pipeline full for more than two years. More than half of this slow-moving inventory will last at least five years and one fourth of it will last over ten years. A full one-eighth of the slow-moving inventory saw no usage at all in 1998 and 1999.

These components can be assembled into finished grips and sold at a discount to reduce inventory holding costs and improve overall inventory turns. Appendix G describes one approach to identifying which items and how many of each to dispose. From past efforts to reduce slow movers, however, management has found that the grips must be packaged with other accessories (such as faces and base adapters) on the shelf to provide true customer solutions.

The Future, Step 3: Optimize Component Safety Stocks

As noted above, the move from MRP to pull production and kanbans for safety stocks resulted in significant reductions in inventory holdings. However, the credo, "the enemy of better is best," while forcefully driving team efforts to successful implementation, left room for further improvement through optimization. A method for optimizing safety stock levels is presented in Appendix H and its development and results are summarized below.

The (Q,r) model described in Chapter 3 establishes safety stock levels for individual components based on the desired service level, typically 95% on-the-shelf availability. When this 95% value is applied to each component in an assembly, then the probability of all required components being available when needed is inversely proportional to the number of components in the assembly.

For example, with a two-part assembly, if each has a 95% probability of being on-the-shelf, then the probability of both parts being on-the-shelf is (0.95 * 0.95) = 90.25%. The 5 kN wedge grip has seventeen component parts required for assembly, so the probability of all seventeen parts being available drops to $(0.95)^{17}$ or only 41 percent!

The straightforward correction to this problem fixes the probability of assembly at 95% and increases the on-the-shelf probabilities of the components. Using a common z-variate for the seventeen parts, the individual probabilities rise to 99.7%, but this causes the component safety stocks to rise as well, by as much as forty percent.

The best solution of the problem is found by allowing the z-variates to take on independent, optimal values[1]. Appendix H develops this analysis and minimizes the total average inventory costs by changing the z-variates while constraining the assembly probability to 95%. The optimization technique offers a twelve percent reduction over the common z-variate method mentioned above while maintaining a 95% service level. This twelve percent reduction is available across all EM grip inventories at the relatively insignificant cost of several days of optimization analysis and recoding of kanban order cards.

Concluding Recommendation

As a final note, Instron should consider adopting the methods presented in this thesis to other product lines. Appendix I outlines the step-by-step procedures. At the end of 1998, total corporate inventory stood at just over $36 million while the EM grip inventory ended the year at a small percent of the total. A reasonable next step is to scale up the project tenfold for a significant reduction in inventory during the year 2000. The most likely candidate for this target is the EM custom machine product line.

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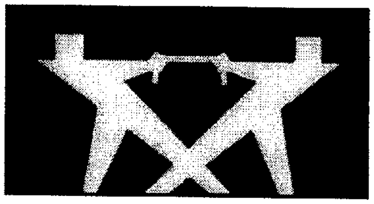
[1] Rosenfield, D. B., and A. W. Drake, advisors to the internship, June-Dec. 1999.



Appendices

A

Strategic Inventory Placement

Chapter 1 introduces the overall approach to the Instron inventory reduction project as "Divide and Conquer." The division of the supply chain into two separate problems is suggested by the application of the Strategic Inventory Placement (SIP) model[1]. Its application to Instron supply chains is described in this appendix.

The SIP model determines the placement and levels of safety stock that minimize the total inventory costs across the supply chain under conditions of uncertain demand. One of its chief contributions is a method for avoiding the local sub-optimization that can occur when each stage of a manufacturing process independently determines its own safety stocks[2]. The model may also be used, as it is here, to determine that local sub-optimization is an appropriate policy when cycle and lead time requirements for the manufacturing stages permit decoupling.

Supply chains have various topologies. The simple serial chain is the most elementary, with a single component stage feeding a single finished goods stage. Assembly chains have multiple components feeding a single finished goods stage and distribution chains have a single component stage feeding multiple finished goods. These simple chains can be combined to form more complex, multi-stage supply chains.

The SIP model operates with a base-stock control policy in which each stage reviews its demand periodically and orders a replenishment quantity from its upstream stage to fill demand. The model operates on several assumptions and production rules:

> Demand is independent and normally-distributed.
>
> Capacity is unconstrained.
>
> Each stage has a production lead time and specifies a service time to its downstream stage by which it will deliver product.
>
> Each stage also stipulates a service level defining the expected stock-out probabilities; a typical service level is 95% leading to stock-outs one time out of twenty.
>
> Finally, each stage adds cost to the product.

---

[1] Graves, S. C., "Strategic Inventory Placement Model Assignment," in-class assignment, 15.762 Operations Management Models and Applications, March 1999.

[2] Willems, S. P., "Strategic Safety Stock Placement in Integrated Production/Distribution Systems," Master's Thesis, MIT Operations Research Center, May 1996, p. 6.

The model optimizes the safety stock levels across the chain by minimizing the total holding costs subject to the constraint that the safety stock at each stage cannot exceed the stage's production lead time plus the service time quoted to the stage from the upstream stage[1].

Most of Instron's EM grip supply chains can be represented as assembly topologies. Component parts held at the job shop are assembled into finished goods, also held at the job shop. Figure 35 shows a simplified diagram of the 5 kN wedge grip supply chain. The assembly stage at the right has a production lead time of only two hours and quotes a 95% service time of two weeks. The three component stages at the left of the figure require several weeks to fabricate from raw materials. If the Binghamton supplier maintains finished components, then the production lead times shrink to one or two days. In either case, the SIP model minimizes safety stocks by placing them entirely at the component stage; all finished goods are made to order.

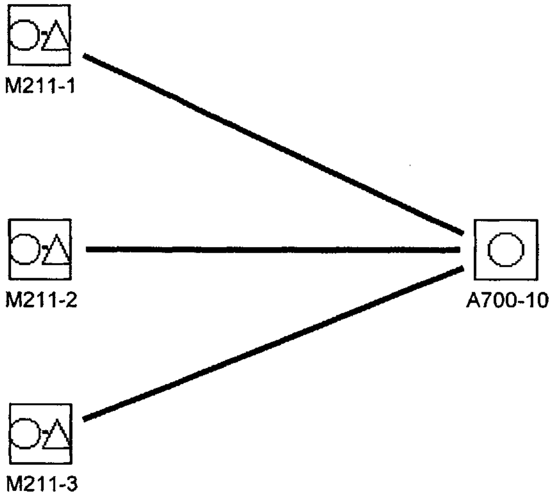


Figure 35. Simplified Assembly Supply Chain

The 5 kN wedge grip chain is typical of the 56 grip products; in almost every case, the model recommends placement of safety stocks at the component stage, decoupling the assembly process from the fabrication processes without a loss in optimization. In simple terms, we can supply all grips by building to order because the assembly process time is so short (two hours) compared to the required customer lead time (two weeks).

---

[1] Willems, S. P., "Strategic Safety Stock Placement in Integrated Production/Distribution Systems," Master's Thesis, MIT Operations Research Center, May 1996, p. 14.

B

Safety Stock Consolidation

Chapter 1 mentions that the consolidation of the two supply chains results in lower levels of safety stocks and overall inventories. This appendix provides the details that lead to this result.

The analysis begins with the (Q,r) model from Chapter 3. The expected level of stock is equal to the safety stock plus the average cycle stock:

$$E\{I\} = SS + (EOQ/2)$$

The safety stock is equal to the z-variate (representing the desired service level) times the standard deviation of demand times the square root of the lead time, again assuming independent time increments.

$$SS = z * \sigma * \sqrt{LT}$$

With two identical but independent supply chains, the total inventory is the sum of the inventory in the two chains:

$$I = I_1 + I_2$$

$$E\{I_{separate}\} = 2 * SS + EOQ$$

When the two chains are combined, however, the required safety stock must be recalculated based on the combined demand stream and its standard deviation. If the two chains are independent and have identical demand streams, then the combined standard deviation is the root of the sums of their variances:

$$SS_{combined} = \sqrt{(z^2 * \sigma^2 * LT) + (z^2 * \sigma^2 * LT)} = \sqrt{2} * SS$$

The safety stock for the combined supply chain is therefore equal to 1.4 times the safety stock of an individual chain. The consolidated chain has about thirty percent less inventory than the sum of the two individual chains.

C

Distribution by Value

The technique of distribution by value (DBV) seeks to discover the Pareto pattern within inventory holdings. If a significant few can be identified among the trivial many, then management resources can be assigned to greatest effect. The technique involves the following steps[1].

1. Identify the scope of the analysis by listing all items of concern by stock-keeping unit (SKU) number.

2. Collect pertinent data for each SKU, including item cost and demand (usage) over the past period of interest, one year in this case.

3. Determine the cost volume for each item for the period, equal to the item cost times the annual demand.

4. Sort the resulting data in descending cost volume order.

5. Determine cumulative percentages of the quantity of SKUs.

6. Determine cumulative percentages of the cost volume.

7. Graph the cumulative percentage of cost volume against the cumulative percentage of SKU quantity and determine break points for classification.

Completing this exercise for the Instron grip inventory project yields the graph shown in Figure 19 of Chapter 3. A sample of the data used to generate the graph is shown in Figure 36 below.

Note from the table that less than five percent of the SKUs (PctItem column) contribute almost sixty percent of the annual dollar volume (CumVpct column).

---

[1] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, pp. 32-35.

Item Number	Item Description	Std Cost	Demand	DV	Pct TDV	Cum Vpct	Pct Item
M202-5	Body	966.66	23	22,308	11.7%	0.0%	0.1%
M697-65	Body	457.34	101	46,354	7.1%	11.7%	0.3%
M299-32	Jaw Frame	151.12	62	9,333	4.3%	13.8%	0.4%
M564-57	Body	104.11	201	20,956	3.9%	14.7%	0.5%
M80-90	Carrier	389.73	31	12,231	2.1%	16.8%	0.7%
M57-51	Jaw Frame 20000 Lb	143.50	68	9,732	2.1%	17.7%	0.8%
M104-88	Housing S.E. Tension	1,473.28	7	10,037	2.1%	21.6%	0.9%
M318-80	Frame Pneumatic C	174.63	94	16,349	2.0%	23.5%	1.1%
M488-43	20 000 Jaw Frame	1,086.39	70	76,468	1.5%	25.0%	1.2%
M492-54	Upper & Lower Frame	72.77	118	8,622	1.5%	32.2%	1.3%
M267-53	Seal Metal Bellows	46.53	81	3,777	1.5%	36.5%	1.5%
M97-1	Block Stationary	111.19	145	16,131	1.4%	37.4%	1.6%
M594-44	Check Nut	28.31	553	15,653	1.3%	39.5%	1.7%
M587-65	Plunger Housing	23.32	581	13,550	1.2%	40.6%	1.9%
M215-90	Cord Tire Frame	173.35	84	14,627	1.1%	42.0%	2.0%
M159-39	Jaw Frame	145.30	11	1,590	1.0%	43.5%	2.1%
M121-66	Jaw Frame	446.67	20	9,100	1.0%	44.3%	2.3%
M755-37	Jaw Frame	324.16	127	41,301	0.9%	45.1%	2.4%
M619-61	Body, Grip, 300Kn	1,545.89	7	10,551	0.9%	46.3%	2.5%
M107-40	Jaw Frame	67.82	324	21,967	0.9%	47.6%	2.7%
M54-60	Upper & Lower Frame	259.29	87	22,496	0.9%	49.0%	2.8%
M513-22	Breco Socket 1As1-H	5.60	792	4,436	0.8%	49.4%	2.9%
M491-52	Rubber Face Screw	56.46	144	8,108	0.8%	49.8%	3.1%
M331-28	Jaw Holder-Right Dj	83.69	158	13,196	0.8%	50.1%	3.2%
M347-64	Piston Housing	74.78	61	4,558	0.6%	51.0%	3.3%
M198-93	Spindle	101.68	44	4,505	0.5%	52.0%	3.5%
M102-62	Knurled Knob Screws	37.59	141	5,295	0.5%	52.8%	3.6%
M344-14	Body Grip	87.26	74	6,499	0.5%	53.2%	3.7%
M637-87	Plunger	11.70	486	5,689	0.4%	53.7%	3.9%
M500-65	Multiplying Link	8.74	1,286	11,245	0.4%	54.3%	4.0%
M491-59	Body	314.08	16	4,893	0.4%	54.7%	4.1%
M788-47	Body, Screw Grip	28.52	113	3,230	0.4%	55.3%	4.3%
M470-92	Valve Cap	5.99	702	4,200	0.4%	55.7%	4.4%
M346-95	Pin Retaining Fj	8.89	1,126	10,010	0.3%	56.7%	4.6%
M640-23	Spindle 20000 Lb Jaw	119.53	46	5,456	0.1%	56.9%	4.7%
M690-53	Jaw Frame	380.90	330	125,663	0.0%	57.4%	4.8%

Figure 36. Sample Data from DBV Analysis

D

Job Shop Capacity Model

Chapter 2 introduces the capacity model to answer the question of how many grips to assemble at one time. This appendix describes the model in detail and provides the lot sizes for all fifty-six grips. Several "what-if" extensions are also included: first, the available labor hours are varied in both directions, then the nominal setup times are reduced, and finally, the work load of the job shop is expanded beyond EM grips to include the assembly of other accessories.

Baseline Case (1.7 Heads, 0.5 Hours Nominal Setup Time)

The baseline job shop capacity model is built within the Excel spreadsheet shown in Figure 37. The upper left corner of the spreadsheet (cells A1 through C6) contains the operating parameters for the work cell. Instron's cost of holding inventory is estimated at 30%. Instron's capital costs are estimated at 15%, property taxes, insurance, and storage costs are approximately 10%, and disposition costs are estimated at 5%.

There are 1880 hours each year (365 days times 5/7 days per week less ten holidays times 7.5 hours per day) and 157 hours each month (1880/12) per person. With staffing set at 1.7 heads as an initial estimate, the work cell has 3,197 hours available each year to complete the work.

Columns A and B of the spreadsheet list the 56 grips by model number. For each grip, the annual demand, setup time, run time, and standard cost are given as inputs to the model. The holding cost is calculated by multiplying the standard cost times the holding cost percentage in cell C1. The total run times are calculated in Column H by multiplying the annual demands times the individual run times.

As noted in Chapter 2, the optimum lot size for any one grip is derived from the economic lot size model. The optimum lot size (Q) balances setup or ordering costs (A) with holding costs (h) based on demand (D).

$$\textbf{Economic Lot Size } Q = \sqrt{(2 * A * D / h)}$$

Extension of the model to multiple grips is accomplished by converting the assembly times, demands, and holding costs to arrays and then inserting a Lagrangian multiplier, λ, common to all grips as a multiplier of the setup times[1].

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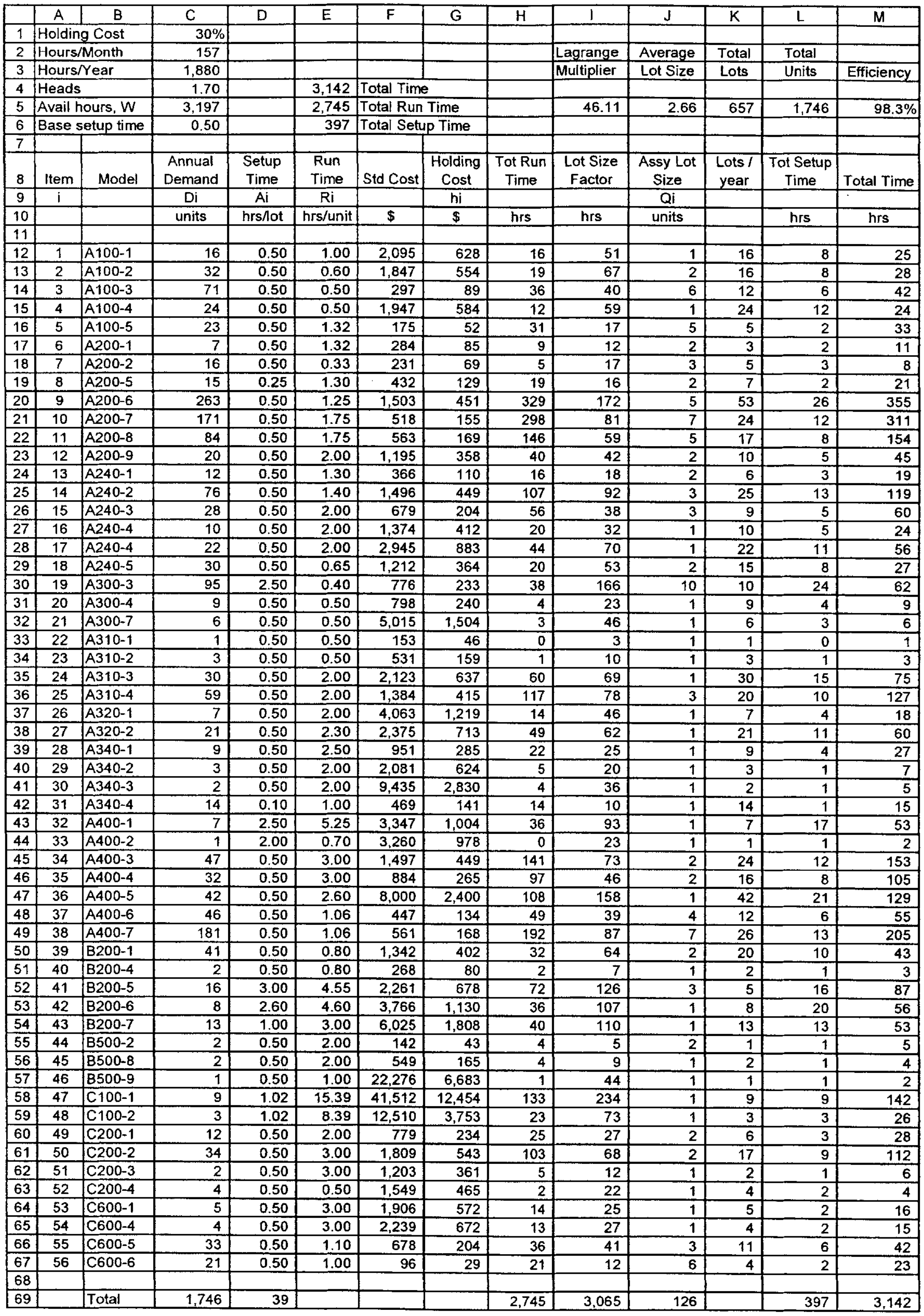
[1] Winston, W. L., "Introduction to Mathematical Programming," (1995), Duxbury Press, Belmont, California, p. 716.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Holding Cost		30%										
2	Hours/Month		157						Lagrange	Average	Total	Total	
3	Hours/Year		1,880						Multiplier	Lot Size	Lots	Units	Efficiency
4	Heads		1.70		3,142	Total Time							
5	Avail hours, W		3,197		2,745	Total Run Time			46.11	2.66	657	1,746	98.3%
6	Base setup time		0.50		397	Total Setup Time							
7													
8	Item	Model	Annual Demand	Setup Time	Run Time	Std Cost	Holding Cost	Tot Run Time	Lot Size Factor	Assy Lot Size	Lots / year	Tot Setup Time	Total Time
9	i		Di	Ai	Ri		hi			Qi			
10			units	hrs/lot	hrs/unit	$	$	hrs	hrs	units		hrs	hrs
11													
12	1	A100-1	16	0.50	1.00	2,095	628	16	51	1	16	8	25
13	2	A100-2	32	0.50	0.60	1,847	554	19	67	2	16	8	28
14	3	A100-3	71	0.50	0.50	297	89	36	40	6	12	6	42
15	4	A100-4	24	0.50	0.50	1,947	584	12	59	1	24	12	24
16	5	A100-5	23	0.50	1.32	175	52	31	17	5	5	2	33
17	6	A200-1	7	0.50	1.32	284	85	9	12	2	3	2	11
18	7	A200-2	16	0.50	0.33	231	69	5	17	3	5	3	8
19	8	A200-5	15	0.25	1.30	432	129	19	16	2	7	2	21
20	9	A200-6	263	0.50	1.25	1,503	451	329	172	5	53	26	355
21	10	A200-7	171	0.50	1.75	518	155	298	81	7	24	12	311
22	11	A200-8	84	0.50	1.75	563	169	146	59	5	17	8	154
23	12	A200-9	20	0.50	2.00	1,195	358	40	42	2	10	5	45
24	13	A240-1	12	0.50	1.30	366	110	16	18	2	6	3	19
25	14	A240-2	76	0.50	1.40	1,496	449	107	92	3	25	13	119
26	15	A240-3	28	0.50	2.00	679	204	56	38	3	9	5	60
27	16	A240-4	10	0.50	2.00	1,374	412	20	32	1	10	5	24
28	17	A240-4	22	0.50	2.00	2,945	883	44	70	1	22	11	56
29	18	A240-5	30	0.50	0.65	1,212	364	20	53	2	15	8	27
30	19	A300-3	95	2.50	0.40	776	233	38	166	10	10	24	62
31	20	A300-4	9	0.50	0.50	798	240	4	23	1	9	4	9
32	21	A300-7	6	0.50	0.50	5,015	1,504	3	46	1	6	3	6
33	22	A310-1	1	0.50	0.50	153	46	0	3	1	1	0	1
34	23	A310-2	3	0.50	0.50	531	159	1	10	1	3	1	3
35	24	A310-3	30	0.50	2.00	2,123	637	60	69	1	30	15	75
36	25	A310-4	59	0.50	2.00	1,384	415	117	78	3	20	10	127
37	26	A320-1	7	0.50	2.00	4,063	1,219	14	46	1	7	4	18
38	27	A320-2	21	0.50	2.30	2,375	713	49	62	1	21	11	60
39	28	A340-1	9	0.50	2.50	951	285	22	25	1	9	4	27
40	29	A340-2	3	0.50	2.00	2,081	624	5	20	1	3	1	7
41	30	A340-3	2	0.50	2.00	9,435	2,830	4	36	1	2	1	5
42	31	A340-4	14	0.10	1.00	469	141	14	10	1	14	1	15
43	32	A400-1	7	2.50	5.25	3,347	1,004	36	93	1	7	17	53
44	33	A400-2	1	2.00	0.70	3,260	978	0	23	1	1	1	2
45	34	A400-3	47	0.50	3.00	1,497	449	141	73	2	24	12	153
46	35	A400-4	32	0.50	3.00	884	265	97	46	2	16	8	105
47	36	A400-5	42	0.50	2.60	8,000	2,400	108	158	1	42	21	129
48	37	A400-6	46	0.50	1.06	447	134	49	39	4	12	6	55
49	38	A400-7	181	0.50	1.06	561	168	192	87	7	26	13	205
50	39	B200-1	41	0.50	0.80	1,342	402	32	64	2	20	10	43
51	40	B200-4	2	0.50	0.80	268	80	2	7	1	2	1	3
52	41	B200-5	16	3.00	4.55	2,261	678	72	126	3	5	16	87
53	42	B200-6	8	2.60	4.60	3,766	1,130	36	107	1	8	20	56
54	43	B200-7	13	1.00	3.00	6,025	1,808	40	110	1	13	13	53
55	44	B500-2	2	0.50	2.00	142	43	4	5	2	1	1	5
56	45	B500-8	2	0.50	2.00	549	165	4	9	1	2	1	4
57	46	B500-9	1	0.50	1.00	22,276	6,683	1	44	1	1	1	2
58	47	C100-1	9	1.02	15.39	41,512	12,454	133	234	1	9	9	142
59	48	C100-2	3	1.02	8.39	12,510	3,753	23	73	1	3	3	26
60	49	C200-1	12	0.50	2.00	779	234	25	27	2	6	3	28
61	50	C200-2	34	0.50	3.00	1,809	543	103	68	2	17	9	112
62	51	C200-3	2	0.50	3.00	1,203	361	5	12	1	2	1	6
63	52	C200-4	4	0.50	0.50	1,549	465	2	22	1	4	2	4
64	53	C600-1	5	0.50	3.00	1,906	572	14	25	1	5	2	16
65	54	C600-4	4	0.50	3.00	2,239	672	13	27	1	4	2	15
66	55	C600-5	33	0.50	1.10	678	204	36	41	3	11	6	42
67	56	C600-6	21	0.50	1.00	96	29	21	12	6	4	2	23
68													
69		Total	1,746	39				2,745	3,065	126		397	3,142

Figure 37. Job Shop Capacity Model

The subscript *i* in the following formula denotes the individual grip models.

$$Q_i = \sqrt{(2 * \lambda * A_i * D_i / h_i)}$$

By adding the sum of all the setup times to the sum of all the assembly times and setting the result equal to the total available labor, we can solve for lambda (λ) and then calculate all of the lot sizes. In economic terms, λ is a shadow price representing the implicit cost of time[1].

$$W = \sum (A_i * D_i / Q_i) \quad + \quad \sum (D_i * R_i)$$

In the above equation, R_i is the assembly run time in hours per unit and D_i / Q_i equals the number of lots built each year. Substituting the expression for Q_i into the equation for W and then solving for lambda yields the following result:

$$\lambda = \left(\frac{\sum (D_i * A_i * \sqrt{h_i / (2 * D_i * A_i)})}{W - \sum (D_i * R_i)} \right)^2$$

The numerator of the term within the outermost parentheses is the sum of 56 "lot size factors." The lot size factors depend on parameters unique to each grip and are tabulated in Column I of Figure 37. The value of lambda is shown in cell I5. For this case it has a dimensionless value of 46.11.

The assembly lot sizes are then calculated using the economic lot size formula and are presented in Column J of the spreadsheet. For the base case (1.7 heads and 0.5 hours nominal setup time), the assembly lot sizes vary from a forced minimum of one to a maximum of ten. The maximum finished goods inventory can be estimated by multiplying the lot size times the standard cost for each item, then summing these values. Dividing this maximum in half yields the expected finished goods inventory; for the baseline case, the value is indexed at 110.

Several other statistics are shown in the spreadsheet, including lots per year, total setup time, total time, and per piece time for each grip. Aggregate statistics are also given across the top of the sheet, most notably the efficiency rating in the upper right corner. The value of 98.3% looks good from an efficiency point of view (the workers are almost always busy), but can be troublesome from a queuing theory point of view (as efficiency approaches 100%, the queue length grows to infinity).

---

[1] Rosenfield, D. B., and A. W. Drake, advisors to the internship, June-Dec. 1999.

The Tradeoff between Labor and Inventory

Management is interested in the model's predictions when the labor hours are varied. What happens when there are more and less than 1.7 heads assigned to the job shop, and is there an optimal level for staffing?

The absolute minimum number of labor hours is found by summing all the run times for the grips needed to satisfy annual demand and adding to this number one setup time for each grip; the result is 2784 hours, or about 1.5 heads. In this minimum staffing case, each catalog number is assembled only once or twice each year and the lot sizes are large enough to satisfy annual demand. Some low-volume grips are assembled in lot sizes that span several years of demand.

The average lot size increases from 2.7 for the baseline case to 14.5 for the minimum staffing case. Efficiency is 99.9% and average inventory soars to an indexed value of 432. The annual holding costs on the 322-point increase in inventory value is offset by only 19 index points in labor savings.

On the other end of the spectrum, the maximum realistic number of labor hours can be found by assuming that more common grips are built in lot sizes of one unit each. Adding the run times and setup times for each grip, multiplying by the annual demand, and then summing the result yields a total labor hour requirement of 3882 hours, or about two heads. With this value as an input, the model's solution causes the average lot size to decrease to 1.5. This value is 1.5 (rather than 1.0) because the less common grips are allowed to be larger. For this case, the efficiency drops to 92% and the average inventory index drops slightly to 88.

The decrease in holding costs of 6.5 points is more than offset by the annual increase in labor expense of over 24 points. As Figure 38 shows, the optimal staffing level is somewhere near 1.7 heads.

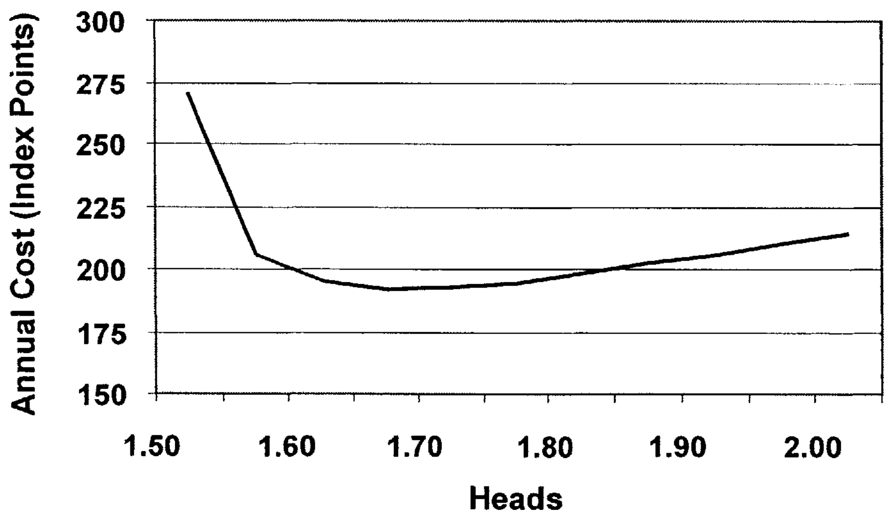


Figure 38. Tradeoff Between Labor and Inventory

Reducing Setup Times Also Reduces Lot Sizes and Inventory

A second "what if" analysis is concerned with setup time reduction. For many of the grips, the mechanics are allocated thirty minutes for setting up the assembly process. Activities include gathering consumables and tools, picking and unwrapping component details, and cleaning and straightening the assembly area. If this nominal half hour can be reduced to fifteen minutes while maintaining the same total labor hours, then the available time for setup can be spread across more lots, and the lot sizes decrease. The model suggests an average decrease from 2.7 units per lot to 1.75 units per lot. Efficiency drops from 98.3% to 96.8% and the average inventory index drops from 110 to 94.

Adding Accessories Completes the Picture

The scope of the inventory reduction project was set by Instron management to include all EM grip hardware. The job shop responsible for EM grip assembly, however, is also responsible for assembling a wide variety of accessories for EM machines. Examples of these accessories are pneumatic foot switches, tension couplings, and test fixtures. The job shop assembles a total of 183 unique catalog numbers, of which 56 are EM grips. Pertinent statistics for this extension of the product line follow.

	Grips	All Accessories
Catalog Numbers	56	183
Annual Demand (units)	1746	4735
Total Run Time (hrs)	2745	3264
Minimum Setup Time (hrs)	39	15
Minimum Total Time (hrs)	2784	3279
Maximum Total Time (hrs)	3882	4632
Minimum Staffing (heads)	1.5	1.74
Maximum Staffing (heads)	2.0	2.46
Optimal Staff (heads)	1.7	1.95
Average inventory (index)	110	136

Although the annual demand for non-grip accessories is twice that of the grips, many of these products take only a few minutes to assemble. As the total run time statistics show, the grips account for about eighty percent of the job shop load.

Applying the same minimum and maximum conditions as above, the optimum level of staffing for the job shop is just under two heads. The average lot size is three units per lot and efficiency remains at 98%.

E

Job Shop Queues

As described in Appendix D, the capacity model budgets the available labor hours across the 56 grips so that the job shop can complete its annual work load. The model tends to use every available labor hour, driving worker utilization to almost 100%. This high level of utilization can be desirable when demand is deterministic, but leads to congestion and queuing when demand is probabilistic. Queuing theory helps identify the reserve capacity needed to relieve congestion[1].

A simplified case using the M/M/1 system is presented first to develop the queuing theory concepts applied to the job shop. This system assumes Poisson arrivals and exponential service times[2]. The M/M/1 system also assumes a single server rather than the 1.8 heads recommended by the capacity model; restricting the workload to that seen by Canton alone (before the supply chain consolidation) allows a reasonable application. The restriction is then lifted and the M/M/c model is applied, with $c = 2$ workers. A final case restricts the load once again, but releases the service time distribution from exponential to general, the M/G/1 system.

Baseline Case: Canton Demand and M/M/1

The Canton workload is 1048 jobs per year, a subset of the company-wide load of 1746 jobs. A single server or mechanic represents 1880 hours per year of available labor. This capacity can also be interpreted as the hours during which the job shop is open for business and able to serve customers. The job arrival rate is then

$$\lambda = \frac{1048 \text{ jobs / year}}{1880 \text{ hours / year}} = 0.5571 \text{ jobs/hour.}$$

---

[1] Rosenfield, D. B., and A. W. Drake, advisors to the internship, June-Dec. 1999.

[2] Bertsekas, D., and R. Gallagher, "Data Networks," 2nd ed. (1992), Prentice Hall, Upper Saddle River, NJ, pp 162-166.

From the capacity model with one head, the 1048 jobs require 1647 hours in run time and 214 hours in setup time, totaling 1861 hours per year. The service rate is therefore

$$\mu = \frac{1048 \text{ jobs / year}}{1861 \text{ hours / year}} = 0.5630 \text{ jobs/hour.}$$

The utilization is the ratio of the arrival rate to the service rate, or 0.9895. Application of the equations for the expected values for waiting time, queue length, time in the system, and total number of jobs in the system is straightforward[1].

Expected waiting time, $E\{W_q\} = \lambda / (\mu * (\mu - \lambda)) = 168$ hours.

Expected queue length, $E\{L_q\} = \rho^2 / (1 - \rho) = 93.2$ jobs.

Expected system time, $E\{W\} = 1 / (\mu - \lambda) = 169$ hours.

Expected number in system, $E\{L\} = \rho / (1 - \rho) = 94.2$ jobs.

Of more interest is the waiting time distribution. For the M/M/1 system, the distribution is[2]:

$$W_q(t) = \begin{cases} 1 - \rho & t = 0 \\ 1 - \rho e^{-\mu(1-\rho)t} & t > 0 \end{cases}$$

The waiting time distribution is graphed in Figure 39. Note that only fifty percent of the jobs are completed within two weeks and it takes more than nine weeks to complete 95% of the jobs. These levels are unacceptable, so some reserve capacity must be added.

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[1] Bertsekas, D., and R. Gallagher, "Data Networks," 2nd ed. (1992), Prentice Hall, Upper Saddle River, NJ, p. 266.

[2] Gross, D., and C. M. Harris, "Fundamentals of Queueing Theory," 2nd ed. (1985), John Wiley & Sons, New York, p. 76.

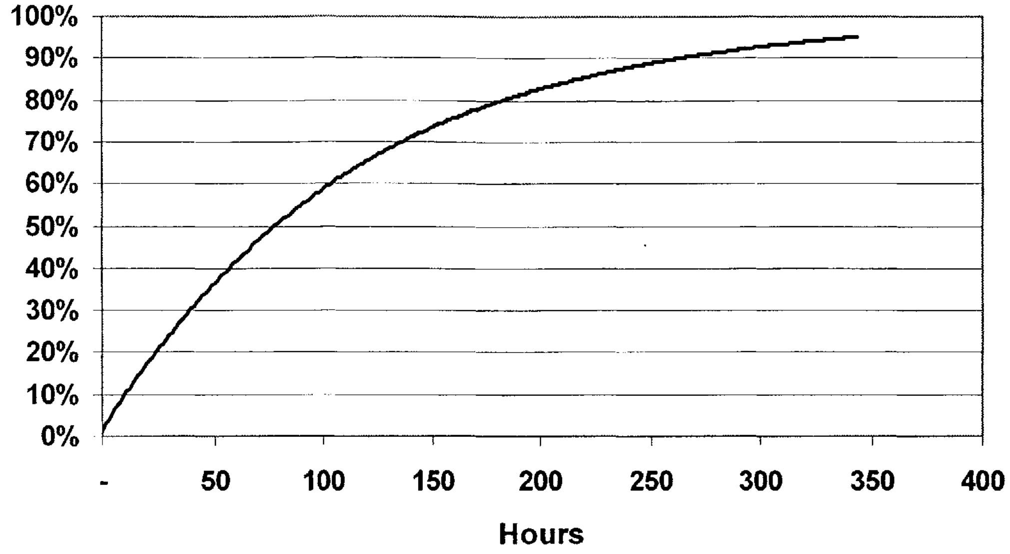

Figure 39. M/M/1 Waiting Time Distribution

The reserve needed to complete 95% of the jobs within two weeks can be found by setting the distribution equation equal to 0.95 and solving for rho for the desired time period. In this case, set t = 73.2 hours (75 hours of total time for two weeks less the average assembly time of 1.8 hours). Rho equals 0.9287, which scales the available hours down from 1880 to 1746 and results in a capacity reserve of 134 hours per year. Figure 40 presents this analysis for comparison with Figure 37 in Appendix D.

With these new values, the capacity model specifies only 98 hours of setup time (down from 214). The service rate increases to 0.6004 jobs/hour and utilization drops to .9279 as desired. The expected values of waiting times and queue lengths all decrease as well.

Expected waiting time, $E\{W_q\}$ = 20.9 hours.

Expected queue length, $E\{L_q\}$ = 11.6 jobs.

Expected system time, $E\{W\}$ = 22.6 hours.

Expected number in system, $E\{L\}$ = 12.5 jobs.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Holding Cost		30%		0.9279	Utilization = rho								
2	Hours/Month		157		0.5571	Arr rate = lambda								
3	Hours/Year		1,880		0.6004	Svc rate = mu			Lagrange	Average	Total	Total	w/o Rsrv	w/ Rsrv
4	Heads		1.00		1.6656	Avg time = 1/mu			Multiplier	Lot Size	Lots	Units	Efficiency	Efficiency
5	Reserve factor		0.9287		1,745	Total Time								
6	Avail hours, W		1,746		1,647	Total Run Time			573.28	6.50	161	1,048	99.9%	92.8%
7	Base setup time		0.50		98	Total Setup Time								
8														
9	Item	Catalog	Canton Demand	Setup Time	Run Time	Std Cost	Holding Cost	Tot Run Time	Lot Size Factor	Assy Lot Size	Lots / year	Tot Setup Time	Total Time	Per Piece Time
10	i		Si	Ai	Ri		hi			Qi				
11			units	hrs/lot	hrs/unit	$	$	hrs	hrs	units		hrs	hrs	hrs
12														
13	1	A100-1	10	0.50	1.00	2,095	628	10	39	3	3	2	12	1.17
14	2	A100-2	19	0.50	0.60	1,847	554	12	52	4	5	2	14	0.73
15	3	A100-3	43	0.50	0.50	297	89	21	31	17	3	1	23	0.53
16	4	A100-4	14	0.50	0.50	1,947	584	7	46	4	4	2	9	0.63
17	5	A100-5	14	0.50	1.32	175	52	18	14	12	1	1	19	1.36
18	6	A200-1	4	0.50	1.32	284	85	5	9	5	1	0	6	1.42
19	7	A200-2	10	0.50	0.33	231	69	3	13	9	1	1	4	0.39
20	8	A200-5	9	0.25	1.30	432	129	12	12	4	2	1	12	1.36
21	9	A200-6	158	0.50	1.25	1,503	451	197	133	14	11	6	203	1.29
22	10	A200-7	102	0.50	1.75	518	155	179	63	19	5	3	182	1.78
23	11	A200-8	50	0.50	1.75	563	169	88	46	13	4	2	90	1.79
24	12	A200-9	12	0.50	2.00	1,195	358	24	33	4	3	2	26	2.13
25	13	A240-1	7	0.50	1.30	366	110	10	14	6	1	1	10	1.38
26	14	A240-2	46	0.50	1.40	1,496	449	64	72	8	6	3	67	1.46
27	15	A240-3	17	0.50	2.00	679	204	33	29	7	2	1	35	2.07
28	16	A240-4	6	0.50	2.00	1,374	412	12	25	3	2	1	13	2.17
29	17	A240-4	13	0.50	2.00	2,945	883	27	54	3	4	2	29	2.17
30	18	A240-5	18	0.50	0.65	1,212	364	12	41	5	4	2	14	0.75
31	19	A300-3	57	2.50	0.40	776	233	23	129	27	2	5	28	0.49
32	20	A300-4	5	0.50	0.50	798	240	3	18	4	1	1	3	0.63
33	21	A300-7	3	0.50	0.50	5,015	1,504	2	36	1	3	2	3	1.00
34	22	A310-1	0	0.50	0.50	153	46	0	2	2	0	0	0	0.75
35	23	A310-2	2	0.50	0.50	531	159	1	8	2	1	0	1	0.75
36	24	A310-3	18	0.50	2.00	2,123	637	36	54	4	5	2	38	2.13
37	25	A310-4	35	0.50	2.00	1,384	415	70	60	7	5	3	73	2.07
38	26	A320-1	4	0.50	2.00	4,063	1,219	8	36	1	4	2	11	2.50
39	27	A320-2	13	0.50	2.30	2,375	713	29	48	3	4	2	32	2.47
40	28	A340-1	5	0.50	2.50	951	285	13	20	3	2	1	14	2.67
41	29	A340-2	2	0.50	2.00	2,081	624	3	16	1	2	1	4	2.50
42	30	A340-3	1	0.50	2.00	9,435	2,830	2	28	1	1	1	3	2.50
43	31	A340-4	8	0.10	1.00	469	141	8	8	3	3	0	8	1.03
44	32	A400-1	4	2.50	5.25	3,347	1,004	22	72	3	1	3	25	6.08
45	33	A400-2	0	2.00	0.70	3,260	978	0	18	1	0	1	1	2.70
46	34	A400-3	28	0.50	3.00	1,497	449	85	56	6	5	2	87	3.08
47	35	A400-4	19	0.50	3.00	884	265	58	36	6	3	2	60	3.08
48	36	A400-5	25	0.50	2.60	8,000	2,400	65	122	2	12	6	71	2.85
49	37	A400-6	28	0.50	1.06	447	134	29	30	11	3	1	31	1.11
50	38	A400-7	109	0.50	1.06	561	168	115	68	19	6	3	118	1.09
51	39	B200-1	24	0.50	0.80	1,342	402	19	49	6	4	2	21	0.88
52	40	B200-4	1	0.50	0.80	268	80	1	5	3	0	0	1	0.97
53	41	B200-5	9	3.00	4.55	2,261	678	43	98	7	1	4	47	4.98
54	42	B200-6	5	2.60	4.60	3,766	1,130	22	83	4	1	3	25	5.25
55	43	B200-7	8	1.00	3.00	6,025	1,808	24	85	2	4	4	28	3.50
56	44	B500-2	1	0.50	2.00	142	43	3	4	4	0	0	3	2.13
57	45	B500-8	1	0.50	2.00	549	165	2	7	2	1	0	2	2.25
58	46	B500-9	1	0.50	1.00	22,276	6,683	1	34	1	1	0	1	1.50
59	47	C100-1	5	1.02	15.39	41,512	12,454	80	181	1	5	5	85	16.41
60	48	C100-2	2	1.02	8.39	12,510	3,753	14	56	1	2	2	16	9.41
61	49	C200-1	7	0.50	2.00	779	234	15	21	4	2	1	16	2.13
62	50	C200-2	21	0.50	3.00	1,809	543	62	53	5	4	2	64	3.10
63	51	C200-3	1	0.50	3.00	1,203	361	3	9	1	1	0	3	3.50
64	52	C200-4	3	0.50	0.50	1,549	465	1	17	2	1	1	2	0.75
65	53	C600-1	3	0.50	3.00	1,906	572	8	20	2	1	1	9	3.25
66	54	C600-4	3	0.50	3.00	2,239	672	8	21	1	3	1	9	3.50
67	55	C600-5	20	0.50	1.10	678	204	22	32	7	3	1	23	1.17
68	56	C600-6	13	0.50	1.00	96	29	13	10	16	1	0	13	1.03
69														
70		Total	1,048	39				1,647	2,374	316		98	1,745	

Figure 40. M/M/1 Job Shop with Reserve Capacity

The waiting time distribution is graphed in Figure 41. Note that 95% of all jobs are now completed within two weeks. The lot sizes increase, however, to offset this benefit with higher average inventory. With no reserve, the average inventory index is about 117; with the seven percent labor reserve, the average inventory index grows to 204, a seventy percent increase.

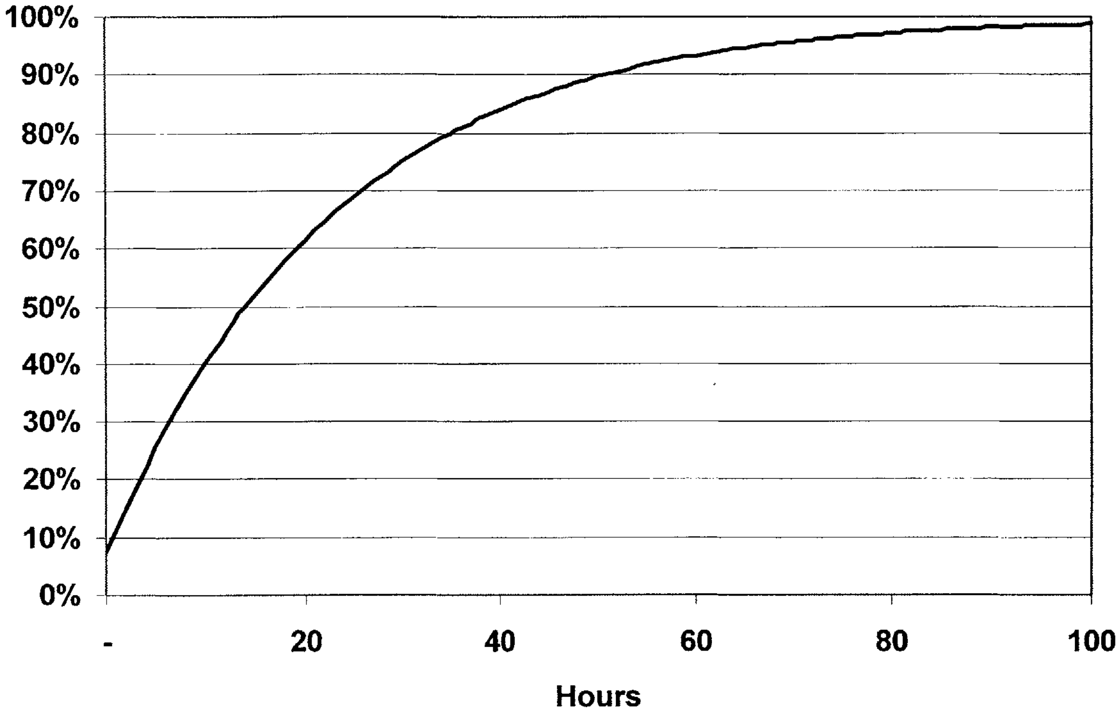

Figure 41. Waiting Time Distribution with Reserve Capacity

Full Demand and M/M/c

The first extension to the baseline case includes the total demand and assumes additional mechanics (servers). The workload grows to 1746 jobs per year. The job shop is "open for business" for the same number of hours as in the baseline case, however, so the arrival rate is now 1746/1880, or 0.9287 jobs / hour.

Assuming one additional mechanic (c = 2), the capacity model specifies a total run time of 2669 hours and a total setup time of 743 hours, effectively the maximum setup time (the average lot size is 1.3 units). The total service time is their sum, 3412 hours per year, and the service rate is 1746/3412 or 0.5117 jobs/hour. The utilization for the M/M/2 system is $\rho = \lambda / c\mu$, in this case equal to 0.9074.

The expressions for the expected waiting time and queue lengths are more complicated than in the M/M/1 system and depend on the probability of there being no jobs in the system upon arrival, p_0 and on the probability of a job having to wait upon arrival, P_Q[1].

$$p_0 = \left(\sum_{k=0}^{c-1} \frac{(c\rho)^k}{k!} + \frac{(c\rho)^c}{c!\,(1-\rho)} \right)^{-1} \qquad P_Q = \frac{p_0 * (c\rho)^c}{c! * (1-\rho)}$$

In this case, $p_0 = 0.0485$ and $P_Q = 0.8625$. There's a five percent chance of finding no jobs in the shop upon arrival and an 86 percent chance of finding a queue upon arrival. Expectations of waits and queues are shown below[2].

Expected waiting time, $E\{W_q\} = \rho * P_Q / (\lambda(1-\rho)) = 9.15$ hours.

Expected queue length, $E\{L_q\} = \rho * P_Q / (1-\rho) = 10$ jobs.

Expected system time, $E\{W\} = (1/\mu) + \rho * P_Q / (\lambda(1-\rho)) = 11$ hours.

Expected number in system, $E\{L\} = (c * \rho) + (\rho * P_Q)/(1-\rho) = 12$ jobs.

The waiting time distribution for the M/M/c system is also complicated[3]:

$$W_q(t) = \begin{cases} 1 - \dfrac{c(\lambda/\mu)^c}{c!\,(c-\lambda/\mu)} & t = 0 \\[2ex] \dfrac{(\lambda/\mu)^c\,(1-e^{-(\mu c-\lambda)t})}{(c-1)!\,(c-\lambda/\mu)}\, p_0 + W_q(0) & t > 0 \end{cases}$$

With two servers, 95% of the jobs are completed within 30 hours. This result fits well with the capacity model's prediction of only 90% utilization; the workers are idle ten percent of the time and most jobs are finished within one week. So there's already reserve capacity in the system.

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[1] Bertsekas, D., and R. Gallagher, "Data Networks," 2nd ed. (1992), Prentice Hall, Upper Saddle River, NJ, p. 267.

[2] *Ibid*, p. 267.

[3] Gross, D., and C. M. Harris, "Fundamentals of Queueing Theory," 2nd ed. (1985), John Wiley & Sons, New York, p. 90.

Unfortunately, the M/M/c model does not lend itself readily to fractional servers, due to the presence of factorials in the equations. An approximation can be made however, using Stirling's formula for factorials[1]:

$$n! = e^{-n} n^{n} \sqrt{2\pi n}, \text{ approximately}$$

Values of $n = 1.7$ and $n = 1.8$ lead to 95% completion times of 106 hours and 55 hours, respectively, which are roughly in line with the result for $c = 2$.

General Service Time Distribution, M/G/1

Figure 15 of Chapter 2 shows the grip assembly time distribution. The mean assembly time is just over 1.5 hours and the standard deviation is very close to one hour. The shape of the distribution curve is much more normal than exponential, so it makes sense to check the reserve capacity calculations against a general distribution.

The expected waiting times and queue lengths for the M/G/1 system can be found from the following equations[2]:

$$\text{Expected waiting time, } E\{W_q\} = \lambda \overline{X^2} / (2 * (1 - \rho)) = 60 \text{ hours.}$$

$$\text{Expected queue length, } E\{L_q\} = \lambda^2 \overline{X^2} / (2 * (1 - \rho)) = 33 \text{ jobs.}$$

$$\text{Expected system time, } E\{W\} = 1/\mu + E\{W_q\} = 62 \text{ hours.}$$

$$\text{Expected number in system, } E\{L\} = \rho + E\{L_q\} = 34 \text{ jobs.}$$

Note[3] that $\overline{X^2} = \mu^2 + \sigma^2$.

Again, the average inventory increases when reserve capacity is added. With no reserve and 1.7 heads, the average inventory index is about 110; adding the reserve increases this value to 151, a 37% boost. With 1.8 heads, the penalty is not as severe: the reserve increases the average inventory index only fifteen percent from 101 to 115.

The above values were calculated using the actual service time parameters and compare reasonably well with the results from the M/M/1 system analysis. Closed form solutions are increasingly difficult to find as the queuing model complexity grows, highlighting the value of

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[1] Beyer, W. H., "Standard Mathematical Tables," 25th ed. (1978), CRC Press Inc., Boca Raton, FL, p. 76.

[2] Bertsekas, D., and R. Gallagher, "Data Networks," 2nd ed. (1992), Prentice Hall, Upper Saddle River, NJ, p. 268.

[3] Walpole, R. E., and R. H. Myers, "Probability and Statistics for Engineers and Scientists," 5th ed. (1993), Prentice Hall, Englewood Cliffs, NJ, p. 93.

simulation models. The general result from this queuing theory analysis for the Instron job shop is the recommendation to reserve about seven percent of the available labor hours in the capacity model before determining optimal assembly lot sizes. .

F

Job Shop Simulation

As Appendix E points out, finding a close formed solution for the capacitated job shop under probabilistic demand presents a difficult problem. Simulation of the operating conditions provides a measure of confidence in the outcome of the analysis and a means to test various "what-if" scenarios. This appendix presents an Excel spreadsheet simulation of the job shop.

During a simulation run, the model generates a highly structured random number to simulate daily demand for each grip, filling the demand from stock if available, checking reorder points, and scheduling a daily build plan. The model provides the daily load as its primary output, along with a ten-day moving average and projected idle times and overtime periods. To ease development and understanding, the simulation model is separated into five main sections: input, demand, stock, build, and output.

Input Section

A sample of the input section is shown in Figure 42 for a staffing level of 1.8 heads. This section contains the operating parameters for the job shop, including the setup and run times, lot sizes

Input Section											
Base Setup	0.50		Global Init QOH			1					
Heads	1.80		Global ROP			-					
Hours / day	7.83										
Avail hrs	14.1						Daily Demand for				
				Lot			Each Month in Qtr				Init
Models	Setup	Run	Qi	Time	ROP		1st	2nd	3rd		QOH
A100-1	0.50	1.00	1	1.5	-		0.06	0.10	0.13		1
A100-2	0.50	0.60	2	1.7	-		0.14	0.22	0.31		1
A100-3	0.50	0.50	3	2.0	-		0.34	0.37	0.68		1
A100-4	0.50	0.50	2	1.5	-		0.18	0.23	0.32		1
A100-5	0.50	1.32	2	3.1	-		0.10	0.09	0.23		1
A200-1	0.50	1.32	1	1.8	-		0.02	0.03	0.09		1
A200-2	0.50	0.33	1	0.8	-		0.02	0.02	0.03		1
A200-5	0.25	1.30	1	1.6	-		0.09	0.09	0.19		1
A200-6	0.50	1.25	3	4.3	-		0.38	0.49	0.84		1
A200-7	0.50	1.75	4	7.5	-		0.52	0.62	1.20		1
A200-8	0.50	1.75	3	5.8	-		0.35	0.53	0.79		1

Figure 42. Simulation Input Section

from the capacity model, and daily demand probabilities for each grip, as well as the overall staffing level, base setup time, and labor hours per day. Global variables for the initial quantities on hand and reorder points are available to simplify analysis of various policies.

The daily demand probabilities are derived from four and a half years (18 quarters) of historical usage. The quarterly hockey stick pattern is randomly generated by taking the average of the 18 values in the first, second, and third months of each quarter for each grip. For example, the monthly demands for the A200-8 grip are shown in Figure 43.

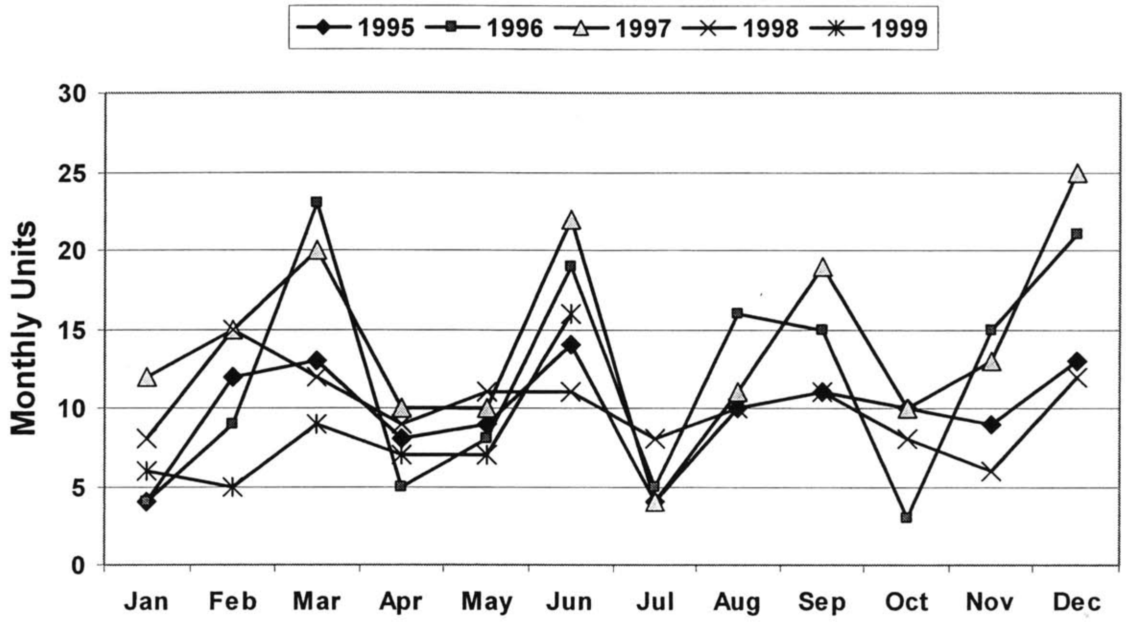


Figure 43. Monthly Demand for the A200-8 Grip

Averaging the five January, five April, four July, and four October values yields a mean of about seven grips for the first month of any quarter. The second and third months average out to eleven and fifteen grips, respectively. Dividing these values by twenty provides the daily probabilities of demand, namely 0.35, 0.53, and 0.79 (as shown in the bottom row of Figure 41). For the A200-8 grips, on each day of the first month in a quarter, there is a 35% probability that an order will occur. The probability of an order rises to 53% for each day during the second month and to 79% during the third month.

Demand Section

Figure 44 presents the first two weeks of the demand section of the spreadsheet. Each column represents one workday and each row corresponds to a specific grip. The model generates a random number between 0 and 1 for each grip for each day in the spreadsheet. If the random number is greater than the probability of an order occurring on that day based on the thresholds specified in the input section, then an order signal is generated.

Demand Section	1	2	3	4	5	6	7	8	9	10
Month	1	1	1	1	1	1	1	1	1	1
Week	1	1	1	1	1	2	2	2	2	2
Day	1	2	3	4	5	1	2	3	4	5
New Demand										
A100-1	-	-	-	-	-	-	-	-	-	-
A100-2	-	1	1	-	-	-	-	1	-	-
A100-3	-	1	1	1	-	-	-	-	1	-
A100-4	-	-	-	-	-	-	-	-	-	-
A100-5	1	-	-	-	-	-	-	-	-	-
A200-1	-	-	-	-	-	-	-	-	-	-
A200-2	-	-	-	-	-	-	-	-	-	-
A200-5	-	-	-	-	-	-	-	1	-	-
A200-6	-	1	-	1	-	1	-	-	-	-
A200-7	-	1	-	1	-	1	1	1	-	1
A200-8	-	-	-	-	1	1	1	1	1	-

Figure 44. Simulation Demand Section

The demand section also has 56 rows to store unfilled demand from the previous day. Unfilled demand can result from a series of orders during the peak demand period. These unfilled orders are added to any new orders for each day and passed on to the stock section of the model.

Stock Section

The purpose of the stock section is to keep track of on-the-shelf inventory. There are five subsections to track sunrise stock at the beginning of each day, the daily demand that is filled, the demand that is not filled due to shortages, the inventory level after demand is filled, and the sunset stock level after new grips are built. Figure 45 shows the first two weeks of the sunrise stock subsection (each column represents one day).

Stock Section										
Sunrise Stock										
A100-1	1	1	1	1	1	1	1	1	1	1
A100-2	1	1	1	1	2	2	1	1	1	1
A100-3	1	1	3	3	3	2	2	2	1	1
A100-4	1	1	1	1	1	1	1	1	1	2
A100-5	1	1	1	1	1	2	2	2	1	1
A200-1	1	1	1	1	1	1	1	1	1	1
A200-2	1	1	1	1	1	1	1	1	1	1
A200-5	1	1	1	1	1	1	1	1	1	1
A200-6	1	1	3	3	3	2	1	1	1	3
A200-7	1	4	4	3	3	3	2	1	1	4
A200-8	1	3	3	2	2	2	1	3	2	1

Figure 45. Sunrise Stock Subsection

The sunrise stock is equal to the sunset stock from the previous day. For the first day of the simulation, the sunrise stock is equal to the initial quantity-on-hand global variable. If the sunrise stock is greater than the demand, then demand is filled from stock. If the sunrise stock cannot cover demand, then the stock is depleted and the unfilled demand is stored as an input to the next day's demand review.

The inventory level after daily demand has been satisfied is stored in its own subsection; grips that are built (as determined by the following section) are then added to this "after demand" level to equal the sunset stock.

Build Section

The build section begins by generating pull signals for all 56 grips. For each grip, if the "after demand" level of stock is less than or equal to the reorder point, then a pull signal is generated. Setup and run times for each pull are calculated using the assembly lot size quantities from the capacity model. The section provides a build plan, partially shown in Figure 46, specifying how many grips of each model to build each day.

Build Plan (Units)										
A100-1	-	-	-	-	-	-	-	-	-	1
A100-2	-	-	2	-	-	-	-	-	-	-
A100-3	-	-	3	-	-	-	3	-	-	-
A100-4	-	-	-	-	-	2	-	-	-	-
A100-5	-	-	2	-	-	-	-	-	-	-
A200-1	1	-	-	-	-	-	-	-	-	-
A200-2	-	-	-	-	-	-	-	-	-	-
A200-5	-	-	-	-	-	-	-	-	-	-
A200-6	-	3	-	-	-	-	-	-	-	3
A200-7	4	-	-	-	-	-	-	-	4	-
A200-8	-	3	-	-	-	-	3	-	-	-

Figure 46. Simulation Build Section

The build section also sums all of the setup and run times for each grip to arrive at the total hours required for the daily build. These values are used by the output section.

Output Section

The output section analyzes the load characteristics and presents the simulation results. It begins by dividing the total hours by the number of hours available per day per person to yield the daily staffing requirement in heads. A ten-day moving average value is also calculated and the two are shown together in Figure 47 for six months.

The average load across the graph is about 1.7 heads. The load exceeds the job shop's daily capacity fairly regularly, but with a ten-day cycle time requirement, the load becomes excessive only in the third month of each quarter. The practical response to this period of peak demand is to authorize overtime or shift an additional worker to the job shop.

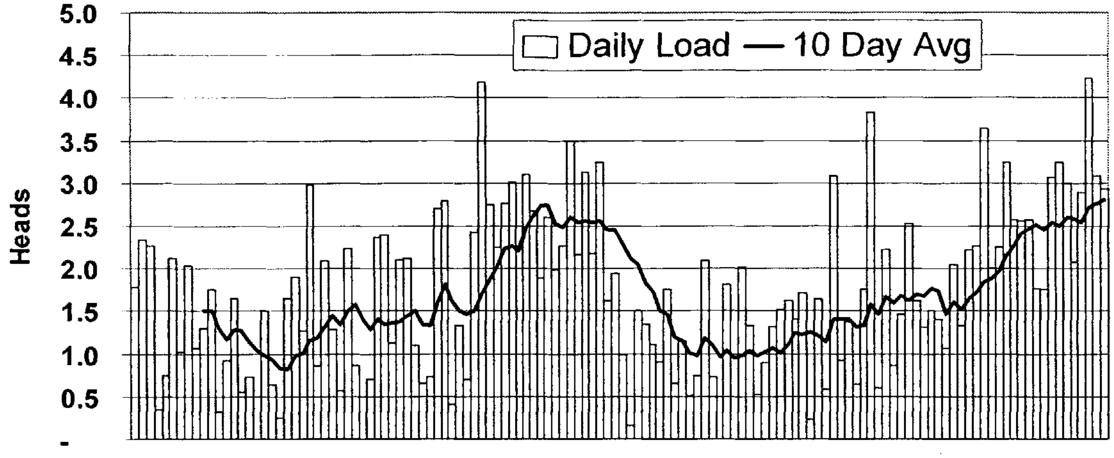


Figure 47. Simulated Job Shop Loading

The output section also calculates average finished goods inventory levels. After repeated simulation runs, the average index level is around 145. This relatively high level compared to the expected output of 85 index points from the capacity model is due to the simplifying assumption of a global quantity-on-hand variable. Many of the low-volume grips should not be held in finished goods at all, but made to order.

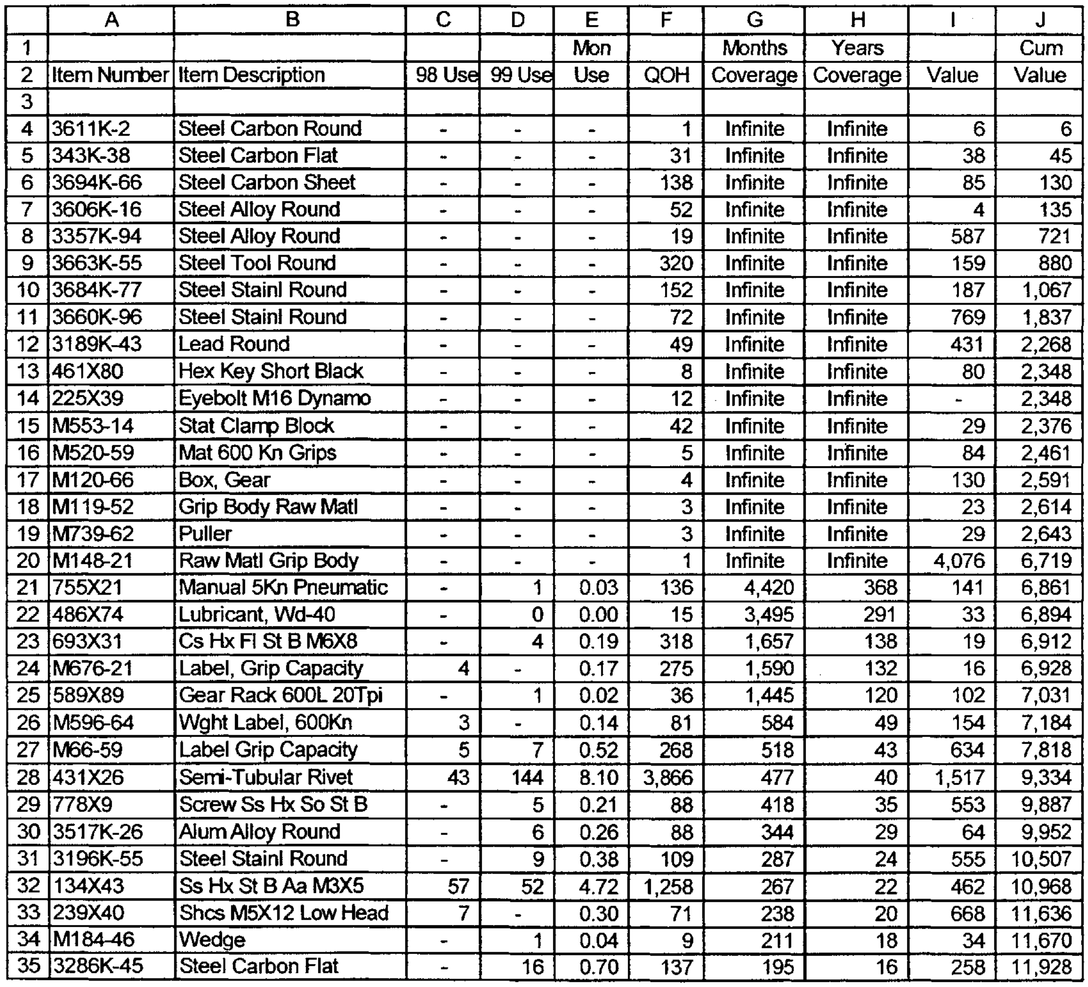
Figure 47 compares well with the actual demand data in Figure 13 of Chapter 2. The average grip requires 1.5 - 2.0 assembly hours, so one person can build about four grips per day. Figure 13 shows the 10-day moving average demand ranging from four grips per day to twelve grips per day, or between one and three heads. The agreement of the simulation to the actual demand data provides a strong measure of confidence in the simulation results, load statistics, and recommendations for job shop staffing and assembly lot sizes.

G

Disposition of Slow-Moving Stock

One of the recommendations from Chapter 5 for future actions is to dispose of slow-moving inventory. This appendix describes an approach for identifying the slow movers and refers to a method for deciding how much to keep and how much to sell off.

The identification of slow moving items begins with the list of items and their usage for the past two years, as shown in the spreadsheet in Figure 48. The average monthly use is also shown as

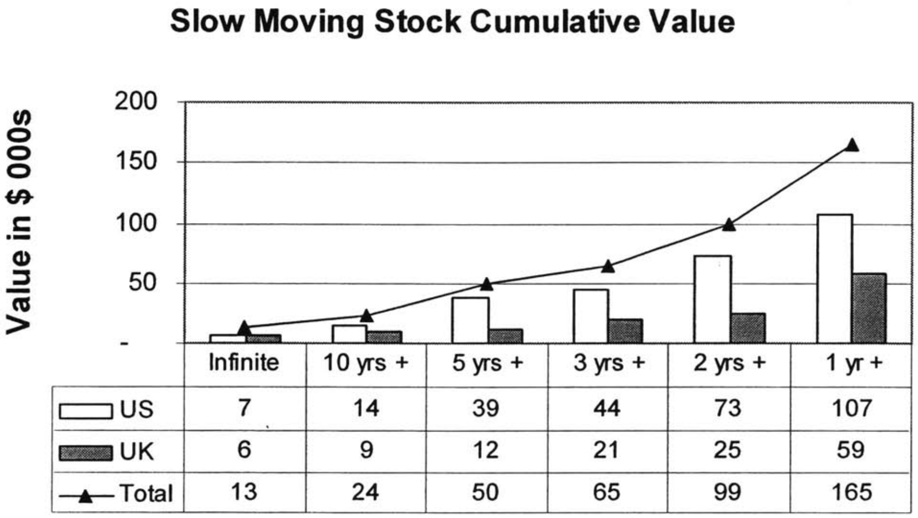


	A	B	C	D	E	F	G	H	I	J
1					Mon		Months	Years		Cum
2	Item Number	Item Description	98 Use	99 Use	Use	QOH	Coverage	Coverage	Value	Value
3										
4	3611K-2	Steel Carbon Round	-	-	-	1	Infinite	Infinite	6	6
5	343K-38	Steel Carbon Flat	-	-	-	31	Infinite	Infinite	38	45
6	3694K-66	Steel Carbon Sheet	-	-	-	138	Infinite	Infinite	85	130
7	3606K-16	Steel Alloy Round	-	-	-	52	Infinite	Infinite	4	135
8	3357K-94	Steel Alloy Round	-	-	-	19	Infinite	Infinite	587	721
9	3663K-55	Steel Tool Round	-	-	-	320	Infinite	Infinite	159	880
10	3684K-77	Steel Stainl Round	-	-	-	152	Infinite	Infinite	187	1,067
11	3660K-96	Steel Stainl Round	-	-	-	72	Infinite	Infinite	769	1,837
12	3189K-43	Lead Round	-	-	-	49	Infinite	Infinite	431	2,268
13	461X80	Hex Key Short Black	-	-	-	8	Infinite	Infinite	80	2,348
14	225X39	Eyebolt M16 Dynamo	-	-	-	12	Infinite	Infinite	-	2,348
15	M553-14	Stat Clamp Block	-	-	-	42	Infinite	Infinite	29	2,376
16	M520-59	Mat 600 Kn Grips	-	-	-	5	Infinite	Infinite	84	2,461
17	M120-66	Box, Gear	-	-	-	4	Infinite	Infinite	130	2,591
18	M119-52	Grip Body Raw Matl	-	-	-	3	Infinite	Infinite	23	2,614
19	M739-62	Puller	-	-	-	3	Infinite	Infinite	29	2,643
20	M148-21	Raw Matl Grip Body	-	-	-	1	Infinite	Infinite	4,076	6,719
21	755X21	Manual 5Kn Pneumatic	-	1	0.03	136	4,420	368	141	6,861
22	486X74	Lubricant, Wd-40	-	0	0.00	15	3,495	291	33	6,894
23	693X31	Cs Hx Fl St B M6X8	-	4	0.19	318	1,657	138	19	6,912
24	M676-21	Label, Grip Capacity	4	-	0.17	275	1,590	132	16	6,928
25	589X89	Gear Rack 600L 20Tpi	-	1	0.02	36	1,445	120	102	7,031
26	M596-64	Wght Label, 600Kn	3	-	0.14	81	584	49	154	7,184
27	M66-59	Label Grip Capacity	5	7	0.52	268	518	43	634	7,818
28	431X26	Semi-Tubular Rivet	43	144	8.10	3,866	477	40	1,517	9,334
29	778X9	Screw Ss Hx So St B	-	5	0.21	88	418	35	553	9,887
30	3517K-26	Alum Alloy Round	-	6	0.26	88	344	29	64	9,952
31	3196K-55	Steel Stainl Round	-	9	0.38	109	287	24	555	10,507
32	134X43	Ss Hx St B Aa M3X5	57	52	4.72	1,258	267	22	462	10,968
33	239X40	Shcs M5X12 Low Head	7	-	0.30	71	238	20	668	11,636
34	M184-46	Wedge	-	1	0.04	9	211	18	34	11,670
35	3286K-45	Steel Carbon Flat	-	16	0.70	137	195	16	258	11,928

Figure 48. Inventory Coverage

column E and the current inventory on hand is tabulated in column F. The months of coverage value is calculated by dividing the quantity on hand by the monthly use. The spreadsheet is then sorted in descending order by the months of coverage and the slowest moving items are brought to the top of the list for review[1]. The spreadsheet also calculates the years of coverage as well as the individual and cumulative values of the on-hand inventory. Note that the top 17 items saw no usage in 1998 or 1999, resulting in "infinite" coverage. The on-hand value of these 17 items is over seven thousand dollars.

Figure 48 shows US inventory only. A similar spreadsheet analyzes the UK inventory and the two are summarized in Figure 49. The time periods indicate how long the on-hand inventory is likely to last without the need for replenishment. Instron is holding $165K in inventory that will last longer than one year.



	Infinite	10 yrs +	5 yrs +	3 yrs +	2 yrs +	1 yr +
☐ US	7	14	39	44	73	107
▨ UK	6	9	12	21	25	59
—▲— Total	13	24	50	65	99	165

Figure 49. EM Grip Slow-Moving Inventory Value

One approach for deciding how much of this slow-moving inventory to keep and how much to sell makes use of a model that values each unit of inventory and compares them to their salvage values[2]. The number of units to keep is

$$n^* = \left\lfloor \log((V + r/i)/(A + r/i))/\log(M(i)) \right\rfloor$$

where the clipped brackets denote the largest integer less than the quantity they enclose.

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[1] Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York, pp. 367-369.

[2] Rosenfield, D. B., "Disposal of Excess Inventory," *Operations Research,* Vol. 37, No. 3 (1989), pp. 404-409.

In the above formula,

V = the salvage value as a percent of the current value
r = the holding cost not including capital costs
i = the discount rate
A = the average ultimate sales value as a percent of current value
λ = the average number of units demanded per unit time
$M(i) = \lambda / (\lambda + i)$, assuming Poisson demand episodes.

Applying this model to the items in rows 21 through 35 of Figure 48 and assuming $V = 0.2$, $r = 0.15$, $i = 0.15$, and $A = 0.5$ suggests that almost all of the inventory for these items should be sold for salvage. This result is robust for many different combinations of values for A and V.

H

Optimization of Safety Stocks

Chapter 3 presents the order quantity, order point (Q, r) model and includes a method for determining the appropriate safety stock level for an individual item. This appendix extends the analysis to an assembly process in which multiple components in an assembly are considered.

Setting the safety stock level for an item so that a stockout occurs only once for every twenty orders (or twenty pulls from the component bin) yields a 95% probability that the component will be available when needed. With an assembly consisting of, say, ten component items, the probability of all ten items being available for assembly drops considerably (assuming independence between the individual items):

$$\text{Prob (ten items in stock)} = \prod_{i=1}^{10} \text{Prob (item i in stock)}$$

$$\text{Prob (ten items in stock)} = (0.95)^{10} = .60$$

So for this example, the probability that all ten items will be in stock is only sixty percent, and assembly will be delayed eight times for every twenty orders. Clearly, the component safety stock levels should be set higher, but which ones and how high?

One approach to solving this problem is to set up an optimization model[1]. The goal is to minimize average inventory cost by choosing the best values for the z-variates subject to the constraint that the in-stock probability product is at least 0.95.

Figure 50 presents a sample of Instron grip data that includes seventeen components required to assembly a 5 kN wedge grip. The table shows pre-optimization z-variates all set at 1.64 to achieve 95% availability for each component item number. These settings result in an average inventory value of about $15 thousand, but the probability of all seventeen components being available is only 42 percent.

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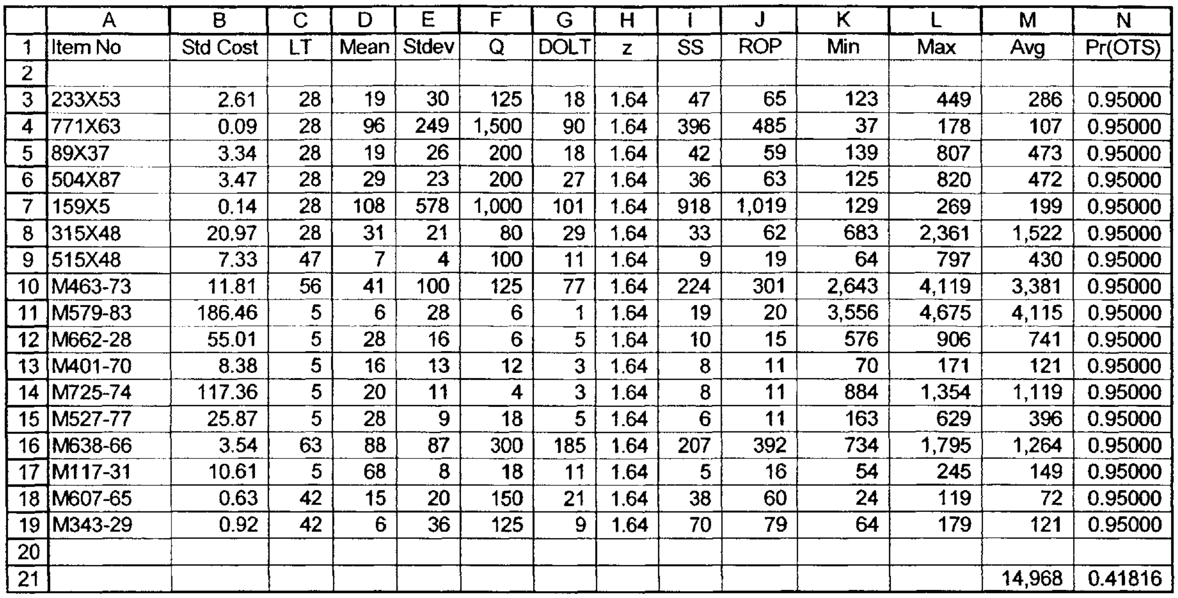
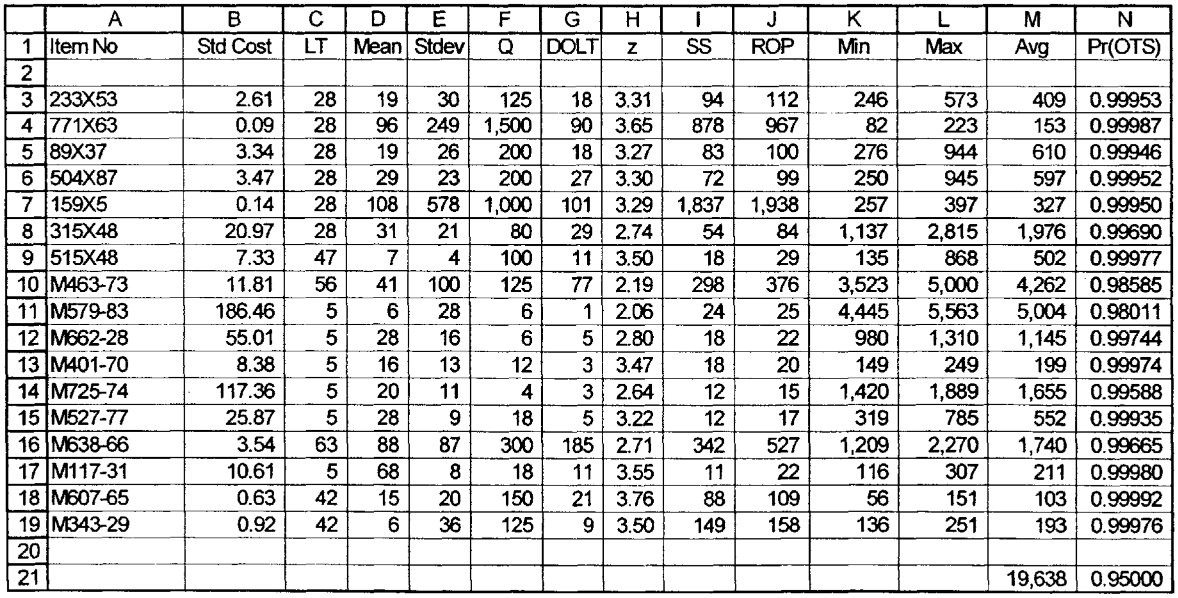
[1] Rosenfield, D. B., and A. W. Drake, advisors to the internship, June-Dec. 1999.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Item No	Std Cost	LT	Mean	Stdev	Q	DOLT	z	SS	ROP	Min	Max	Avg	Pr(OTS)
2														
3	233X53	2.61	28	19	30	125	18	1.64	47	65	123	449	286	0.95000
4	771X63	0.09	28	96	249	1,500	90	1.64	396	485	37	178	107	0.95000
5	89X37	3.34	28	19	26	200	18	1.64	42	59	139	807	473	0.95000
6	504X87	3.47	28	29	23	200	27	1.64	36	63	125	820	472	0.95000
7	159X5	0.14	28	108	578	1,000	101	1.64	918	1,019	129	269	199	0.95000
8	315X48	20.97	28	31	21	80	29	1.64	33	62	683	2,361	1,522	0.95000
9	515X48	7.33	47	7	4	100	11	1.64	9	19	64	797	430	0.95000
10	M463-73	11.81	56	41	100	125	77	1.64	224	301	2,643	4,119	3,381	0.95000
11	M579-83	186.46	5	6	28	6	1	1.64	19	20	3,556	4,675	4,115	0.95000
12	M662-28	55.01	5	28	16	6	5	1.64	10	15	576	906	741	0.95000
13	M401-70	8.38	5	16	13	12	3	1.64	8	11	70	171	121	0.95000
14	M725-74	117.36	5	20	11	4	3	1.64	8	11	884	1,354	1,119	0.95000
15	M527-77	25.87	5	28	9	18	5	1.64	6	11	163	629	396	0.95000
16	M638-66	3.54	63	88	87	300	185	1.64	207	392	734	1,795	1,264	0.95000
17	M117-31	10.61	5	68	8	18	11	1.64	5	16	54	245	149	0.95000
18	M607-65	0.63	42	15	20	150	21	1.64	38	60	24	119	72	0.95000
19	M343-29	0.92	42	6	36	125	9	1.64	70	79	64	179	121	0.95000
20														
21													14,968	0.41816

Figure 50. Safety Stock Levels - Individual 95% Probabilities

Figure 51 shows the same data after running Excel Solver. The objective function (cell M21) is the sum of the average component inventories. The decision variables (cells H3 through H19) are the z-variates for the components, and the constraint (cell N21) is the product of the component on-the-shelf probabilities. The total inventory value is about $20 thousand and the probability of being able to assemble the grip is 95 percent.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Item No	Std Cost	LT	Mean	Stdev	Q	DOLT	z	SS	ROP	Min	Max	Avg	Pr(OTS)
2														
3	233X53	2.61	28	19	30	125	18	3.31	94	112	246	573	409	0.99953
4	771X63	0.09	28	96	249	1,500	90	3.65	878	967	82	223	153	0.99987
5	89X37	3.34	28	19	26	200	18	3.27	83	100	276	944	610	0.99946
6	504X87	3.47	28	29	23	200	27	3.30	72	99	250	945	597	0.99952
7	159X5	0.14	28	108	578	1,000	101	3.29	1,837	1,938	257	397	327	0.99950
8	315X48	20.97	28	31	21	80	29	2.74	54	84	1,137	2,815	1,976	0.99690
9	515X48	7.33	47	7	4	100	11	3.50	18	29	135	868	502	0.99977
10	M463-73	11.81	56	41	100	125	77	2.19	298	376	3,523	5,000	4,262	0.98585
11	M579-83	186.46	5	6	28	6	1	2.06	24	25	4,445	5,563	5,004	0.98011
12	M662-28	55.01	5	28	16	6	5	2.80	18	22	980	1,310	1,145	0.99744
13	M401-70	8.38	5	16	13	12	3	3.47	18	20	149	249	199	0.99974
14	M725-74	117.36	5	20	11	4	3	2.64	12	15	1,420	1,889	1,655	0.99588
15	M527-77	25.87	5	28	9	18	5	3.22	12	17	319	785	552	0.99935
16	M638-66	3.54	63	88	87	300	185	2.71	342	527	1,209	2,270	1,740	0.99665
17	M117-31	10.61	5	68	8	18	11	3.55	11	22	116	307	211	0.99980
18	M607-65	0.63	42	15	20	150	21	3.76	88	109	56	151	103	0.99992
19	M343-29	0.92	42	6	36	125	9	3.50	149	158	136	251	193	0.99976
20														
21													19,638	0.95000

Figure 51. Optimized Safety Stock Levels

Additional algorithms and their results are presented below. Case 1 corresponds to Figure 50. Case 2 sets the z-values to 3.00 to achieve 99.9 % individual probabilities. Case 3 combines cases 1 and 2 by setting most component z-values to 3.00, then tightening those values to 1.64 for the three most expensive components.

Case	Inventory	Prob. of Assembly	Optimal Inventory	Percent Savings
1. z = 1.64	$ 14,968	41.8 %	$ 11,633	29 %
2. z = 3.00	23,261	97.7	21,368	9
3. Heuristic	19,114	84.0	16,639	15
4. Optimal 90%	17,937	90.0		
5. Optimal 95%	19,638	95.0		
6. Optimal 99%	23,002	99.0		

The two columns on the far right show the optimal inventory value and percent savings over the non-optimal value for the given probability of assembly for each case. Note that the optimal settings lead to savings of ten to twenty-five percent over first pass calculations.

Cases 4, 5, and 6 result from running Excel Solver with various constraints on the assembly probability. Case 5 corresponds to Figure 51 and represents the best all around solution for Instron.

I

How to Reduce Inventory at Instron

This appendix provides step-by-step instructions for carrying the EM grip project methodology to other product lines at Instron. An important feature of the EM grip product line is the individual nature of the bills of materials - very few component parts are shared among different end items. The value of this legacy structure is the ability to decouple component and finished goods inventories for simplified analysis and optimization. The structure is shared by many of Instron's other product lines, encouraging the adoption of the grip project methodology.

The main steps in the process are to: (1) select a product line; (2) set up measurements and goals; (3) identify the stock-keeping units (SKUs); (4) classify the items using the distribution by value tool; (5) characterize the product line demand, calculate assembly lots sizes, and calculate component stock levels; (6) implement pull production; and (7) evaluate the results.

Product Line Selection. The inventory reduction methodology has been proven for the EM grips, so it makes sense to scale up the effort ten-fold and target a significant portion of Instron's inventory. Good candidates include the EM tensile test machines and the Wilson hardness testers. The consolidated machine assembly line is another attractive target.

Specific catalog numbers should be selected for the reduction effort with highest volume, highest value catalog numbers specifically identified for treatment. There is a tradeoff in selecting only a portion of the products that are assembled in one location however. If only some are selected, then dual systems must be implemented (MRP and pull) and shop personnel must keep track of which components fall under which system. On the other hand, if the methodology is applied to all products within a work center, then the analysis and implementation effort can suffer from tedium, increased errors, and increased costs.

Measurements and Evaluation. The Instron Business System (IBS) contains the inventory measurement data. Once the catalog numbers have been identified, the next task is to explode the bills of materials (BOMs) to their lowest levels and consolidate duplicate entries. This is a fairly big task, given the duplication of item numbers populated through the different BOM levels. IBS provides a non-standard structured query language that can help, especially the SELECT and UNION statements using the UNIQUE modifier. The alternative is to download the BOMs from IBS to Excel and painstakingly sort and cull the list of items to eliminate duplicates.

Once the list of unique item numbers has been built, it must be "permanently" saved as a Select List. If the list was built using IBS statements, then a simple SAVE-LIST command will work. If the list was built in Excel, then it must be uploaded to IBS and saved. An IBS menu function provides the capability to preserve the list for use beyond 15-30 days. The list can then be called from various reports to provide inventory measurement data. Several reports exist in IBS that are currently used to maintain measurements of EM grip inventory, providing blueprints for future efforts. Examples of these reports include E*GRIPINV and E*GRIPWIP, which are used to track the overall EM grip inventory levels as presented in Figure 6.

In addition to inventory levels at discrete moments in time, the production output over a period is needed to calculate inventory turns. The production output (also known as cost of goods sold) can be measured through the use of another IBS report, E*GRIPOUTSUM. This report provides the quantities and costs of shipped grips over a user-selectable time period based on a list of catalog numbers.

SKU Identification. The list of item numbers derived from the catalog number BOMs typically includes many non-stocked items. These artifacts exist for billing and accounting purposes and must be removed to accurately apply the models and analysis tools. "Phantom" stock numbers with type codes AO, AON, and N are non-stocked. Drawings and test specifications with type code D should also be excluded. Items coded F are free stock (typically fasteners and consumables) which may be better handled by inventory management agreements with suppliers.

Item Classification. Separating finished goods from components is relatively straightforward, based on the features of the SKU item number. If the SKU is a stocked catalog number or begins with the letters "OP" or "A" then it is normally a finished good. Some "A" numbers are sub-assemblies, however, and should be excluded on a case-by-case basis.

The distribution by value technique described in Chapter 3 and Appendix C provides an appropriate method for classifying item numbers. Application of the tool results in each SKU being categorized as Class A, B, or C and different inventory control policies are recommended for each class.

Demand Characterization and Model Calculations. The best single source for demand characterization is the usage data available in IBS for each item number. The data is viewable from IBS menus through the item number displays. For bulk downloads, the IWHS file contains several fields specifying monthly usage data for each item for the current and previous years. Team members developed special purpose Excel spreadsheets to import and parse this data en masse.

Monthly means and standard deviations can be calculated directly from the IBS usage data. Chapter 3 presents an example of this data (Figure 21) and discusses how this data is interpreted and used to calculate the reorder points and order quantities for components. The annual demand data is also used by the job shop capacity model in Chapter 2 to determine optimal lot sizes.

Implementing Pull Production. The order quantities and reorder points are transcribed to kanban cards which are placed in safety stock bags along with the reorder point quantities for each item number (see Figure 23). Instron shop and stockroom personnel are becoming more and more familiar with this process as pull production is implemented throughout the company.

Annotated Bibliography

Alvarez, M. J., "Analysis of the Accessory Business: Focus on ElectroMechanical Grips," Masters Thesis, MIT Leaders for Manufacturing Program, May 1999. This thesis was written by the LFM student interning at Instron from June - December 1998. Alvarez developed the (Q,r) inventory model applied to EM grips as a foundation for this work.

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Nahmias, S., "Production and Operations Analysis," 3rd ed. (1997), Irwin, Chicago. This intermediate level textbook on production and operations management provides two chapters devoted to inventory control, one with known demand and one with uncertain demand. Low-volume demand is specifically addressed, with application to many of Instron's products.

Rosenfield, D. B., "Disposal of Excess Inventory," *Operations Research*, Vol. 37, No. 3 (1989), 404-409. This paper discusses slow-moving inventory and provides a method for determining how much to keep in relation to salvage value and holding costs. The issue is of particular interest to Instron and its broad product line with mostly low-volume, indeterminant demand.

Rosenfield, D. B., and A. W. Drake, advisors to the internship, June-Dec. 1999. Both advisors provided numerous suggestions and guidelines on research direction during several visits to Instron and continuing correspondence.

Silver, E. A., D. F. Pyke, and R. Peterson, "Inventory Management and Production Planning and Scheduling," 3rd ed. (1998), John Wiley & Sons, New York. This textbook provides an excellent general treatment of inventory management. As noted above, it covers ABC classification, distribution of SKUs by value, exchange curves for determining aggregate values, derivations of the economic order quantity model, lot-sizing, determining safety stock with probabilistic demand, and a host of suggestions and decisions rules for managing inventory under a wide variety of conditions, especially Class A and Class C items. A chapter on supply chain management is included in the third edition, with many references.

Simpson, K. F., "In-Process Inventories," *Operations Research*, 6 (1958), 863-873. This article introduces the simplest supply chain model, the serial line, and the problem of where to place inventory along the line. The paper provides the interesting result that there is an "all or nothing" optimal solution to the problem – either a stage has no safety stock or the stage has enough safety stock to decouple it from its downstream stage.

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Winston, W. L., "Introduction to Mathematical Programming," (1995), Duxbury Press, Belmont, California. An introductory text on linear programming, this book has one chapter devoted to nonlinear programming and a section treating Lagrangian multiplier techniques.