FACTORY PHYSICS

Solutions Manual for Even Numbered Problems

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Factory Physics principles were invented at Northwestern University in the late 80's and early 90's. At that time, Mark Spearman and Wally Hopp were both professors in the Industrial Engineering Department. Having both been physics majors in their undergraduate years, they looked at manufacturing the way a physicist would look at the natural world—by trying to understand the natural laws and relationships that would explain the behavior of manufacturing operations and supply chains.

The fundamental insight of the Factory Physics approach is that there is a comprehensive, *practical* framework and set of concepts for predictively and profitably explaining and managing manufacturing operations and supply chains—a practical science of manufacturing. Executives and managers who imbed these principles into their management intuition will advance both their companies' profitability and their own careers.

In my 23 years in manufacturing, it has been disconcerting to see that many, if not most, American manufacturers have approached profitability in operations performance using three primary methods: information technology, academics, or improvement initiative.

Information technology is a massive business but there is no software program in the world that will run your supply chain for you. It is discouraging to see how much money has been spent on massive software systems with the long term result being that planners and managers mostly use spreadsheets to run operations. A primary cause of this has been a lack of understanding of the science involved with managing the underlying operations, both on the part of the software vendors and the end users.

" Academics have placed so much emphasis on mathematical precision that they have shied away from realistic problems that did not lend themselves to clever quantitative solutions. Note that this was a more a matter of trying to 'look scientific' than of actually being scientific." –Spearman and Hopp, Factory Physics

Improvement initiatives have mass appeal; it's easy to agree with the mantra, "Reduce waste." On the other hand, it's also easy to agree with the financial strategy of "Buy low, sell high." I wouldn't claim that either was a guiding policy that provides enough information to make predictive strategic and tactical decisions. Yet there is any number of examples of manufacturing executives whose strategy to improve performance is to implement Lean Manufacturing or Lean Sigma or Six Sigma or Theory of Constraints. Implementing an initiative is a tactic not a strategy. Sustainable results in initiative implementation have been mixed at best.

Through a practical scientific understanding of operations and supply chain behavior, the tools of Lean, Six Sigma, information technology and any appropriate others can be brought to bear quickly and effectively. The practical science and the tools of operations performance are not mutually exclusive. They are, in fact, all necessary to profitably design, implement, and control manufacturing operations and supply chains.

In 1992 as an MBA student at Northwestern, all I had was class notes. There was no book but, having already worked in manufacturing for four years, I knew Mark and Wally were on to something. "Factory Physics" was first published in 1995 and was awarded book of the year by the Institute of Industrial Engineers in 1998. Nowadays, the book sells more to industry users than to academia. This solution manual was prompted by constant requests from industry.

Profitable manufacturing is typically a difficult business. Lots of complexity and uncertainty. Since Factory Physics Inc. was formed in 1991, we have received support from the National Science Foundation to develop advanced software (www.fpcsuite.com) now being used around the world at Fortune 500 companies. The seminars and training we provide is much advanced, i.e. simpler and more practical, than the typical university classroom approach. Factory Physics Inc. still shares the original goal of Drs. Hopp and Spearman—improve the management of manufacturing and supply chain operations. More simply, as one seminar participant put it, “I’d like to [work in manufacturing and] have a Saturday off every now and then.” If you want to address that goal by picking up the book and working through the concepts, we hope this solution manual helps.

Edward S. Pound
COO
Factory Physics Inc.

Using the Book

Recommended use of the book in industry is a bit different than the typical academic classroom approach. Start at the end. Chapter 19 provides a good vignette as a description of applying the principles in practice. Mark and Wally also claim it provides their first and last attempt at non-fiction prose.

The next recommended sequence would be the heart of the book: Chapters 6 though 9. Here is where the foundation of the Factory Physics framework is laid out. Sections 6.2 and 6.3 provide the underlying philosophical approach. Section 6.5 lays out a simple but time-tested approach for application in practice. Chapters 7 though 9 provide the basic science of the Factory Physics framework.

The remaining chapters provide observations of manufacturing management, e.g.

- Chapter 1 – Manufacturing in America
- Chapter 5 – What Went Wrong

or in-depth discussions of topics in manufacturing and supply chain management, e.g.

- Chapter 2 – Inventory Control: From EOQ to ROP
- Chapter 13 – A Pull Planning Framework

based on the framework and approach laid out in Chapters 6 through 9.

Contents

Chapter 1

Study Questions

2. Some key impacts of Frederick W. Taylor's Scientific Management on the practice of manufacturing management in America were:

    - Recognition that management is something that can be studied and developed as a profession.

    - Separation of planning (i.e., by the managers) from doing (i.e., by the workers). Scientific Management was a result of and a contributor to the adversarial relationship between management and labor in America.

    - Emphasis on setting standards for how tasks should be done and at what rate.

    - Framed debate over what motivates workers. Although Taylor viewed money as the prime motivator for workers, he did recognize some psychological component. His followers, particularly Lillian Gilbreth, pursued this issue more explicitly.

4. Some signs of a decline of American manufacturing include:

    - Perceived inferior quality of American goods relative to some foreign goods, since at least the 1970's.

    - US Market share of the "Big Three" automakers (Chrysler, Ford and GM) has fallen from 70% in 1991 to 44% in 2010. In 2009, Toyota surpassed GM as the largest automobile manufacturer in the world. Recall that Robert MacNamara once said "What's good for GM is good for the country."

    - The fraction of U.S. patents granted to foreigners has doubled since 1970.

    - Loss of some high visibility markets. For instance, there is no significant American manufacturer of flat panel TV screens.

    - China's manufacturing sector is on the brink of passing that of the United States, according to a report released in June 2010 by the economic research firm IHS Global Insight. The value of goods produced by China's factories reached about $1.6 trillion last year, compared to $1.7 trillion by U.S. manufacturers.

6. Some post WWII management trends that may have contributed to the decline of American manufacturing include:

    - *Finance View*: encouraged myopic focus on short-term returns.

    - *Marketing View*: fostered conservative view of product development (i.e., by relying too heavily on the numbers) and diminished use of manufacturing as a strategic weapon.

    - *Fast Track Manager System*: diluted experience of upper management.

- *Profit Center Approach*: encouraged segmentation of business enterprise rather than integration of various functions with manufacturing to achieve business goals.

8. Pros of a portfolio management approach to managing a manufacturing enterprise are:

   - It encourages use of measurable performance criteria (e.g., ROI)

   - It encourages balancing activities with respect to risk (e.g., diversifying the product lines to avoid being catastrophically sensitive to conditions in a single market).

   Cons of this approach are:

   - It can pit parts of the firm against one another (e.g., as each tries to achieve individual numbers rather than supporting overall corporate performance).

   - It neglects the fact that performance of a manufacturing enterprise, unlike that of an externally purchased financial instrument, is subject to internal control. Too much effort spent trying to massage ROI by buying and selling companies can sap needed efforts in making better products and selling them profitably.

10. A "professional" manager (i.e., a manager who is allegedly capable of managing any business) and a manager of a purely financial portfolio both are accustomed to looking at businesses in general financial terms, the financial analyst to evaluate stocks, the professional manager to evaluate performance. Both view ``business as business," the financial analyst buying stocks from any sector, the professional manager managing any business.

    The professional manager is unlikely to appreciate the deeper non-financial determinants of a business's success and therefore may be prone to a conservative maintenance approach rather than a technologically innovative leadership approach.

12. Managers may pursue *imitative designs* even in circumstances where it can be documented that *innovative designs* have had markedly better long term performance, because imitation is safer. If you are evaluated on short-term criteria, then a high probability of a small success is better than a lower probability of a big success (with a significant probability of a high-visibility failure).

14. The essential skill a manufacturing manager requires to be able to appreciate the "big picture" and still pay attention to important details without becoming completely overwhelmed is good *intuition*. A manager with sound intuition can focus on the areas that offer leverage without being distracted by the myriad of details that do not.
    - Who knows? But, tomorrow's success stories are figuring this out today.

Chapter 2

Study Questions

2. Inventory carrying costs.
   - Carrying cost can be a surrogate for WIP, since the higher the carrying cost, the less WIP the model will be inclined to carry.
   - Another term for interest rate is "discount rate." This charge is supposed to represent the opportunity cost of money (i.e., the rate of return that could be attained if the money were invested in the best alternative use.

4. Appropriate (A) and less appropriate (L) applications of EOQ:
   - Automobile manufacturer ordering screws from a vendor: *A*
   - Automobile manufacturer deciding on how many cars to paint per batch of a particular color: *L*
   - A job shop ordering bar stock: *A*
   - Office ordering copier paper: *A*
   - A steel company deciding how many slabs to move at once between the casting furnace and the rolling mill: *L*

6. The key difference between Wagner-Whitin and the EOQ assumptions is that Wagner-Whitin assumes non-constant (although still deterministic) demand.

8. Four criticisms of the validity of the Wagner-Whitin model are:
   - Demands are assumed fixed and known.
   - Setup costs are very difficult to specify, since as in EOQ, they may really be a proxy for capacity, which is context sensitive.
   - Wagner-Whitin property implies that production should be for an integer number of periods of demand. This completely ignores capacity and yield issues, which may make it attractive to produce different quantities than permitted under this property.
   - Variable lot sizes may present process problems where there are physical reasons for maintaining lot sizes that are multiples of some number (e.g., tote sizes are set, negatives in an expose operation can produce a specific number of items before wearing out, a casting furnace produces 250 tons of steel per load (heat) and cannot be run with partial loads, etc.).

10. The statement "the reorder point, r, affects customer service, while the replenishment quantity, Q, affects replenishment frequency" is true in rough terms but is not precisely true because:
    - Q certainly does govern order frequency (i.e., if annual demand is D, then the number of orders per year is $F = D/Q$).
    - Once Q is fixed, then r determines the customer service (i.e., the probability of an order being filled out of stock).
    - However, if we change Q for a given r, customer service changes. The reason is that if Q is made large, then the number of times per year that inventory falls to a level where stockouts occur is reduced. Thus, for a fixed r, service level increases with Q.

    This interaction between Q and r in determining service level is the reason for introducing Type I Service, which by definition is governed only by r. This greatly simplifies solution of the model and for cases where Type I Service is a good approximation of the actual service level, provides useful heuristics.

12. When stocking parts purchased from vendors in a warehouse you could use a (Q,r) model to determine whether a vendor of a part with a higher price but a shorter lead time is offering a

good deal by solving the model with both price/leadtime pairs and see which resulted in the lowest overall cost.

Other factors you should consider in deciding to change vendors include issues related to vendor reliability, quality, cost of certifying the new vendor (if you have a vendor certification program), etc.

14. One would expect the event that this particular man brings a bomb on the plane (denote it as Event A) and the event that another person brings a bomb on the plane (denote as Event B) should be independent (unless there is a conspiracy). Now the probability of two independent events occurring is

$$P\{A \cap B\} = P\{A\} \bullet P\{B\}$$

but the probability of Event B occurring *given* Event A has occurred is

$$P\{B|A\} = \frac{P\{A \cap B\}}{P\{A\}} = \frac{P\{A\}P\{B\}}{P\{A\}} = P\{B\}$$

so this guy will not alter the probability that another person brings a bomb on the plane. Even worse, the authorities won't buy his logic and he will wind up in jail.

Problems

2. We examine the probability of winning the fabulous prize first with the decision not to switch and then with the decision to switch. The only way to win if we do not switch is for the fabulous prize to be behind the door we initially choose. Since there are three doors, this has a probability of 1/3.

   To compute the probability of winning given that we switch, we condition on whether the prize is behind the first door. The probability of switching and winning *given* the prize was behind the first door is, obviously, zero. Now consider the probability of winning given the prize was *not* behind the first door. Since the prize is not behind the first choice of door and since the host will not reveal the prize when opening up another door, it must be behind the remaining door. Thus, the probability of winning when switching and when the prize is not behind the first door is one. Then,

$$\text{P\{win\}} = \text{P\{win|1st door correct\} P\{1st door correct\}} + \text{P\{win|1st door incorrect\} P\{1st door incorrect\}}$$

$$\text{P\{win\}} = 0 \times 1/3 + 1 \times 2/3 = 2/3$$

   Since you had a 1/3 probability of being right on your first choice but now, if you switch, you have a 2/3 probability of being right, it is best to switch.

   Note that this requires that the host always play the game the same way. He will always make the offer to choose another door regardless of the contestant's first choice.

4. This satisfies all the assumptions of the EOQ model. The only tricky thing is to keep the units consistent.
   a)
   $$D = 60 \text{ units/wk} \times 52 \text{ wk/yr} = 3120 \text{units/yr}$$
   $$h = ic = 0.25/\text{yr} \times \$0.02 = \$0.005/\text{yr}$$
   $$A = \$12$$
   $$Q^* = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2 \times 12 \times 3120}{0.005}} = 3869.88 \cong 3870$$
   The time between orders is given by
   $$T^* = \frac{Q^*}{D} = \frac{3870}{3120} = 1.24 \text{ yr} = 14.88 \text{ mo}$$
   b) Setup cost is
   $$A\frac{D}{Q} = \$12\frac{3120\text{units/yr}}{3870\text{units}} = \$9.67/\text{yr}$$
   Holding cost is $\frac{Q}{2}h = \frac{3870\text{units}}{2}\$0.005/\text{yr} = \$9.675/\text{yr}$.
   The costs are essentially the same. This is always true in the case of the EOQ model.
   c) The problem could be where to store all the items. If we were to order 1.24 years worth of styrofoam ice chests at a time it could take up a lot of room.

6.
   a) The EOQ with 60 per week was computed to be 3,870 and the optimal reorder period was 1.24 years or 14.88 months. The closest power of two is 16 months or 1.33 years with a cost of
   $$TC(1.33) = TDh/2 + A/T = (1.33\text{yr})(3120/\text{yr})(\$0.005/\text{yr})/2 + \$12/1.33\text{yr} = \$19.37/\text{yr}$$
   The power of two on the other side of 14.88 mo is 8 mo or 0.67 yr with a cost of
   $$TC(0.67) = TDh/2 + A/T = (0.67\text{yr})(3120/\text{yr})(\$0.005/\text{yr})/2 + \$12/0.67\text{yr} = \$23.20/\text{yr}$$
   b) The minimum cost without the power of two restriction is
   $$\sqrt{2ADh} = \sqrt{2(12)(3120)(0.005)} = \$19.35/\text{yr}$$
   so 16 months has a cost that is only 0.1% over the optimal while the 8 month solution is around 20% over optimal. The total cost in the EOQ model is relatively insensitive to order quantity used. Since the order period is directly proportional to the order quantity the cost is not very sensitive to the period used as well.
   c) The robustness of the EOQ to errors in parameter estimates and the effectiveness of a power-of-2 policy are basically the same phenomenon.

8.
   a) The schedule is developed in reverse. From the table we see that demand for period 12 is made in period 11. Thus, the quantity made in period 11 contains demand for both period 11 and 12, $Q_{11} = D_{11} + D_{12} = 79 + 56 = 135$
   We are now left with a 10 period problem. From the table, demand for period 10 is made in period 10, or $Q_{10} = 67$
   Again, demand for period 9 is made in period 8 so that
   $$Q_8 = 67 + 45 = 112$$
   If we continue in this fashion we obtain,
   $$Q_5 = 121, Q_3 = 97, Q_1 = 98.$$

b) If we start at period 6, a different schedule emerges.

$$Q_4 = D_4 + D_5 + D_6 = 148$$

Demand for period 3 is produced in period 1, so

$Q_1 = 69 + 29 + 36 = 134$

10. This is a single period stochastic inventory model—the "news vendor problem." Since the shirts sell for $20 and cost $5 any unit we are short will "cost" us $15. Since shirts that are not sold at the event can be discounted and sold for $4, the excess cost is $1. Thus,

$c_o = 1$

$c_s = 15$

At this point it is clear that printing too few shirts is worse than printing up too many so their policy is not a good one.

If $G(x)$ represents the distribution function for the demand, from the news vendor model we have

$$G(Q^*) = \frac{c_s}{c_s + c_o} = \frac{15}{15+1} = 15/16 = 0.9375 = s$$

where s is the "service rate." The question now is what distribution function to use. We estimate the mean to be 12,000 and know there is a "significant amount of uncertainty." Since 12,000 is a large number, the normal distribution should be a reasonable approximation. If X is a random variable representing the demand during the event we can write and expression for Q^* in terms of the mean and standard deviation of the demand.

$$P\{X \le Q^*\} = \frac{c_s}{c_s + c_o} = s$$

or

$$\text{P}\left\{\frac{X - 12000}{\sigma} \le \frac{Q^* - 12000}{\sigma}\right\} = s$$

so that

$$\frac{Q^* - 12000}{\sigma} = z_s = 1.53$$

or

$$Q^* = 12000 + 1.53\sigma$$

If demand were Poisson, the standard deviation would be the square root of the mean or

$\sigma = \sqrt{12000} = 109.54$ so that

$Q^* = 12{,}167.6 \cong 12{,}168$.

12. Tammi's Truck Stop. $\mu = 35$, $\sigma = 10$. $c_s = 65\text{-}40 = 25$, $c_o = (0.35)(40)/52 = 0.27$.

a)

$$\frac{c_s}{c_s + c_o} = \frac{25}{25 + 0.27} = 0.989$$

$$Q^* = \mu + z_{0.989}\sigma = 35 + (2.39)(10) = 59 \text{ cushions}$$

So Tammi should buy 59-12=47 cushions to bring her stock back up to the order-up-to-level of 59.

b) Now c_s=5, so

$$\frac{c_s}{c_s + c_o} = \frac{5}{5 + 0.27} = 0.9488$$

$$Q^* = \mu + z_{0.9488}\sigma = 35 + (1.64)(10) = 51 \text{ cushions}$$

So Tammi should buy 51-12=39 cushions to bring her stock back up to the order-up-to-level of 51.

14. The chairs are made in-house and so we are attempting to determine the appropriate parameters for a base-stock system. We assume that the wholesalers order once per month.

a) The holding cost is $h = \$5$ while the backorder cost is $b = \$20$. The distribution of demand during a month is well approximated by a normal distribution with a mean of 1,000 chairs and a standard deviation of 200 chairs. Then, if X represents the demand during one month,

$$G(R^*) = \frac{b}{h+b} = \frac{20}{5+20} = 0.8$$

and so

$$G(R^*) = P\{X \le R^*\} = P\left\{\frac{X-1000}{200} \le \frac{R^*-1000}{200}\right\} = 0.8$$

The value of the standard normal with 0.8 probability is obtained from a standard normal table or using the Excel function NORMSINV(0.8) and yields 0.84. Then the order up to point is computed as

$R^* = 1000 + 0.84 \times 200 = 1168$.

b) If the sale is lost (as opposed to backordered) then the shortage cost must be the profit that would have been made which is \$100. The computation is then similar,

$$G(R^*) = \frac{100}{5+100} = 0.9524$$

$$z_{0.9524} = 1.67$$

$$R^* = 1000 + 1.67 \times 200 = 1334$$

c) Since the cost of being short is higher in the second case, we want to carry more inventory to avoid that possibility.

16.

Constraints		**Costs**	
S (service level)	98%	Backorder cost (b)	\$15
		Holding rate (h)	3%

(a)

I	c_i (\$/unit)	D_i (units/mo)	ℓ_i (mos)	theta$_i$ (units)	sigma$_i$ (units)	Q_i (units)	r_i (units)	F_i (order freq)	S_i (fill rate)	B_i (backorder level)	I_i (inventory invest)	Holding (\$/yr)	Order (\$/yr)	Total (\$/yr)
A	150	7	1	7.0	2.6	1.0	13.0	7.0	0.987	0.010	\$1,051.45	\$378.52	35.00	413.52
B	15	30	0.5	15.0	3.9	1.0	23.0	30.0	0.981	0.024	\$135.36	\$48.73	150.00	198.73
		37						18.5	98.18%		\$1,186.81	\$427.25	185.00	612.25

(b)

I	c_i (\$/unit)	D_i (units/mo)	ℓ_i (mos)	theta$_i$ (units)	sigma$_i$ (units)	Q_i (units)	r_i (units)	F_i (order freq)	S_i (fill rate)	B_i (backorder level)	I_i (inventory invest)	Holding (\$/yr)	Order (\$/yr)	Total (\$/yr)
A	150	7	1	7.0	2.6	4.0	12.0	1.8	0.988	0.009	\$1,126.41	\$405.51	8.75	414.26
B	15	30	0.5	15.0	3.9	26.0	18.0	1.2	0.980	0.033	\$247.99	\$89.28	5.77	95.05
		37						1.5	98.16%		\$1,374.40	\$494.78	14.52	509.30

The higher values of Q make it possible to achieve the same service with lower r values.
But inventory is higher due to increased cycle stock caused by bulk ordering.
Total cost (inventory plus order cost) is reduced considerably, however, by ordering in bulk.

(c)	c_i	D_i	ℓ_i	theta$_i$	sigma$_i$	Q_i	r_i	F_i	S_i	B_i	I_i
I	($/unit)	(units/ mo)	(mos)	(units)	(units)	(units)	(units)	(order freq)	(fill rate)	(backorder level)	(inventory invest)
A	150	7	1	7.0	2.6	4.0	9.0	1.8	0.913	0.094	$689.10
B	15	30	0.5	15.0	3.9	26.0	22.0	1.2	0.997	0.004	$307.55
		37						1.5	98.11%		$996.65

This lowers service for part A (expensive one) and raises it for part B, so the same average service is achieved with lower total inventory. Note that it's even below the base stock inventory level where Q=1!

(d)	c_i	D_i	ℓ_i	theta$_i$	sigma$_L$	sigma$_i$	Q_i	r_i	F_i	S_i	B_i	I_i
I	($/unit)	(units/ mo)	(days)	(units)		(units)	(units)	(units)	(order freq)	(fill rate)	(backorder level)	(inventory invest)
A	150	7	30	7.0	7	3.1	4.0	9.0	1.8	0.913	0.094	$ 689.10
B	15	30	15	15.0	15	15.5	26.0	44.0	1.2	1.000	0.000	$ 637.50
		37							1.5	98.35%	0.094	$1,326.6

The variability in the lead times inflates the reorder points - in this case for part B (rounding can result in no change).
Note that predictions of service, backorder level, and inventory level are no longer exact, since these are for the model with fixed lead times. In general, they're all too low.

Chapter 3

Study Questions

2. Independent demand originates outside the system which can, in turn, create demand for lower level items (which is dependent demand). If lower level items are sold on their own as spare parts, then they also have independent demand. An example of independent demand is an automobile; a tire is an example of both dependent demand (goes into automobiles) and independent demand (replacement tires). A special transistor that goes into the speaker of a phone is an example of a product with only dependent demand.

4. The Master production schedule (MPS) is the source of all demand for the MRP system. It gives the quantity and due dates for all parts that have independent demand (including external demand for lower level parts).

6. Scheduled receipts are adjusted before any net requirements are computed so that the first net requirement will occur after all scheduled receipts have been exhausted. If we did not we could have a situation in which we have a net requirement followed by a scheduled receipt followed by another net requirement. Presumably, scheduled receipts can be expedited easier than new orders can be placed. Therefore, it makes sense to expedite any outstanding scheduled receipts before we have any new order releases.

8. Lot sizing rules trade off carrying extra inventory versus having more setups. Larger lots result in fewer setups at the expense of more inventory.

10. The following lot sizing rules possess the so-called Wagner-Whitin property:
    - Wagner-Whitin -- *yes*
    - lot-for-lot -- *yes*
    - fixed order quantity (e.g., all jobs have size of 50) -- *no*
    - fixed order period - *yes*
    - part-period balancing -- *yes*

12. The assumption in MRP that makes the implicit assumption of infinite capacity is the assumption of fixed lead times (i.e., the assumption that lead times depend only on the part and not on the status of the line). The impact of this assumption is to inflate planned lead times (more penalty for late jobs than for excess inventory) thereby increasing inventory.

14. A firm planned order is a planned order release that has not been released *and* is not allowed to be changed by future MRP processing. It is treated exactly as a scheduled receipt in MRP calculations (i.e., it is included in the coverage).

16. A bill of material "explosion" happens when the planned order releases for an item create demand for all of the items that are required to make it. At that point the BOM is "exploded" to generate the demand for the other parts.

18. Safety stock if subtracted from on-hand inventory before computing net requirements. Consequently, the use of safety stock "lies" to the system; it can cause demand when there is no real demand.

20. "Nervousness" in an MRP system is characterized by a small change in the MPS causing a large change in the planned order release schedule. It can be caused by lot sizing rules that try to consolidate jobs. It can generate large swings in the schedule, causing people to lose faith in the

system. Some remedies are the use of lot-for-lot to eliminate nervousness at the expense of increased setup and the use of firm planned orders early in the MPS to forcibly eliminate nervousness at expense of the ability to respond to demand changes.

22. Rough-cut capacity planning is used to provide a quick capacity check of a few critical resources to ensure the feasibility of the Master production Schedule. RCCP makes a bill of resources including projected number of hours needed per part. It is optimistic because it doesn't perform any offsetting. It assumes that all work can be done in one period without regard to scheduling. It is pessimistic because it doesn't perform any netting and therefore assumes that none of the demand can be met from inventory.

24. The purpose of dispatching is to schedule the shop floor in a practical manner. Dispatching rules are essentially a queuing discipline. The rules determine which job in a queue should be performed next. The "shortest process time" rule tends to keep machines busy by keeping them clear of long jobs. The "earliest due date" rule works well when all the jobs are the same size but with different due dates.

26. Many ERP systems continue to use the same infinite capacity model used in the original MRP systems. SCM systems, many of which are simply ERP systems that were renamed during the Y2K, they also suffer from the same defect. Layering on other functionality and better interfaces does not resolve the inconsistencies that result from a planning model that results in infeasible schedules.

Problems

2. The MRP table is shown below:

	Week	1	2	3	4	5	6	7	8	9	10
	Demand	41	44	84	42	84	86	7	18	49	30
On Hand	120	79	35	-49	0	0	0	0	0	0	0
	Net Demand	0	0	49	42	84	86	7	18	49	30
	Plan Order Receipts	0	0	49	42	84	86	7	18	49	30
	Plan Order Releases	49	42	84	86	7	18	49	30	0	0

4. The table for the solution is shown below. This shows the optimal cost to make the demand for period *x* in period *y*. For instance, the minimum cost to make the demand for period 7 in period 5 would be $542. This is obtained by adding the minimum cost before period 5 ($242 in period 4) to $200 (the setup cost) plus $86 (to carry 86 parts one period) plus $14 (to carry 7 parts two periods). Shown at the bottom of the table are the minimum cost and the period that the demand should be made in to achieve that cost.

Demand for period		3	4	5	6	7	8	9	10
Net Demand	0	49	42	84	86	7	18	49	30
Make in period	3	200	242	410	668				
	4		400	484	656				
	5			442	528	542	596	792	
	6				610	617	653	800	
	7					728	746	844	
	8						742	791	851
	9							796	826
	10								991

Min:	200	242	410	528	542	596	791	826
t*	3	3	3	5	5	5	8	9

6. We add another row called "offset for safety LT" to compute the "effective" due date The table is shown below:

	Week	1	2	3	4	5	6	7	8	9	10
	Demand	41	44	84	42	84	86	7	18	49	30
On Hand	120	79	35	-49	0	0	0	0	0	0	0
	Net Demand	0	0	49	42	84	86	7	18	49	30
	Plan Order Receipts	0	0	49	42	84	86	7	18	49	30
	Offset for safety LT	0	49	42	84	86	7	18	49	30	0
	Plan Order Releases	91	84	86	7	18	49	30	0	0	0
		Late									

Again, we see that the first planned order release appears as late. As when using safety stock, the use of safety lead time can indicate "problem" conditions when there really are none.

8. The solution is given below:

	Gear	1	2	3	4	5	6	7	8	9	10
	Demand	45	65	35	40	0	0	33	0	32	25
	Sch Receipts					50					
	Adj Sch Receipts				50						
On Hand	150	105	40	5	15	15	15	-18	-18	-50	-75
	Net Demand	0	0	0	0	0	0	18	0	32	25
POQ=2	Plan Ord Receipts	0	0	0	0	0	0	18	0	57	0
L=3	Plan Ord Releases	0	0	0	18	0	57	0	0	0	0
		OK									

a) The scheduled receipt needs to be expedited to period 4, where the first net demand occurs.

b) The planned order releases are given above.

10. This problem illustrates that even with the "optimal" Wagner-Whitin lot sizing rule, nervousness can still occur.

a) The table for the end item with a separate row for "part-periods" is shown below:

	Week(Item)	1	2	3	4	5	6	7	8	9	10
	Demand	20	4	2	0	0	0	0	50	0	0
On Hand	25	5	1	-1	0	0	0	0	0	0	0
	Net Demand	0	0	1	0	0	0	0	50	0	0
	Part Periods	0	0	0	50	100	150	200	250	0	0
	Plan Order Receipts			1					50		
	Plan Order Releases	0	1	0	0	0	0	50	0	0	0
		OK									

Since the setup cost is $248 and the number of part-periods (and therefore the carrying cost) for combining the 50 units in period 8 would be $250 we do not combine that demand with the demands in periods 1, 2, and 3.
This generates demand for the lower level item. Its table is shown below:

	Week(Component)	1	2	3	4	5	6	7	8	9	10
	Demand	0	1	0	0	0	0	50	0	0	0
On Hand	10	10	9	9	9	9	9	-41	0	0	0
	Net Demand	0	0	0	0	0	0	41	0	0	0
	Plan Order Receipts	0	0	0	0	0	0	41	0	0	0
	Plan Order Releases	0	0	0	41	0	0	0	0	0	0
		OK									

Both schedules are good.

b) Now change the demand in week from 50 to 49. The resulting table is shown below:

	Week(Item)	1	2	3	4	5	6	7	8	9	10
	Demand	20	4	2	0	0	0	0	49	0	0
On Hand	25	5	1	-1	0	0	0	0	0	0	0
	Net Demand	0	0	1	0	0	0	0	49	0	0
	Part Periods	0	0	0	49	98	147	196	245	0	0
	Plan Order Receipts			50							
	Plan Order Releases	0	50	0	0	0	0	0	0	0	0
		OK									

Notice that now the inventory carrying cost to produce the 49 in period 8 is less than the setup cost. We therefore produce all the demand in one period. This causes problems in the component schedule as is shown in the table below.

	Week(Component)	1	2	3	4	5	6	7	8	9	10
	Demand	0	50	0	0	0	0	0	0	0	0
On Hand	10	10	-40	0	0	0	0	0	0	0	0
	Net Demand	0	40	0	0	0	0	0	0	0	0
	Plan Order Receipts	0	40	0	0	0	0	0	0	0	0
	Plan Order Releases	40	0	0	0	0	0	0	0	0	0
		Late									

So we have a problem since the component has only one week in which to be finished and the planned lead time is three weeks.

c) Now consider what happens when we have firm planned orders.

	Week(Item)	1	2	3	4	5	6	7	8	9	10
	Demand	20	4	2	0	0	0	0	49	0	0
	FPO	0	1								
On Hand	25	5	2	0	0	0	0	0	-49	0	0
	Net Demand	0	0	0	0	0	0	0	49	0	0
	Plan Order Receipts			0					49		
	Plan Order Releases	0	1	0	0	0	0	49	0	0	0
		OK									

	Week(Compt)	1	2	3	4	5	6	7	8	9	10
	Demand	0	0	0	0	0	0	49	0	0	0
On Hand	10	10	10	10	10	10	10	-39	0	0	0
	Net Demand	0	0	0	0	0	0	39	0	0	0
	Plan Order Receipts	0	0	0	0	0	0	39	0	0	0
	Plan Order Releases	0	0	0	39	0	0	0	0	0	0
		OK									

We see that the FPO in period 1 (acting like a scheduled receipt in the computations) prevents the distant demand from being pulled in while fixing the early schedule to eliminate the nervousness. Note the planned order release in period 2 includes the FPO.

12.

a) The bills of capacity are constructed using the bill of material information and adding up the time that is spent, for all components, in Lamination (Lam) and Core Circuitize (Core Circ). The result is shown below:

Bill of Capacity

	Trinity	Pecos	Brazos
Lam	0.044	0.044	0.046
Core Circ	0.048	0.051	0.055

b) The load for the next six weeks is given by multiplying the value given in the bill of capacity by the requirements for the week and summing over the three board types for each process center. For instance, in week one for lamination we have (7474)(0.044)+(6489)(0.044)+(3898)(0.046)=793.68. The time available for Lamination is given by (5 days/wk)(6 presses)(24 hr./day) = 720 press hr./wk. Surplus (shortage) is computed by simply subtracting the load from the available. The results for the all the boards in all the weeks is shown in the table below.

Week	1	2	3	4	5	6
Trinity	7474	2984	5276	5516	3818	3048
Pecos	6489	5596	7781	7781	3837	4395
Brazos	3898	3966	6132	6132	5975	6051
TOTAL	17861	12546	19189	19429	13630	13494
Lam Load	793.68	559.956	856.58	867.14	611.67	605.838
Lam Avail	720	720	720	720	720	720
Surplus(shortage)	-73.68	160.044	-136.58	-147.14	108.33	114.162
Core Circ Load	904.081	646.758	987.339	998.859	707.576	703.254
Core Circ Avail	960	960	960	960	960	960
Surplus(shortage)	55.919	313.242	-27.339	-38.859	252.424	256.746

Chapter 4

Study Questions

2. The JIT goal of zero defects implies that quality improvements must *always* be sought, while an acceptable quality level implies that complacency is all right. The idea is that time is better spent looking for ways to permanently avoid quality problems than to continually fix them.

4. Many of the benefits of JIT (e.g., smooth predictable flow, lower production costs, improved quality, and better customer responsiveness) are directly attributable to lower WIP levels. Using an adage like "inventory is evil" serves to focus attention on finding ways to reduce WIP.

6. Asking "why?" five times simply means pursuing the cause of a problem beyond the obvious answer. Because a production environment places pressure on everyone to "get product out the door" it is often difficult to find time to analyze the cause of breakdowns, quality problems, scheduling errors, etc. Ohno was urging us to make time to do just this.

8. Quality is important to JIT because low WIP operation is not possible if quality problems frequently disrupt work. At the same time, low WIP operation supports improving quality because shorter queues mean that quality problems will be detected closer to their source and (hopefully) traced to their causes.

10. Flexible labor is important in JIT because the emphasis is on the flow of material. Therefore, if additional help is needed at a particular point in the line to keep the flow moving smoothly, a cross-trained workforce is necessary to allow the needed switching.

12. Mixed model production, by allowing production of multiple finished products in small batches, enables management to match production more closely to demand than is possible with batch production.

14. Two-card kanban is equivalent to one-card kanban if the move resources are treated as workstations. If one-card kanban is used without representing move resources as workstations, then there is less control over where the inventory between workstations is held (i.e., there is no distinction between the outbound stockpoint of station i and the inbound stockpoint of station $i+1$.

16. Possible reasons Toyota's kanban system has not been universally adopted elsewhere include:
    - It was designed and demonstrated specifically for the automotive system of Toyota.
    - It was evolved over a long period of time, during which many customized solutions were developed at Toyota. Other firms may have lacked the patience to work out the details in such excruciating detail.
    - Ohno and others used somewhat confusing language to describe JIT, so that the American descriptions of it required practitioners to fill in considerable detail.

18. The theoretical rigidity of JIT is softened in practice by the use of:
    - capacity buffers
    - cross-trained workers
    - setup reduction
    - WIP buffers (they are not really zero, after all)

20. In a push system, the best place for the bottleneck is at the front of the line, since this would tend to prevent "WIP explosions" because the rest of the line would be able to clear out whatever it received from the bottleneck. In a pull system, the location of the bottleneck is less important, since releases

will be tied to the amount of WIP in the system (and hence in front of the bottleneck) regardless of where it is located.

Chapter 5

Study Questions

2. American faith in the scientific method may have contributed to the failure to develop effective OM tools because we placed so much emphasis on mathematical precision that we shied away from realistic problems that did not lend themselves to clever quantitative solutions. Note that this was a more a matter of trying to "look scientific" than of actually being scientific, however.

4. "W" = well, "P"=poorly

   - A fabrication plant operating at less than 80 percent of capacity with relatively stable demand - W
   - A fabrication plant operating at less than 80 percent of capacity with extremely lumpy demand - P
   - A fabrication plant operating at above 95 percent of capacity with relatively stable demand - P
   - A fabrication plant operating at above 95 percent of capacity with extremely lumpy demand - P (very!)
   - An assembly plant that uses all purchased parts and highly flexible labor - W
   - An assembly plant that uses all purchased parts and fixed labor running at over 95 percent of capacity - P

6. *Romantic JIT* refers to the glowing rhetoric used to describe JIT, while *pragmatic JIT* refers to the various specific techniques (e.g., setup reduction, kanban) associated with JIT. In America, upper management may have been wooed by the appeal of romantic JIT, while those charged with implementing it may have been confused by the lack of systematization in pragmatic JIT.

8. It took Toyota 25 years to reduce punch press setups from three hours to three minutes. This kind of perseverance on a mundane engineering problem seems exceedingly rare in modern day American manufacturing.

Chapter 6

Study Questions

2. Even if A implies B and we observe B to be true, there can be another reason for B to be true, say A'. Most clothing ads run something like this: A = "Brand A&F make the man more attractive." B = "Man attracts a beautiful woman." The advertisement demonstrates the link between If A then B. However, we know that B can also be caused by the man being caring and knowing Factory Physics.

4. A "brain-storming" session can be facilitated using the "conjecture and refutation" scheme with good results. By putting forth a conjecture and hoping to see what refutations can be made, the speaker distances himself from the conjecture and therefore has very little of his ego attached to it. Each refutation develops better understanding of the system and leads to better conjectures.

6. Scale (i.e., size), level of automation, layout (linear versus job-shop), speed (e.g., 1/100 second per page at a printer, 30 seconds per car, 1 hour on a CNC machine, 30 days for fermentation in bio pharma) commodity versus make to order, product complexity, technology involved, amount of capital involved, and so on.

8. Before JIT, inventory was thought to "grease the wheels of manufacturing." Although it has become clear that zero inventory is not a good thing, good inventory levels were so far below existing inventory levels that targeting zero was not a bad idea. Likewise, before TQM, people discussed the "optimal" defect level. This was evaluated considering the cost of a defect versus the cost of detection. Unfortunately, the cost of a defect usually did not consider the devastating consequences of having a shoddy product in a market with better offerings. Nor did it consider the cost of the "hidden factory," that is, the cost of rework, scrap, delays, etc.

   Also, in their heyday, both JIT and TQM became more of a religion than a methodology. As with most dogma, the tenants of JIT and TQM could not be questioned. Tradeoffs acknowledge that there are areas of gray.

   The impact was both positive and negative. On the positive side, the objectives were simple, reduce inventory for JIT, improve quality for TQM, and could be accomplished. On the negative side, many people did not understand *why* what they were doing was good and, consequently, the ideas were often applied in areas that had little impact. Furthermore, as more and more "new" manufacturing techniques were developed, people developed a strong cynicism for *all* new methods.

10. Profit is revenue less operating expenses. ROI is Profit divided by Assets.

    There are plant activities that are not reflected in these measures. These include employee relations, safety, community relations, and the ability to meet future needs (i.e., flexibility). For each of these, specific goals should be set and evaluated with respect to their impact on the other measures (i.e., revenue, operating expenses, and assets).

12. The decision to improve a product depends greatly on what the competition might do. If they improve their products, it may become important that we improve our products on order to stay in the market.

Problems

2.

a) We compute the profit by subtracting labor, material, and overhead costs from revenue. The revenue for the plan will be 750*$350+428*$500+300*$620=$662,500. The labor cost is fixed for each month with 3 operators * $20/hr * 300 hr/mo = $18,000/mo. The overhead cost is given to be $460,000. The material cost is 750*$80 + 428*$150 + 300*$160 = $172,200. Thus the profit per month will be $662,500 - $18,000 - $460,000 - $172,000 = $12,500.

b) The table below shows the computations.

Product	Hr./unit	Hr./mo.	Fraction	Allocated Overhead	Overhead per unit	Cost per unit	Profit per unit
X-100	0.483333	362.50	0.4275	$196,662	$262.22	$351.88	($1.88)
X-200	0.55	235.40	0.2776	$127,708	$298.38	$459.38	$40.62
X-300	0.833333	250.00	0.2948	$135,629	$452.10	$628.76	($8.76)
TOTAL		**847.9**					

The "Hr./unit" entry comes from adding up the labor time for each product. "Hr./mo." is the product of Hr./unit and the number of units made per month. The "Fraction" is Hr./mo. divided by the total Hr./mo. (847.9). The "Allocated Overhead" is simply the Fraction times the total overhead cost ($460,000). The "Overhead per unit" is the Allocated Overhead divided by the number produced per month. The "Cost per unit" is the sum of the Overhead per unit plus the material cost plus the labor cost per unit (labor used, not fixed labor cost). The "Profit per unit" comes from subtracting the cost per unit from the price. If we sum up the products of the Profit per unit and the number of units produced per month we obtain $13,342 for the monthly profit. This differs from $12,500 in (a) because here we consider the cost of only the labor used as if we would only have to pay for 847.9 hours instead of 900 hours. The computation in (a) is more accurate.

If we consider the above unit profit, we should try to make all of the X-200 that we can, followed by X-100, and then, finally, the X-300. Since the maximum demand for X-200 is 500 we schedule production for 500 units of X-200. This leaves the following amount of time for each station:

Mach Time	Used	Remaining
Mot Assem	116.67	183.33
Fin Assem	100.00	200.00
Test	58.33	241.67

Using the following information

Product	M. Assem (min/unit)	F. Assem (min/unit)	Test (min/unit)
X-100	8	9	12

we see that we can make 1208 units of X-100 with the remaining capacity. This yields a profit of $26,160 which is significantly better than before.

c) The ABC cost allocation method is shown in the table below (labor hours are computed using the schedule given in (a)).

Category	Plant/Equipment	Management	Purchasing	Sales/Shipping	Total
Total Cost	$250,000	$100,000	$60,000	$50,000	$460,000
Base	Sq. ft	Labor Hr.	Purch Orders	Cust Orders	
Total Units Used	120000	847.9	2000	150	
Units Used X-100	30000	362.5	500	100	
Units Used X-200	40000	235.4	600	30	
Units Used X-300	50000	250	900	20	
Unit Cost	$2	$118	$30	$333	
Total OH X-100	$62,500	$42,753	$15,000	$33,333	$153,586
Total OH X-200	$83,333	$27,763	$18,000	$10,000	$139,096
Total OH X-300	$104,167	$29,485	$27,000	$6,667	$167,318
					$460,000

The unit allocation of overhead is computed by dividing the Total OH by the scheduled production. The total unit cost is the unit overhead plus the material cost plus the labor cost. The unit profit is this number subtracted from the price.

Unit OH	Unit Cost	Unit Profit
$204.78	$294.45	$55.55
$324.99	$485.99	$14.01
$557.73	$734.39	($114.39)

i. The most profitable is now X-100 instead of X-200. A check is provided by multiplying each unit profit by the production schedule and summing. This results in $13,342, the same as in (a) when assuming variable labor costs.

ii. Build all you can of X-100, then X-200, and finally X-300. Since Test takes the most time for X-100 (12 min) we can compute how many X-100's are possible.

$$\text{Max Production of X-100} = \frac{300\text{hr}}{12\text{min}/60\text{min}/\text{hr}} = 1500\text{units}$$

Since the maximum demand is 1500 units, we schedule 1500 units of X-100. This uses up all the time at Test so there is no time to schedule anything else.
The resulting profit is a *loss* of $69,500 assuming labor is variable or a loss of $73,000 assuming labor is fixed.

iii. The problem with this approach is that it uses only *costs* and does not take into account how much of a critical resource might be consumed by a particular product. In the above example, labor costs were fairly insignificant compared to other costs. However, labor is a *limited* resource and so we must be careful how it is allocated.
By the way, the schedule to make 1062 of X-100, 500 of X-200, and 125 of X-300 yields a profit of $41,391 assuming labor to be variable or $41,240 assuming labor is fixed. We discuss how to find these solutions in chapter 16.

Chapter 7

Study Questions

2. Since

$$TH = \frac{WIP}{CT}$$

one can have the same TH with high WIP levels and long cycle times or with low WIP levels and short cycle times. Obviously, the later is better since you have better control, less money tied up in inventory, shorter cycle times for better responsiveness, less reliance on forecasts, and better quality.

4. Practical worst case represents the maximum randomness case; when you neither see an empty queue nor a full queue all the time. The throughput and cycle time for practical worst case are always between best and worst case scenarios.
If there is extremely high variability or there is batching, performance will be worse than PWC. When this happens, throughput decreases and cycle time increases.

6. The expected time until completion is 10 minutes, no matter how long the job has been running. This is because of the memoryless property of the exponential distribution.

Problems

2. Station 1: 60/15 = 4/hr, Station 2: (60/12)(0.75) = 3.75/hr, Station 3: 60/14 = 4.29/hr

   a) r_b = 3.75/hr, T_0 = 15 + (12/0.75) + 14 = 45 min = 0.75/hr, $W_0 = r_bT_0$ = (3.75)(0.75) = 2.81 jobs

   b) Station 2: (60/12)(0.5) = 2.5/hr = r_b, T_0 = 15 + (12/0.5) + 14 = 53 min = 0.883/hr, $W_0 = r_bT_0$ = (2..5)(0.883) = 2.2 jobs. The critical WIP is smaller because it is easier for the other stations to keep up with a slower bottleneck. But reducing the availability of station 2 reduces the capacity of the bottleneck, which will likely result in lower throughput as well as lower WIP.

4. $r_a(1)$ = 8,000 + 5,000 = 13, 000, $r_a(2)$ = 8,000. u(1) = 13,000/15,000 = 0.867, u(2) = 8,000/10,000 = 0.8, so Station 1 (punching) is the bottleneck, since it has the highest utilization.

6. When all jobs are processed before moving, we approach the worst case performance with cycle time given by $CT = wT_0$.

   a) The base parameters do not change from problem 1 for any of the cases. However, the performance sometimes does change from problem 1.

   b) There is no change from (a) regarding cycle time and throughput. This is in contrast with problem 1.

   c) Speeding up station 2 reduces the raw process time and therefore reduces cycle time and increases throughput for all WIP levels.

   d) If all the jobs are worked on by only one machine (assumed in the problem) at station 1, there is absolutely no change in performance.

   e) If station one is speeded up this will reduce the raw process time as in problem 1 and so will improve performance for all WIP levels.

8. The parameters of the system are

Station	Process Time	Number of Machines	Production Rate per Min
1	15	5	0.333
2	30	12	0.400
3	3	1	0.333

a) Adding up the process times yields $T_0 = 48$ min while the minimum production rate is $r_b = 0.333$ jobs / min. Multiplying these yields a critical WIP of 16 jobs.

b) The cycle time with WIP = 20 jobs for

i. Best case: $\text{CT} = 20 / 0.333 = 60\,\text{min}$

ii. Worst case: $\text{CT} = (20)(48\,\text{min}) = 960\,\text{min}$

iii. Practical worst case:

$$\text{CT} = T_0 + \frac{w-1}{r_b} = 48 + \frac{20-1}{0.333} = 105\,\text{min}$$

c) To get a throughput of 90 percent of the bottleneck we need:

i. Best case: $0.9r_b = \frac{w}{T_0} = \frac{w}{W_0} r_b$ so that $w = 0.9W_0 = (0.9)(16) = 14.4\,\text{jobs}$ or 15 jobs.

ii. Worst case: "You can't get there from here."

iii. Practical worst case: $0.9r_b = \frac{w}{W_0 + w - 1} r_b$ or $(0.9)(16 + w - 1) = w$

solving for w yields 135 jobs. Quite a difference from the Best case.

d) From the definition of α

$$\alpha = \frac{W_0}{W_0 - 1}\left(\frac{\text{CT}(W_0)}{T_0} - 1\right) = \frac{16}{16-1}\left(\frac{100}{48} - 1\right) = 1.16$$

10. r_b = 2000 per day = 125 per hour, T_0 = 0.5 hours, W_0 = 62.5 cases, TH =1700 cases/day = 106.25 per day, CT = 3.5 hours

a) WIP = TH x CT = 106.25 x 3.5 = 372 cases

b) TH_{PWC}(WIP) = [w/(w+W_0-1)]r_b = [372/(372+62.5-1)]125 = 107.27 per hour, so we are roughly at the performance level of the PWC.

c) Throughput would increase (or at least not decrease), because bottleneck would be blocked/starved less. Unbalancing the PWC line causes it to perform better.

d) Throughput would increase (or at least not decrease), because bottleneck would be blocked/starved less. Replacing single machine stations with parallel machine stations in the PWC causes it to perform better.

e) Moving cases in batches would further inflate cycle time by adding "wait for batch" time.

12.. Since the line is balanced W_0=5 (the number of stations). Since it behaves like the practical worst case, we can use the following to compute the current WIP level:
(a)

$$TH_{PWC}(w) = \frac{w}{w+W_0-1} r_b = \frac{w}{w+4} r_b = 0.75 r_b$$

$$w = 12$$

(b) Since the line is balanced, $T_0=5(1/r_b)$. By Little's law,

$$CT = \frac{w}{TH} = \frac{12}{0.75 r_b} = 16\frac{1}{r_b}$$

$$\frac{CT}{T_0} = \frac{16(1/r_b)}{5(1/r_b)} = 3.2 = 320\%$$

(c) (i) Increase WIP: WIP↑, TH↑, CT↑ [Note that: TH=(13/17)r_b, CT=(13/(13/17)r_b)=17(1/r_b)>16(1/r_b)]
(ii) Decrease variability at a station: WIP→, TH↑, CT↓
(iii) Decrease capacity at a station: WIP→, TH↓, CT↑
(iv) Increase capacity at all stations: WIP→, TH↑, CT↓

Chapter 8

Study Questions

2.

a) Time to complete this set of study questions – LV

b) Time for a mechanic to replace a muffler on an automobile -- LV

c) Number of rolls of a pair of dice between rolls of seven -- MV

d) Time until failure of a recently repaired machine by a good craftsman -- LV

e) Time until failure of a recently repaired machine by a not-so-good mechanic – HV

f) Number of words between typographical errors in the book *Factory Physics* -- MV

g) Time between customer arrivals to an automatic teller machine -- MV

4. If the utilization is *equal* to 1 then the arrival rate will equal the capacity. If there is any randomness in the process times (and there is significant randomness in the M/M/1 case) then, regardless of how much WIP there is, there can always be a sequence of events in which the WIP will be exhausted and the machine starved. Since, on average, this deficit cannot be made up, the only way to maintain 100% utilization is to make sure the machine *never* starves. This can be ensured only with an *infinite* amount of WIP. In order for a queue to be "stable" the average amount of WIP must be less than infinity. Therefore, a M/M/1 queue must have less than 100% utilization in order to be stable.

6. For the M/M/1 case, the number of customers is adequate to fully define the state of the system because process times are memoryless. Thus, knowledge of how long a station has been working on a particular job is irrelevant. This is not the case in the G/G/1 case. For instance, consider the case with zero variability in both arrivals and process times. Such a system will never have a queue. It is also very important to know how long a job has been in process since the next arrival is essentially synchronized with the current job's departure.

Problems

2.

a) The arrival rate is 20 per hour or 1/3 per minute. The utilization is then

$$u = r_a t_e = (1/3 \text{ job}/\text{min})(2.5 \text{ min}) = 5/6 = 0.833$$

b) With exponential process times and exponential inter-arrival times, the system will be an M/M/1 queueing system.

i) $\text{CT} = \dfrac{t_e}{1-u} = \dfrac{2.5\,\text{min}}{1-0.833} = 15\,\text{min}$

ii) $\text{WIP} = r_a \text{CT} = (1/3 \text{ job}/\text{min})(15\,\text{min}) = 5 \text{ customers}$

iii) The probability of finding more than three jobs in the system will be one minus the probability of finding 3 or less jobs in the system. The probability of finding n jobs in the system is

$$p_n = (1-u)u^n$$

so then

$$P\{\text{more than } 3\} = 1 - p_0 - p_1 - p_2 - p_3$$
$$= 1-(1-u)-(1-u)u-(1-u)u^2-(1-u)u^3$$
$$= 1-(1-0.833)(1+0.833+0.833^2+0.833^3) = 0.482$$

c) If the standard deviation is 5.0 then the SCV will be 4.0.

i. The average time in queue and at the station is

$$\text{CT}_q = \frac{1+c_e^2}{2}\frac{t_e u}{1-u} = \frac{1+4}{2}\frac{(2.5)(5/6)}{1-(5/6)} = 31.25\,\text{min}$$
$$\text{CT} = \text{CT}_q + t_e = 31.25\,\text{min} + 2.5\,\text{min} = 33.75\,\text{min}$$

ii. The number of jobs at the station is obtained from Little's law.

$$\text{WIP} = r_a \times \text{CT}$$
$$\text{WIP} = (1/3)\times(33.75) = 11.25$$

iii. The number of jobs in queue is also obtained from Little's law.

$$\text{WIP}_\text{q} = r_a \times \text{CT}_\text{q}$$
$$\text{WIP}_\text{q} = (1/3)\times(31.25) = 10.42$$

4. This is an example of a *non*-preemptive outage. The average number of jobs between outages will be the number corresponding to 60 hours. Since the average process time for 60 panel jobs is 2 hours, the average number of jobs between outage will be $N_S = 60/2 = 30$. Other parameters are

$$t_s = 120\,\text{min},\ \sigma^2 = 120^2 = 14{,}400\,\text{min}^2 \ \ \text{(exponential)}$$

Thus, the effective mean, variance, and SCV will be:

$$t_e = t_0 + t_s / N_s = 120 + 120/30 = 124\,\text{min}$$
$$\sigma_e^2 = \sigma_0^2 + \frac{\sigma_s^2}{N_s} + \frac{N_s - 1}{N_s^2} t_s = 135 + \frac{14400}{30} + \frac{30-1}{900}120^2 = 1079\,\text{min}^2$$
$$c_e^2 = \frac{\sigma_e^2}{t_e^2} = \frac{1079}{120^2} = 0.07493$$

which is not very different from 3(c).

6.

a)

$$r_a = 13.5 \text{ per hour},\ m = 5,\ c_a^2 = 1,\ t_0 = 0.3 \text{ hour},\ c_0^2 = 0.25,\ m_f = 36 \text{ hour},\ m_r = 4 \text{ hour}$$

therefore $A = m_f/(m_f + m_r) = 36/(36+4) = 0.90$

Effective SCV is computed from :

$$\text{c}_\text{e}^2 = c_0^2 + \frac{2A(1-A)m_r}{t_0} = 0.25 + \frac{2(0.9)(1-0.9)(4)}{0.3} = 2.65$$

b)

$$t_e = t_0 / A = 0.3/0.9 = 0.3333$$
$$u = (r_a / m)t_e = (13.5/5)(0.3333) = 0.9$$

c)

$$t_e = t_0 / A = 0.3/0.9 = 0.3333$$
$$u = r_a t_e / m = (13.5)(0.3333)/5 = 0.9$$

d) One machine at a time:

$$\mathrm{CT} = \mathrm{CT}_q + t_e = \frac{c_a^2 + c_e^2}{2}\frac{u}{1-u}t_\mathrm{e} + t_e = \frac{1+2.65}{2}\frac{0.9}{1-0.9}0.3333 + 0.3333 = 5.8\,\text{hour}$$

e) Single queue for 5 machines:

$$\mathrm{CT} = \mathrm{CT}_q + t_e = \frac{c_a^2 + c_e^2}{2}\frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)}t_\mathrm{e} + t_e = \frac{1+2.65}{2}\frac{0.9^{\sqrt{2(5+1)}-1}}{(5)(1-0.9)}0.3333 + 0.3333 = 1.27\,\text{hour}$$

8. There are 10 tasks that take an average time of 6 minutes. The CV (not the SCV) is 0.75 so the standard deviation is 4.5 minutes and the variance is 20.25 minutes squared. Since the tasks are independent, we can add the variances yielding a variance of 202.5 for the combination. The mean for the 10 tasks is 60 minutes, hence the SCV (the variance divided by the mean squared) will be202.5/60^2 which is 0.05625

a) The CV will be the square root of the SCV or 0.237, significantly less than 0.75.

Let c_0^2 = the SCV of the original task, σ_0^2 be the variance of the original task, t_0 be the mean, and n be the number of tasks. Then the SCV of the combined task, c_e^2, comes from

$$c_e^2 = \frac{n\sigma_0^2}{(nt_0)^2} = c_0^2 / n.$$

b)

c) Issues:

i. People tend to do a smaller, simpler, more repetitive task more efficiently than a long complicated task.

ii. People can become bored if the task is too simple and repetitive.

iii. The assumption of task independence is usually not correct so the reduction of variability by combining tasks is usually not as dramatic. A good strategy might be to define the *largest* task possible that a person can do consistently and repeatedly. This will usually result in a rather simple and short task that may result in boredom. A good idea is to tradeoff periodically to prevent boredom but not so often that efficiency suffers (e.g., once per shift).

d) By standardizing production methods, the way a task is done tends to take the same amount of time. This, in itself, reduces variability.

10. Parts a–c use section 8.7.1

a) Since both machines have SCV of 1, we can use the M/M/1/b model

i. TH for the balanced case is given by

$$\mathrm{TH} = \frac{b}{b+1}r_a = \frac{12}{12+1}\frac{1}{20} = 0.046\text{ jobs/min} = 2.77\text{ jobs/hr}\ 92\%\text{ utilization.}$$

ii. WIPP=*b*/2=12/6=6

iii. CT=WIPP/TH+t1 = 6/.046 j/min+20 min=150 min

iv. WIP=TH*CT=0.046*150=6.9

b) TH = 0.0375 jobs/min = 2.25 jobs/hour, an 18.5% decrease, CT = 60 min, a 60% decrease, and WIP = 2.25, a 67% decrease. The drop in throughput probably makes this a bad strategy. However, if demand is less than 2.25 jobs per hour, it could be a good strategy. Nonetheless, utilization has dropped to 75%.

c) TH = 0.0467 jobs/min = 2.8 jobs per hour, CT = 35.7 min, and WIP = 1.67 jobs. The throughput is above what it was initially while cycle time and WIP have dropped significantly. However, the utilization of the second machine is now less than 47%.

d) For this problem we must use section 8.7.2.

i. Since both machines have the same capacity, we use equation (8.47) [which has a typo in the first printing] to obtain an approximation of the TH,

$$\text{TH} \approx \frac{c_a^2 + c_e^2 + 2(b-1)}{2(c_a^2 + c_e^2 + b - 1)} r_e = \frac{0.0625 + 0.0625 + 2(3-1)}{2(0.0625 + 0.0625 + 3 - 1)} \frac{1}{20} = 0.0485 \text{ jobs/min}$$

ii. An approximate upper bound on the **system** WIP is given by equation (8.44) [which contains a typo in the first printing].

$$\text{WIP} \le \min\{\text{WIP}_{nb}, b\}$$

Since WIP_{nb} is infinity in the balanced case, the WIP bound will be *b* or 3.

iii. The lower bound on **system** CT is given by the WIP upper bound divided by TH, or 3/0.0485 = 61.9.

Better approximations predict a WIP of 2.47 and a cycle time of 50.91, both within the bounds.

iv. If we reduce variability, we can increase throughput, reduce cycle times, and reduce WIP while keeping utilization fairly high.

12. Since the line is balanced W_0=5 (the number of stations). Since it behaves like the practical worst case, we can use the following to compute the current WIP level:

a)

$$TH_{PWC}(w) = \frac{w}{w+W_0-1} r_b = \frac{w}{w+4} r_b = 0.75 r_b$$

$$w = 12$$

b) Since the line is balanced, $T_0=5(1/r_b)$. By Little's law,

$$CT = \frac{w}{TH} = \frac{12}{0.75 r_b} = 16\frac{1}{r_b}$$

$$\frac{CT}{T_0} = \frac{16(1/r_b)}{5(1/r_b)} = 3.2 = 320\%$$

c)

i. Increase WIP: WIP↑, TH↑, CT↑ [Note that: TH=(13/17)r_b, CT=(13/(13/17)r_b)=17(1/r_b)>16(1/r_b)]

ii. Decrease variability at a station: WIP→, TH↑, CT↓

iii. Decrease capacity at a station: WIP→, TH↓, CT↑

iv. Increase capacity at all stations: WIP→, TH↑, CT↓

Chapter 9

Study Questions

2. The wait for batch time is larger when utilization is low because it takes longer to create a batch when throughput is less.

4. The proposed policy could do a great deal to reduce variability in that it would eliminate excessively long process times at either station. Reducing variability in process times should increase throughput by preventing blocking and starving in the line.

6. Although there would be maximum throughput with minimum WIP with 4 jobs, even with variable process times, there is still the issue of raw material and finished goods inventories. If customers showed up just when we completed the production of one product, there would be no finished goods inventory. Of course, this is hardly likely and therefore we would either have finished goods inventory or customers would have to wait. In either case, there would be a buffer. We would need similar coordination for raw materials or else we would need to keep a raw material inventory buffer or else periodically starve the system for WIP.
   If demand was constant and the process times were random, we would still need these buffers since the output (and usage) would typically not correspond to the constant demand pattern.

Problems

2. Typical buffers for each would be:
   a) A maker of custom cabinets: time and capacity
   b) A producer of automotive spare parts: inventory
   c) An emergency room: capacity (can't use time, cannot inventory "treated patients")
   d) Wal-Mart: inventory
   e) Amazon.com: inventory and time (for slow movers)
   f) A government contractor that builds submarines: time
   g) A bulk producer of chemical intermediates such as acetic acid: inventory
   h) A maker of lawn mowers for K-Mart, Sam's Club, and Target: inventory
   i) A freeway: capacity and time, the less capacity there is, the more time people spend in traffic
   j) The space shuttle (i.e., as a delivery system for advanced experiments): time
   k) A business school: time

4. This one is easier than it looks.
   a) SCV of arrivals is zero since they are deterministic.
   b) SCV of effective process times is zero since they are deterministic and have not random outages.
   c) The utilization is simply, $r_a\, t_e$. r_a = 2 j/h = (1/30) j/min. Therefore u = 29/30 = 0.9667.
   d) There is no variability. The time in queue for the *D/D/1* queue is always zero.
   e) The total cycle time at station 1 is the process time, 29 minutes.

f) The SCV of arrivals is also deterministic either by using equation (8.10) or by obvious observation.

g) To get the utilization we must first compute t_e.

$t_e = t_0 / A$, where A is the availability, $A = MTTF/(MTTF + MTTR) = 10/(10+1) = 0.909$

therefore, $t_e = 26/0.909 = 28.6$ and the utilization will be $u = r_a t_e = (1/30)(28.6) = 0.9533$

h) The SCV of process times is given by equation (8.6)

$$c_e^2 = c_0^2 + (1 + c_r^2) A(1-A)\frac{m_r}{t_0} = 0 + (1+1)(0.909)(1-0.909)(60)/(26) = 0.3814$$

Because no information was given in the problem, we assumed the repair times were of moderate variability and therefore $c_r^2 = 1$, a conservative assumption. Also, note that c_0^2 is zero because there is no variability.

i) The cycle time at station 2 is given by equation (8.25) with SCV of arrivals being zero and SCV of process time that we computed in (h).

$$CT_q = \left(\frac{c_a^2 + c_e^2}{2}\right)\left(\frac{u}{1-u}\right)t_e = \left(\frac{0+0.3814}{2}\right)\left(\frac{0.9533}{1-0.9533}\right)28.6 = 111.33 \text{ min}$$

j) Total cycle time will be cycle time in queue plus the effective process time, 111.33 min + 28.6 min = 139.93 min.

6. Demand is 160 parts per day. With a 16 hour day, this becomes 160/16 = 10 parts per hour.

a) The maximum capacity is 125 parts divided by the heat treat time of 6 hours which is 20.833 per hour or 333.333 per 16 hour day.

b) If we assume we always do a full batch we must consider the “wait-to-batch-time” (WTBT). We can model this as a two process with a “batcher” before the oven. Once the batcher accumulates a batch, a queue of batches forms in front of the oven. The WTBT would be (125-1)/(2*10pph) = 6.2 h. The utilization would be u = 10pph/20.833pph = 0.48.

The SCV of arrivals would be 1/125 = 0.008 and SCV of process time is $(3\text{h}/6\text{h})^2 = 0.25$. Using the VUT equation we get

$$\text{CT}_q = \left(\frac{0.008 + 0.25}{2}\right)\left(\frac{0.48}{1-0.48}\right) 6 = 0.714 \text{ hour}$$

Add these together with the process time and you get, 6.2h + 0.714h + 6h = 12.91h.

c) The minimum batch size to meet demand is:

$k_{\min} / 6\text{ h} > 10 \text{ pph}$

or

$k_{\min} > 60$

therefore

$k_{\min} = 61$

d) The average CT would be 56.95 h.

e) Searching over the range reveals a minimum at batch size of 91 with a cycle time of 12.02 h. Note that this is the minimum for a policy that batches a given amount and then queues the batch before the furnace. A different policy, say one in which a batch starts with whatever has queued during the last oven load, will have different cycle times.

The maximum the system can hold is $b = 7$, 5 in the buffer and in each machine.

a) For balanced lines, $TH = \frac{b}{b+1} r_e = \frac{7}{7+1}\frac{1}{10} = 0.0875$ jpm

Partial WIP $= b/2 = 7/2 = 3.5$; Using Little's Law for Partial CT = WIP/CT $= 3.5/0.0875 = 40$ min

Total CT $= 40\text{min} + 10\text{ min} = 50$; Total WIP = TH*CT $= 0.0875\text{jpm} * 50\text{ min} = 4.375$ j

b) TH $= 0.090$ jpm; CT $= 60$ min; WIP $= 5.4$ j

c) For unbalanced lines:

$$\text{TH} = \frac{1-u^b}{1-u^{b+1}} r_a = \frac{1-(12/10)^7}{1-(12/10)^8}\frac{1}{10} = 0.07828 \text{ jpm};$$

$$\text{Partial WIP} = \frac{u}{1-u} - \frac{(b+1)u^{b+1}}{1-u^{b+1}} = \frac{1.2}{1-1.2} - \frac{(8)(1.2)^8}{1-1.2^8} = -6.0 - \frac{34.4}{1-4.3} = 4.42$$

(partial WIP is WIP at the second station, in the buffer and at the first station when it is blocked)

Partial CT = Partial WIP/CT= 4.42/0.07828 = 56.5

CT = 56.5 min + 10 min = 66.5 min

WIP= (TH)(CT) = (0.07828)(66.5) = 5.2

8. This problem refers to section 8.7.

d) The calculations for TH and partial WIP are the same except that u is now 10/12 instead of 12/10. TH stays the same. Partial WIP becomes 2.57. This leads to a partial CT = WIPP/TH = 32.9 min and a total CT of 32.9 + 10 = 42.9 min which produces a total WIP = TH*CT = 0.07828*43.9 = 3.51. Notice that we now have less WIP and shorter CT than before (not surprising since the first machine is now the slower).

e) We return to a balanced system with both machines taking 10 minutes, the buffer is 5, and the second machine SCV becomes ¼. Using equation (8.47) we can compute TH.

$$\text{TH} \approx \frac{c_a^2 + c_e^2 + 2(b-1)}{2(c_a^2 + c_e^2 + b - 1)} r_e = \frac{1+0.25+2(7-1)}{2(1+0.25+7-1)}\frac{1}{10} = 0.0914 \text{ jpm}$$

10. This case is different from problem 7 in that the buffers here are large but not infinite.
   a) If we reduce the buffer sizes, the number of jobs that balk will increase, thereby decreasing TH. The maximum WIP level also decreases as does cycle time. Cycle time goes down because it is a convex function of WIP (recall chapter 7).
   b) Reducing the variability should increase TH (slightly by reducing the amount of balking and decrease CT.
   c) If we unbalance the line without changing rb we must add capacity to the other stations otherwise a different station would become the bottleneck with a capacity lower than the current value of rb). If we add capacity, we increase TH (slightly) and decrease CT (more significantly).
   d) The opposite of b.
   e) Decreasing the arrival rate decreases TH (obviously) and also decreases utilization which thereby decreases CT.
   f) If we decrease the variability enough we might see an increase in TH and a reduction in CT.

12. Using the VUT equation, we compute the expected time in queue at the first station to be 45 hours. Using,

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

we compute the squared coefficient of variation (SCV) for arrivals to the second station to be

$$c_a^2(2) = c_d^2(1) = (.09^2)9 + (1 - 0.9^2)1 = 7.48$$

Using this value and the VUT equation again yields an expected queue time of 74.16 hours at the second station. The significant increase is due to the high arrival variability (i.e., $c_a^2(2) = 7.48$). Cycle time is given by the sum of the queue times plus the process times,

CT = 45 + 1 + 74.16 + 1 = 121.16

First, try installing the new machine at the second station. Since this does not affect the first station, the only difference is the expected time in queue at the second station, which is reduced to 34.79, less than half what it was before. This causes total cycle time to fall to 81.79, a decrease of slightly over 32%.

Next, try installing the new machine at the first station. This causes wait time at the first station to decrease from 45 to 5.63 hours, and reduces the SCV of arrivals to the second station from 7.48 to 0.39. This reduced arrival variability reduces expected wait time at the second station from 74.16 to 42.27. The net result is a reduction of overall cycle time from 121.16 to 49.90, a decrease of over 58%, which is 39% lower than the cycle time achieved by placing the flexible machine in the second position.

14. The least cost configuration is computed by computing the minimum number of tools required for each machine choice and choosing the cheapest one.

a) The least cost configuration that meets demand is given in table 1 with a total cost of $468,000.

Station	Number of Machines	Machine Type	Speed (prt/hr)	CV	Total Cost (K$)
MMOD	2	1	42	2.0	100
SIP	2	1	42	2.0	100
ROBOT	2	1	25	1.0	200
HDBLD	9	3	6	0.75	216

Table 2: A "good" solution that meets cycle time and demand.

b) Since there can be any number of tools at any station, there are an infinite number of possible configurations. If we knew beforehand how many tools there should be at each station, there are 96 different combinations of machine types. Therefore, we had best not try to enumerate them all.

c) One way to attack this problem is to build a spreadsheet using the queueing equations of Chapter 8 (in particular, 8.12, 8.13, 8.28 and 8.11). The one piece of data that is missing is $c\frac{2}{a}$ for the MMOD station. Use $c_a^2 = 1$. It is reasonable if there are many sources of demand and conservative if demand is more regular. In this problem, t_e and c_e^2 are given so that $t_e = t_e$ and $c_e^2 = c_o^2$. We also need to convert the production rates to production times. The average time for the Type 1 machine at MMOD is $t_e = t_0 =$ (50prt/job)/(42prt/hr) = 1.19hr/job. Likewise, the arrival rate will be

r_a = (1000prt/day)/(50prt/job)(24hr/day) = 0.833job/hr

Using the spreadsheet and trying different combinations yields a pretty good configuration. Note that this is not necessarily the optimal solution.

16. r_a = 12/396min = 1batch/396min. All times below are in minutes:

$$s_1 = 15 \quad t_1 = 7$$
$$s_2 = 8 \quad t_2 = 3$$
$$s_3 = 12 \quad t_3 = 4$$

a) Let xi be the time to do one batch of part i. The utilizations are:

$$x_1 = 12 \; x \; 7 + 15 = 99 \quad u_1 = 99/396 = 0.25$$
$$x_2 = 12 \; x \; 3 + 8 = 44 \quad u_2 = 44/396 = 0.11$$
$$x_3 = 12 \; x \; 4 + 12 = 99 \quad u_3 = 60/396 = 0.15$$

b) If parts are moved 12 at a time and there is no variability, the cycle time will be the sum of the x values, or 203 minutes.

c) The cycle time for the first part will be the sum of the setup and single processing times,

$$T_1 = \sum_{i=1}^{3}(t_i + s_i) = 49 \; min$$

d) The problem should ask for the average of the cycle time for the 12th part, not the range. Creating a Gantt chart yields 106 min.

e) The problem should ask for the average of the cycle times for parts moved one at a time, not the range. It is 73.9.

f) The cycle times will be:

T_1	49
T_2	53
T_3	57
T_4	61
T_5	65
T_6	69
T_7	73
T_8	78
T_9	85
T_{10}	92
T_{11}	99
T_{12}	106
Avg	73.91 7

g) The utilizations become,

$u_1 = \; .05, u_2 = 0.22, u_3 = 0.3$

Since there is no variability and the utilizations remain below one, the cycle times do not change.

h) Assuming Poisson arrivals indicates $c_a^2(1) = 1$ and all of the stations have $c_e^2 = 0.$ Then for the first station,

$$CT_q(1) = \frac{c_a^2 + c_e^2}{2} \frac{u}{1-u} x_1 + x_1$$

$= (0.5)(0.25)/(1-0.25)(99)$

$= 16.5\ min$

The second station $c_a^2(2) = c_a^2(1)\left(1-u^2(1)\right) + c_e^2u^2 = (1)(1-0.25^2) = 0.9375$

$$CT_q(2) = \frac{c_a^2 + c_e^2}{2}\frac{u}{1-u}x_1 + x_1$$

$= (.9375/2)(0.1111/(1-0.1111)(44)$

$= 2.578\ min$

For the third station $c_a^2(3) = (0.9375)(1-0.1111^2) = 0.9259.$

$CT_q(2) = (.9259/2)(0.15/(1-0.15)(60)$

$= 4.96\ min$

The total cycle time in queue becomes 24 min.

i) If we double the rate, the utilizations double. The computations are the same with the resulting cycle times as:

$CT_q(1) = 49.5$
$CT_q(2) = 4.71$
$CT_q(3) = 9.30$
$Total = 63.5$

Chapter 10

Study Questions

2. WIP can be simply counted, but throughput must be measured relative to capacity, which cannot be directly observed and must therefore be estimated.

4. Pull systems control the robust parameter (WIP) while push systems control the sensitive parameter (releases). The practical implication is that a pull system will have less tendency to get out of control than a push system.

6. Authorizing the downstream operator to reject parts for quality reasons can promote communication between stations in much the same way as pulling would.

Problems

2.

a)

$$\tilde{w} = 3\frac{u}{1-u} = 3\frac{0.9}{1-0.9} = 27$$

b)

$$TH = \frac{w}{w+W_0-1} r_b = \frac{27}{27+3-1} 0.5 = 0.466$$

Because the push system may release work into the line when the queue is very long, average WIP is inflated without achieving high throughput. The more efficient CONWIP line achieves a higher throughput for this same WIP level.

4.

a) Note that r_b=0.5, T_0=6, W_0=3. First consider the push system. Since this is 3 M/M/1 queues in series, the WIP level will be:

$$WIP(TH) = \frac{3u}{1-u} = \frac{3TH / r_b}{1-TH / r_b} = \frac{3TH}{r_b - TH}$$

So the profit is given by:

$$\Pi(TH) = pTH - hWIP(TH) = pTH - \frac{3hTH}{r_b - TH}$$

We can optimize the throughput (release rate) by taking the derivative, setting equal to zero, and solving for TH:

$$\frac{d\Pi}{dTH} = p - \left[\frac{(r_b - TH)3h + 3hTH}{(r_b - TH)^2}\right] = 0$$

$$TH^* = r_b - \sqrt{3hr_b / p}$$

$$= 0.5 - \sqrt{3(0.25)(0.5)/50} = 0.4134$$

$$\Pi^* = pTH^* - \frac{3hTH^*}{r_b - TH^*} = 50(0.4134) - \frac{3(0.25)(0.4134)}{0.5 - 0.4134} = \$17.09$$

Now consider the CONWIP case. Since this line meets the conditions of the PWC, we can write the throughput as a function of WIP (w) as:

$$TH(w) = \frac{wr_b}{w + W_0 - 1}$$

So profit is given by:

$$\Pi(w) = pTH(w) - hw = \frac{pwr_b}{w + W_0 - 1} - hw$$

Again, we optimize by taking the derivative, setting equal to zero and solving:

$$\frac{d\Pi}{dw} = \frac{(w + W_0 - 1) - w}{(w + W_0 - 1)^2} pr_b - h = 0$$

$$w^* = \sqrt{\frac{(W_0 - 1)pr_b}{h}} - W_0 + 1$$

$$= \sqrt{\frac{(3-1)(50)(0.5)}{0.25}} - 3 + 1 = 12.14$$

$$\Pi^* = \frac{pw^* r_b}{w^* + W_0 - 1} - hw = \frac{50(12.14)(0.5)}{12.14 + 3 - 1} - 0.25(12.14) = \$18.43 \text{ per hr}$$

So, we conclude that the CONWIP line generates 7.8% higher profit level than the push system, when both are optimized.

b) Now we consider what happens when we use the controls (TH in push, WIP in CONWIP) from part (a) in a system for which they are not optimal. If t_e=2.2, then r_b=1/2.2, T_0=6.6, W_0=3. Profit for the push system will be:

$$\Pi(TH = 0.4134) = pTH - \frac{3hTH}{r_b - TH} = 50(0.4134) - \frac{3(0.25)(0.4134)}{(1/2.2) - (0.4134)} = \$13.13 \text{ per hr}$$

Profit for the CONWIP line will be:

$$\Pi(w = 12.14) = \frac{pwr_b}{w + W_0 - 1} - hw = \frac{50(12.14)(1/2.2)}{12.14 + 3 - 1} - (0.25)(12.14) = \$16.48 \text{ per hr}$$

So, now CONWIP generates 25.5% greater profit.

Finally, consider the situation where t_e=2.4 for each station. Now, r_b=1/2.4, T_0=7.2, W_0=3. Profit from push using the throughput level from (a) is:

$$\Pi(TH=0.4134) = pTH - \frac{3hTH}{r_b - TH} = 50(0.4134) - \frac{3(0.25)(0.4134)}{(1/2.4)-(0.4134)} = -\$74.24 \text{ per hr}$$

Profit from CONWIP using the WIP level from (a) is:

$$\Pi(w=12.14) = \frac{pwr_b}{w+W_0-1} - hw = \frac{50(12.14)(1/2.4)}{12.14+3-1} - (0.25)(12.14) = \$14.85 \text{ per hr}$$

So, CONWIP generates infinitely higher profit than push, since push loses money. This illustrates how much more robust the CONWIP line is to its control (WIP) than the push line is to its control (TH). Errors in the push system cause much more severe dropoffs in profit.

6.

a)

(i)

J	1		2		3		4			
te(j)	2.5		2		2		2			
ce(j)	0.5		0.5		0.5		0.5			
w	CT1(w)	WIP1(w)	CT2(w)	WIP2(w)	CT3(w)	WIP3(w)	CT4(w)	WIP4(w)	CT(w)	TH(w)
0		0		0		0		0		0
1	2.500	0.294	2.000	0.235	2.000	0.235	2.000	0.235	8.500	0.118
2	2.960	0.601	2.294	0.466	2.294	0.466	2.294	0.466	9.842	0.203
3	3.527	0.927	2.628	0.691	2.628	0.691	2.628	0.691	11.410	0.263
4	4.202	1.277	2.987	0.908	2.987	0.908	2.987	0.908	13.164	0.304
5	4.980	1.654	3.360	1.115	3.360	1.115	3.360	1.115	15.059	0.332
6	5.856	2.060	3.733	1.313	3.733	1.313	3.733	1.313	17.054	0.352
7	6.826	2.499	4.099	1.500	4.099	1.500	4.099	1.500	19.122	0.366
8	7.889	2.971	4.452	1.676	4.452	1.676	4.452	1.676	21.244	0.377
9	9.044	3.477	4.788	1.841	4.788	1.841	4.788	1.841	23.408	0.384
10	10.292	4.019	5.105	1.994	5.105	1.994	5.105	1.994	25.607	0.391
11	11.633	4.597	5.401	2.134	5.401	2.134	5.401	2.134	27.837	0.395
12	13.066	5.210	5.676	2.263	5.676	2.263	5.676	2.263	30.094	0.399

(ii)

J	1		2		3		4			
te(j)	2		2		2.5		2			
ce(j)	0.5		0.5		0.5		0.5			
w	CT1(w)	WIP1(w)	CT2(w)	WIP2(w)	CT3(w)	WIP3(w)	CT4(w)	WIP4(w)	CT(w)	TH(w)
0		0		0		0		0		0
1	2.000	0.235	2.000	0.235	2.500	0.294	2.000	0.235	8.500	0.118
2	2.294	0.466	2.294	0.466	2.960	0.601	2.294	0.466	9.842	0.203
3	2.628	0.691	2.628	0.691	3.527	0.927	2.628	0.691	11.410	0.263
4	2.987	0.908	2.987	0.908	4.202	1.277	2.987	0.908	13.164	0.304
5	3.360	1.115	3.360	1.115	4.980	1.654	3.360	1.115	15.059	0.332
6	3.733	1.313	3.733	1.313	5.856	2.060	3.733	1.313	17.054	0.352
7	4.099	1.500	4.099	1.500	6.826	2.499	4.099	1.500	19.122	0.366
8	4.452	1.676	4.452	1.676	7.889	2.971	4.452	1.676	21.244	0.377
9	4.788	1.841	4.788	1.841	9.044	3.477	4.788	1.841	23.408	0.384
10	5.105	1.994	5.105	1.994	10.292	4.019	5.105	1.994	25.607	0.391
11	5.401	2.134	5.401	2.134	11.633	4.597	5.401	2.134	27.837	0.395

12	5.676	2.263	5.676	2.263	13.066	5.210	5.676	2.263	30.094	0.399

Individual stations are affected by having bottleneck at station 1 or 3, but overall line performance is not

b)

(i)

J	1		2		3		4			
te(j)	2		2		2.5		2			
ce(j)	0.25		0.5		0.5		0.5			
w	CT1(w)	WIP1(w)	CT2(w)	WIP2(w)	CT3(w)	WIP3(w)	CT4(w)	WIP4(w)	CT(w)	TH(w)
0		0		0		0		0		0
1	2.000	0.235	2.000	0.235	2.500	0.294	2.000	0.235	8.500	0.118
2	2.250	0.459	2.294	0.468	2.960	0.604	2.294	0.468	9.798	0.204
3	2.536	0.672	2.630	0.697	3.532	0.935	2.630	0.697	11.329	0.265
4	2.847	0.872	2.996	0.918	4.218	1.292	2.996	0.918	13.056	0.306
5	3.170	1.061	3.376	1.130	5.012	1.678	3.376	1.130	14.934	0.335
6	3.495	1.239	3.758	1.333	5.911	2.096	3.758	1.333	16.922	0.355
7	3.813	1.406	4.133	1.524	6.908	2.547	4.133	1.524	18.988	0.369
8	4.120	1.561	4.495	1.703	8.003	3.032	4.495	1.703	21.112	0.379
9	4.412	1.706	4.838	1.870	9.193	3.554	4.838	1.870	23.281	0.387
10	4.686	1.839	5.161	2.025	10.479	4.111	5.161	2.025	25.486	0.392
11	4.942	1.961	5.461	2.167	11.859	4.705	5.461	2.167	27.723	0.397
12	5.178	2.072	5.739	2.296	13.334	5.335	5.739	2.296	29.988	0.400

(ii)

J	1		2		3		4			
te(j)	2		2		2.5		2			
ce(j)	0.5		0.5		0.25		0.5			
w	CT1(w)	WIP1(w)	CT2(w)	WIP2(w)	CT3(w)	WIP3(w)	CT4(w)	WIP4(w)	CT(w)	TH(w)
0		0		0		0		0		0
1	2.000	0.235	2.000	0.235	2.500	0.294	2.000	0.235	8.500	0.118
2	2.294	0.469	2.294	0.469	2.891	0.592	2.294	0.469	9.773	0.205
3	2.632	0.700	2.632	0.700	3.379	0.899	2.632	0.700	11.275	0.266
4	3.001	0.925	3.001	0.925	3.968	1.224	3.001	0.925	12.973	0.308
5	3.388	1.143	3.388	1.143	4.656	1.571	3.388	1.143	14.821	0.337
6	3.780	1.352	3.780	1.352	5.438	1.945	3.780	1.352	16.779	0.358
7	4.167	1.550	4.167	1.550	6.314	2.349	4.167	1.550	18.816	0.372
8	4.543	1.738	4.543	1.738	7.283	2.786	4.543	1.738	20.910	0.383
9	4.902	1.914	4.902	1.914	8.345	3.258	4.902	1.914	23.051	0.390
10	5.242	2.078	5.242	2.078	9.501	3.766	5.242	2.078	25.228	0.396
11	5.561	2.230	5.561	2.230	10.754	4.311	5.561	2.230	27.438	0.401
12	5.858	2.369	5.858	2.369	12.104	4.894	5.858	2.369	29.677	0.404

It is more effective (i.e., it improves TH more) to reduce variability at bottleneck

c)

(i)

j	1		2		3		4			
te(j)	2		1.5		2.5		2			
ce(j)	0.5		0.5		0.5		0.5			
w	CT1(w)	WIP1(w)	CT2(w)	WIP2(w)	CT3(w)	WIP3(w)	CT4(w)	WIP4(w)	CT(w)	TH(w)
0		0		0		0		0		0
1	2.000	0.250	1.500	0.188	2.500	0.313	2.000	0.250	8.000	0.125
2	2.313	0.498	1.676	0.361	2.988	0.643	2.313	0.498	9.289	0.215
3	2.673	0.742	1.860	0.516	3.604	1.000	2.673	0.742	10.809	0.278
4	3.067	0.980	2.040	0.652	4.350	1.389	3.067	0.980	12.525	0.319
5	3.480	1.209	2.208	0.767	5.225	1.815	3.480	1.209	14.393	0.347
6	3.897	1.428	2.357	0.864	6.223	2.280	3.897	1.428	16.375	0.366
7	4.306	1.635	2.487	0.944	7.342	2.787	4.306	1.635	18.441	0.380
8	4.700	1.828	2.595	1.009	8.578	3.336	4.700	1.828	20.573	0.389
9	5.072	2.006	2.686	1.062	9.928	3.926	5.072	2.006	22.757	0.395
10	5.418	2.169	2.760	1.105	11.389	4.558	5.418	2.169	24.985	0.400
11	5.737	2.316	2.819	1.138	12.957	5.230	5.737	2.316	27.250	0.404
12	6.026	2.447	2.866	1.164	14.630	5.941	6.026	2.447	29.549	0.406

(ii)

j	1		2		3		4			
te(j)	2		2		2.5		2			
ce(j)	0.25		0.25		0.5		0.25			
w	CT1(w)	WIP1(w)	CT2(w)	WIP2(w)	CT3(w)	WIP3(w)	CT4(w)	WIP4(w)	CT(w)	TH(w)
0		0		0		0		0		0
1	2.000	0.235	2.000	0.235	2.500	0.294	2.000	0.235	8.500	0.118
2	2.250	0.463	2.250	0.463	2.960	0.610	2.250	0.463	9.710	0.206
3	2.541	0.683	2.541	0.683	3.541	0.952	2.541	0.683	11.163	0.269
4	2.862	0.892	2.862	0.892	4.249	1.324	2.862	0.892	12.834	0.312
5	3.199	1.090	3.199	1.090	5.080	1.731	3.199	1.090	14.679	0.341
6	3.541	1.276	3.541	1.276	6.028	2.172	3.541	1.276	16.651	0.360
7	3.876	1.450	3.876	1.450	7.086	2.650	3.876	1.450	18.715	0.374
8	4.198	1.611	4.198	1.611	8.249	3.166	4.198	1.611	20.845	0.384
9	4.503	1.760	4.503	1.760	9.516	3.719	4.503	1.760	23.025	0.391
10	4.787	1.896	4.787	1.896	10.883	4.311	4.787	1.896	25.245	0.396
11	5.050	2.020	5.050	2.020	12.349	4.940	5.050	2.020	27.499	0.400
12	5.290	2.132	5.290	2.132	13.912	5.605	5.290	2.132	29.782	0.403

Speeding up non-bottleneck here is better than reducing variability at non-bottlenecks. Note that while this will often be the case, it will not always occur. Depending on the specifics of the problem, including the costs, reducing variability can be more attractive than increasing capacity.

Chapter 11

Study Questions

2. Go slow, use lots of training, provide forums for worker input, use pilot programs, establish real rewards for success, make sure top management *stays* involved in the effort, etc.

4. Real employees' performance is affected by both their own ability/effort and random factors. The red bead example serves as a warning to managers not to overreact to random effects. It also points up the need to base performance measures on things over which employees have a large measure of control (i.e., make responsibility commensurate with authority).

Chapter 12

Study Questions

2. Good internal quality promotes good external quality because:
   - Fewer internal defects slip through inspection to become external defects.
   - Quality inspectors will be under less pressure to let defects slide through.
   - Overall awareness of quality is increased in the organization.

4.
   a) decrease if customer expectations are currently unsatisfied, increase above some point
   b) decrease if customer expectations are currently unsatisfied, increase above some point
   c) decrease due to less rework, yield loss, dealing with customer complaints
   d) decrease by pushing cost of compliance onto supplier
   e) increase direct costs, but decrease costs of loss of customer goodwill

6.
   a) If we define the number of opportunities for errors as the number of tests or inspections, then we can artificially lower the defect rate by inspecting more often. But this is contrary to the "quality at the source" or "do it right the first time" philosophy of quality management. So using this definition both distorts quality measures and promotes inefficiency.
   b) Using value-added transformations to count opportunities for defects is better than using the number of inspections. But we need to be very careful to make sure the transformations are truly needed. In the question, we point out that unnecessary steps, such as rework/repair, cannot be counted as independent opportunities. In the same manner, we need to make sure that transformations are not arbitrarily divided into smaller steps in order to inflate the number of opportunities (and hence reduce the defect rate). For example, we might count assembly of a housing as one transformation. Or, we could count each individual step (place the halves of the housing, insert the screws, tighten the screws, attach the bracket, etc.) as transformations. Unless we are very careful in enforcing a uniform definition of a transformation across operations, the defect rates will not be comparable.

8. Reducing yield loss and/or rework can improve scheduling by:
   - reducing the need to inflate releases (always a difficult task)
   - making the loadings on workstations more predictable (so that completion times can be predicted better).

10. Scrap is like rework in terms of its effect on workstation capacity because replacement parts must be started over from the beginning of the line (i.e., just like a rework loop that goes back to the front of the line). Scrap is different than rework in that the raw materials in scrapped parts are often wasted, while those in reworked parts are not.

Problems

2. Supplier 3 is most capable even though it is skewed. The lower variability compensates for the mean shift.

Supplier	μ	σ	Z_{LSL}	Z_{USL}	z_{min}	C_{pk}
1	3	0.009	-2.0	2.0	2.0	0.67
2	3	0.0044	-4.1	4.1	4.1	1.4

3	2.99	0.003	-2.7	9.3	2.7	0.9

4.

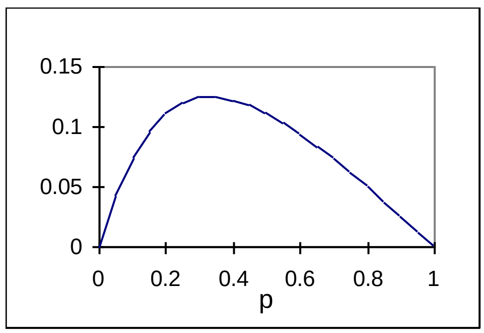
a) Let T_e denote the (random) effective process time. Then

$$E[T_e] = (1-p)1 + p2 = 1 - p + 2p = 1 + p \quad \text{hours}$$
$$E[T_e^2] = (1-p)1^2 + p2^2 = 1 - p + 4p = 1 + 3p$$
$$Var(T_e) = E[T_e^2] - E[T_e]^2 = 1 + 3p - (1+p)^2 = p(1-p)$$

b) The SCV of effective process time is

$$c_e^2 = \frac{Var(T_e)}{E[T_e]^2} = \frac{p(1-p)}{(1+p)^2}$$

which looks like



When p is *0* or *1*, there is no variability at all in the process time (so $Var(T_e)=0$). So, process variability is maximized for an intermediate value of p (at $p=0.33$). Note, however, that mean process time is maximized at $p=1$.

6.

a) Let X represent the (random) delivery time. If X is normally with mean μ and standard deviation σ then from a standard normal table we find that

$$P\{X \le \mu + 2.33\sigma\} = 0.99$$

so for supplier 1 we require a lead time of 15+2.33(1)=17.33 days and for supplier 2 we require a lead time of 15+2.33(5)=26.65 days.

b) A part that takes the mean delivery time to arrive will wait in inventory for 2.33(1)=2.33 days from supplier 1 and 2.33(5)=11.65 days from supplier 2.

c) To ensure 0.99 probability of having all 100 components requires a probability of $(0.99)^{1/100}$=0.9999 for each part. From a standard normal table we find that

$$P\{X \le \mu + 3.62\sigma\} = 0.9999$$

so for supplier 1 we require a lead-time of 15+3.62(1)=18.62 days and for supplier 2 we require a lead-time of 15+3.62(5)=33.1 days.

d) If we wanted to start 99% of the days on-time, we would not need as much safety lead time for the 5 day batches.

Chapter 13

Study Questions

2. The appropriate regeneration frequency will depend on the environment. For instance, a firm whose demand profile is stable and cycle times are long does not need to re-plan its master production schedule as frequently as does a firm with volatile demand and short cycle times.

4. Inconsistencies can lead to ineffective modules and a lack of confidence in the plans. For instance, if unreasonable capacity numbers are used in the aggregate planning module, the resulting plans will be far from the actual execution sequence. The result will be that the aggregate plan will offer little help in identifying bottlenecks, specifying staffing needs, etc. While obviously important, however, consistency may not be achieved in practice because different groups are often responsible for different parts of the plan. Consistency between modeling assumptions and data must be enforced institutionally.

6. If observed data are trending upward, then an exponential smoothing model will tend to undershoot and hence exhibit negative bias. If the data are trending upward at an increasing rate (i.e., nonlinearly), then an exponential smoothing model with a linear trend will still lag behind and exhibit negative bias.

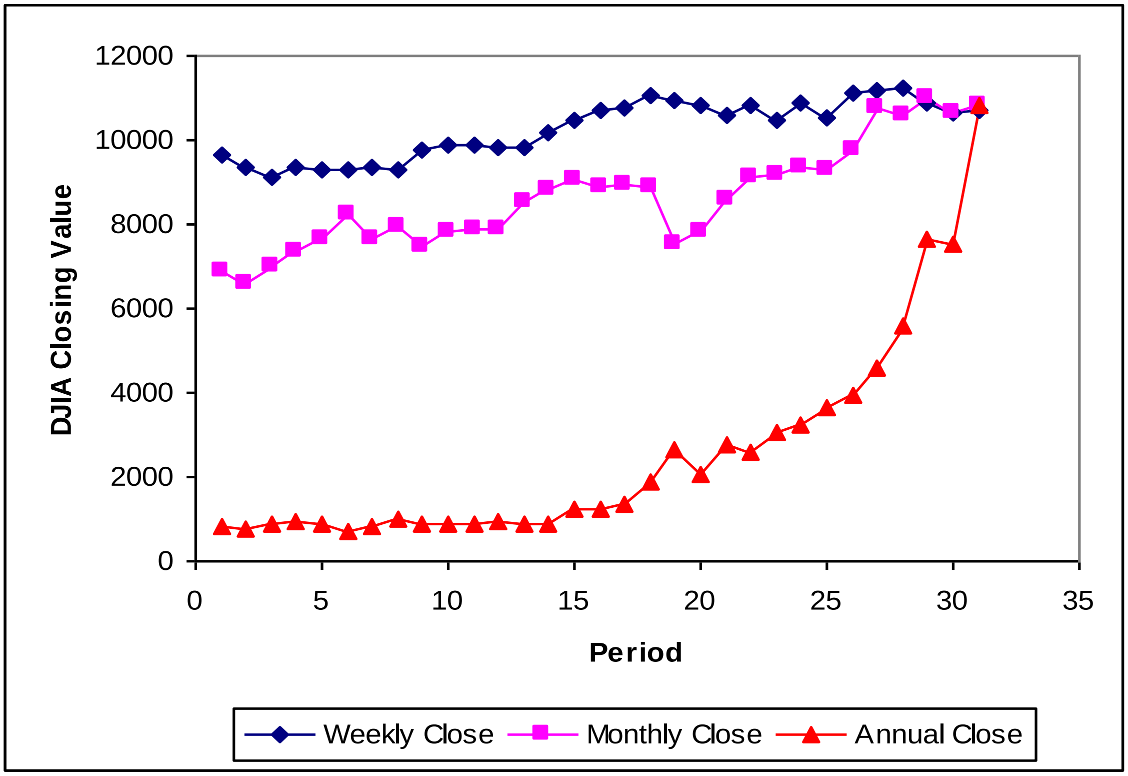
8. People can be thought of as a form of capacity, so in a sense both capacity/facility planning and workforce planning are concerned with matching future capacity to future production requirements. However, people have unique characteristics (e.g., they become more skilled over time, they are sensitive to a company's reputation for treating workers well or poorly, etc.) which must be considered in workforce planning.

10. Higher level modules, such as capacity planning and aggregate planning, must include reductions in maximum utilization of resources to reflect low-level scheduling concerns, such as setups, idleness due to queueing, etc. While these are impossible to predict in detail, at a highly aggregated level it should be possible to make reasonable utilization estimates, particularly if historical performance is tracked and used to adjust these estimates.

12. A weekly schedule may serve as a "work backlog" for the shop floor. However, in most environments the detailed release times will not remain accurate over time. Therefore, a SFC module is still needed to keep track of what work is actually available to work on (i.e., actual WIP position in the line) and perhaps to perform other functions related to material flow (e.g., quality control, tracking status of equipment, collecting statistics on capacity for other modules, etc.). Of course, the nature of the appropriate SFC module may differ greatly from one environment to another.

Problems

2.



DJIA Closing Value
12000
10000
8000
6000
4000
2000
0
0
5
10
15
20
25
30
35
Period
Weekly Close
Monthly Close
Annual Close

a)

	Weekly Data					Monthly Data					Annual Data				
Period	Date	Close	F(t)	T(t)	f(t)	Date	Close	F(t)	T(t)	f(t)	Date	Close	F(t)	T(t)	f(t)
1	1/4/99	9643.3	9643.3	0.0		2/1/97	6877.7	6877.7	0.0		8/1/69	836.7	836.7	0.0	
2	1/11/99	9340.6	9613.0	-3.0	9643.3	3/1/97	6583.5	6848.3	-2.9	6877.7	8/1/70	764.6	829.5	-0.7	836.7
3	1/18/99	9120.7	9561.1	-7.9	9610.0	4/1/97	7009	6861.7	-1.3	6845.3	8/1/71	898.1	835.7	0.0	828.8
4	1/25/99	9358.8	9533.7	-9.9	9553.2	5/1/97	7331	6907.5	3.4	6860.4	8/1/72	963.7	848.5	1.3	835.7
5	2/1/99	9304.2	9501.9	-12.1	9523.9	6/1/97	7672.8	6987.1	11.0	6910.9	8/1/73	887.6	853.5	1.6	849.7
6	2/8/99	9274.9	9468.3	-14.2	9489.8	7/1/97	8222.6	7120.5	23.3	6998.1	8/1/74	678.6	837.5	-0.1	855.1
7	2/15/99	9340	9442.7	-15.4	9454.1	8/1/97	7622.4	7191.7	28.1	7143.8	8/1/75	835.3	837.2	-0.2	837.4
8	2/22/99	9306.6	9415.3	-16.6	9427.4	9/1/97	7945.3	7292.3	35.3	7219.7	8/1/76	973.7	850.7	1.2	837.0
9	3/1/99	9736.1	9432.5	-13.2	9398.7	10/1/97	7442.1	7339.0	36.5	7327.6	8/1/77	861.5	852.8	1.3	851.9
10	3/8/99	9876.4	9465.0	-8.6	9419.3	11/1/97	7823.1	7420.2	40.9	7375.5	8/1/78	876.8	856.4	1.5	854.2
11	3/15/99	9903.6	9501.1	-4.1	9456.4	12/1/97	7908.3	7505.9	45.4	7461.2	8/1/79	887.6	860.9	1.8	858.0
12	3/22/99	9822.2	9529.5	-0.9	9497.0	1/1/98	7906.5	7586.8	49.0	7551.3	8/1/80	932.6	869.7	2.5	862.7
13	3/29/99	9832.5	9559.0	2.2	9528.6	2/1/98	8545.7	7726.7	58.1	7635.8	8/1/81	881.5	873.2	2.6	872.3
14	4/5/99	10173.8	9622.4	8.3	9561.1	3/1/98	8799.8	7886.3	68.2	7784.8	8/1/82	901.3	878.4	2.9	875.8
15	4/12/99	10493.9	9717.0	16.9	9630.7	4/1/98	9063.4	8065.4	79.3	7954.5	8/1/83	1216.2	914.7	6.2	881.2
16	4/19/99	10689.7	9829.5	26.5	9733.9	5/1/98	8900	8220.2	86.8	8144.7	8/1/84	1224.4	951.3	9.3	921.0
17	4/26/99	10789	9949.3	35.8	9856.0	6/1/98	8952	8371.6	93.3	8307.1	8/1/85	1334	997.9	13.0	960.6
18	5/3/99	11031.6	10089.7	46.3	9985.1	7/1/98	8883.3	8506.7	97.5	8464.8	8/1/86	1898.3	1099.6	21.9	1010.9
19	5/10/99	10913.3	10213.7	54.0	10136.0	8/1/98	7539.1	8497.7	86.8	8604.2	8/1/87	2663	1275.7	37.3	1121.5
20	5/17/99	10829.3	10323.9	59.7	10267.7	9/1/98	7842.6	8510.3	79.4	8584.5	8/1/88	2031.7	1384.8	44.5	1312.9
21	5/24/99	10559.7	10401.2	61.4	10383.6	10/1/98	8592.1	8589.9	79.4	8589.7	8/1/89	2737.3	1560.1	57.6	1429.3
22	5/31/99	10799.8	10496.3	64.8	10462.6	11/1/98	9116.6	8714.1	83.9	8669.4	8/1/90	2614.4	1717.3	67.5	1617.6
23	6/7/99	10490.5	10554.0	64.1	10561.1	12/1/98	9181.4	8836.3	87.7	8798.0	8/1/91	3043.6	1910.7	80.1	1784.8
24	6/14/99	10855.6	10641.9	66.5	10618.1	1/1/99	9358.8	8967.6	92.1	8924.1	8/1/92	3257.4	2117.5	92.8	1990.8
25	6/21/99	10552.6	10692.7	64.9	10708.3	2/1/99	9306.6	9084.3	94.6	9059.6	8/1/93	3651.3	2354.4	107.2	2210.3
26	6/28/99	11139.2	10795.8	68.7	10757.6	3/1/99	9786.2	9239.6	100.6	9178.9	8/1/94	3913.4	2606.7	121.7	2461.5
27	7/5/99	11193.7	10897.4	72.0	10864.5	4/1/99	10789	9485.1	115.1	9340.3	8/1/95	4610.6	2916.6	140.5	2728.4
28	7/12/99	11209.8	10993.5	74.4	10969.4	5/1/99	10559.7	9696.2	124.7	9600.2	8/1/96	5616.2	3313.1	166.1	3057.2
29	7/19/99	10911	11052.2	72.8	11067.9	6/1/99	10970.8	9935.9	136.2	9820.9	8/1/97	7622.4	3893.5	207.5	3479.2
30	7/26/99	10655.1	11078.0	68.1	11125.0	7/1/99	10655.1	10130.4	142.0	10072.1	8/1/98	7539.1	4444.9	241.9	4101.1
31	8/2/99	10714.03	11103.0	63.8	11146.2	8/1/99	10829.28	10328.1	147.6	10272.4	8/1/99	10829	5301.0	303.4	4686.8

Weekly: f(31+52)=F(31)+52T(31)=11103+52(63.8) = 14421
Monthly: f(31+12)=F(31)+12T(31) = 10328.1+12(147.6) = 12099
Annual: f(31+1)=F(31)+T(31) = 5301.0+303.4 = 5604

For distant forecasting (e.g., 5 years into the future), the annual model is probably best. For near term forecasting (e.g., next month), the weekly model is probably better. For forecasting one year into the future, the monthly model probably makes the most sense. However, notice that it is only sensitive to recent market performance. If this market is abnormally high (or low) then a time series model like this could be very wrong…

b) Weekly weight = $(1-0.1)^{52}$=0.0042; monthly weight = $(1-0.1)^{12}$ = 0.282; annual weight = 0.1. Clearly, we should not use the same value of α for a model with weekly observations and one with annual observations because this results in drastically different discounting of past data. For the monthly model to give the same weight to a year old observation as the annual model, we need:

$$(1-\alpha_m)^{12} = (1-\alpha_a) = 0.1, \quad \Rightarrow \quad 1-\alpha_m = (1-0.1)^{1/12} = 0.9913 \quad \Rightarrow \quad \alpha_m = 0.0087$$

c)

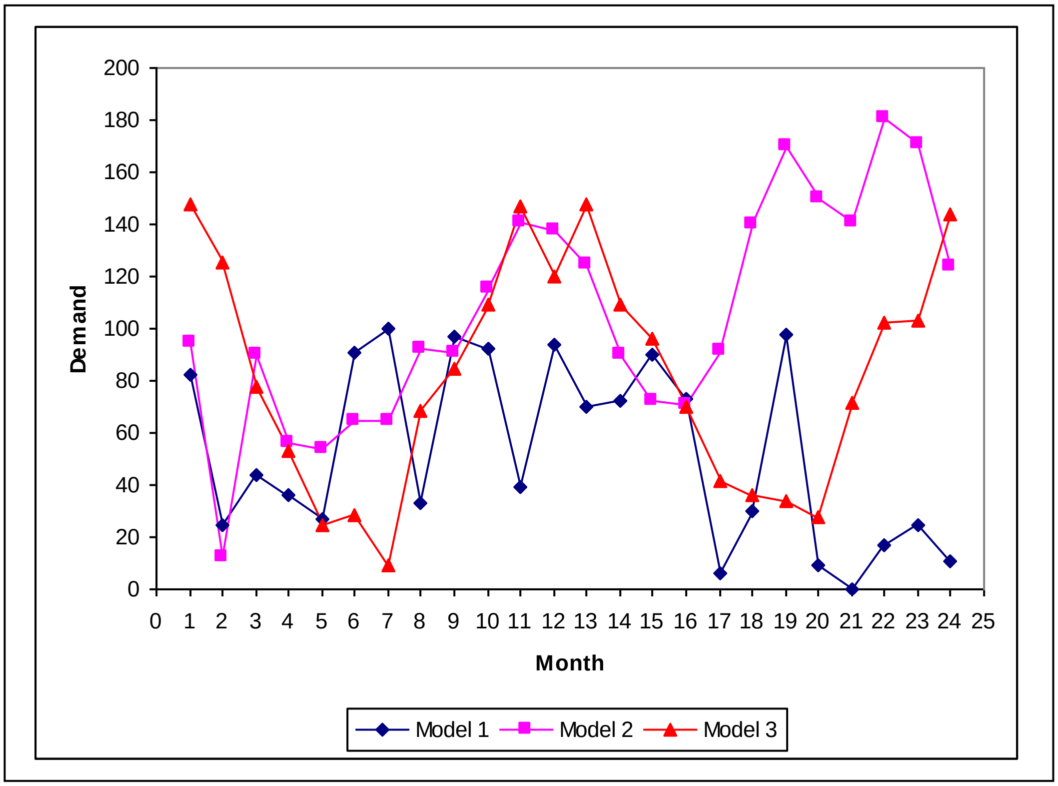
Monthly Data				
Date	Close	F(t)	T(t)	f(t)
2/1/97	6877.7	6877.7	0.0	
3/1/97	6583.5	6875.1	0.0	6877.7
4/1/97	7009	6876.3	0.0	6875.1
5/1/97	7331	6880.2	0.0	6876.3
6/1/97	7672.8	6887.2	0.1	6880.3
7/1/97	8222.6	6898.9	0.2	6887.3
8/1/97	7622.4	6905.5	0.2	6899.1
9/1/97	7945.3	6914.8	0.3	6905.7
10/1/97	7442.1	6919.7	0.4	6915.1
11/1/97	7823.1	6928.0	0.4	6920.1
12/1/97	7908.3	6937.0	0.5	6928.4
1/1/98	7906.5	6945.9	0.6	6937.5
2/1/98	8545.7	6960.5	0.7	6946.5
3/1/98	8799.8	6977.3	0.8	6961.2
4/1/98	9063.4	6996.3	1.0	6978.1
5/1/98	8900	7014.0	1.1	6997.3
6/1/98	8952	7032.0	1.3	7015.1
7/1/98	8883.3	7049.5	1.4	7033.3
8/1/98	7539.1	7055.2	1.5	7050.9
9/1/98	7842.6	7063.6	1.5	7056.7
10/1/98	8592.1	7078.4	1.6	7065.1
11/1/98	9116.6	7097.9	1.8	7080.1
12/1/98	9181.4	7117.9	2.0	7099.7
1/1/99	9358.8	7139.4	2.1	7119.9
2/1/99	9306.6	7160.5	2.3	7141.6
3/1/99	9786.2	7185.7	2.5	7162.8
4/1/99	10789	7219.7	2.8	7188.2
5/1/99	10559.7	7251.7	3.0	7222.5
6/1/99	10970.8	7287.2	3.3	7254.7
7/1/99	10655.1	7319.9	3.6	7290.5
8/1/99	10829.28	7354.1	3.8	7323.5

$$f(31+12)=F(31)+12T(31) = 7354.1+12(3.8) = 7400$$

This makes the monthly forecast closer to the annual forecast because it is much more conservative about predicting a trend. Note however, that this is partly due to the fact that we started the model with an assumed trend of zero. With such a low value of α, it takes a very long time to overcome this. We probably should not use such low smoothing constants unless we have a very large amount of data. The bottom line is the period in a forecasting model should be consistent with the distance into the future you want to predict. Given this, smoothing constants in the range of 0.1 to 0.6 are probably most realistic.

d) Time series models might have some value for intermediate or long-term forecasting of the stock market. But in the short term they have little value, due to the high volatility of the prices. By the time a time series model detects a trend, you are probably broke.

4.



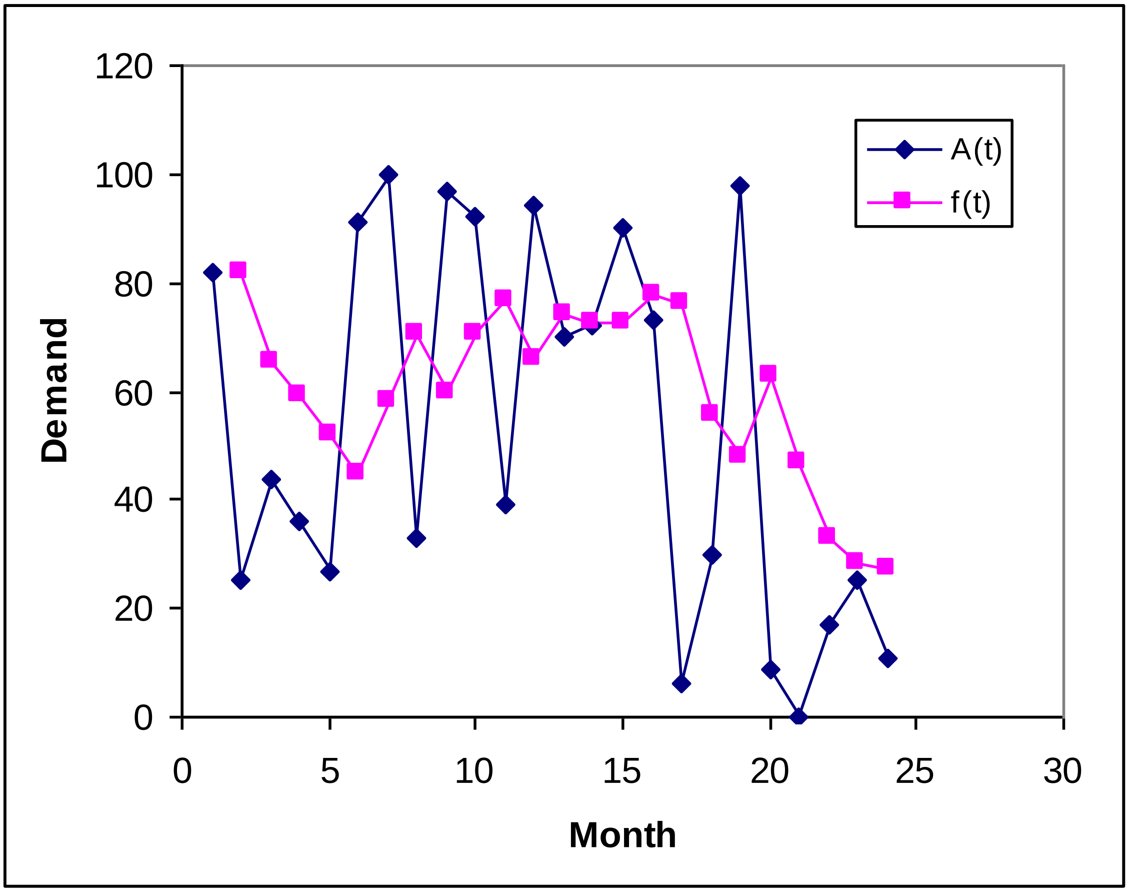
Observe that model 1 seems to have no particular trend, but does have some volatility, so simple exponential smoothing may make sense. Model 2 seems to have a trend, along with some volatility, so exponential smoothing with a trend may make sense. Model 3 may exhibit seasonality, so Winters method might be appropriate.

a) Optimizing over α using solver yields the following. Fit is not great due to noise from month to month.

alpha 0.294304

Month	A(t)	f(t)	f(t)-A(t)	|f(t)-A(t)|	(f(t)-A(t))^2
1	82	#N/A	#N/A	#N/A	#N/A
2	25	82.00	57.00	57.00	3249.00
3	44	65.22	21.22	21.22	450.49
4	36	58.98	22.98	22.98	528.00
5	27	52.22	25.22	25.22	635.83
6	91	44.79	-46.21	46.21	2134.94
7	100	58.39	-41.61	41.61	1731.14
8	33	70.64	37.64	37.64	1416.63
9	97	59.56	-37.44	37.44	1401.67
10	92	70.58	-21.42	21.42	458.84
11	39	76.88	37.88	37.88	1435.17

12	94	65.73	-28.27	28.27	798.95
13	70	74.05	4.05	4.05	16.43
14	72	72.86	0.86	0.86	0.74
15	90	72.61	-17.39	17.39	302.51
16	73	77.73	4.73	4.73	22.33
17	6	76.34	70.34	70.34	4947.01
18	30	55.64	25.64	25.64	657.16
19	98	48.09	-49.91	49.91	2490.95
20	9	62.78	53.78	53.78	2892.20
21	0	46.95	46.95	46.95	2204.47
22	17	33.13	16.13	16.13	260.29
23	25	28.39	3.39	3.39	11.46
24	11	27.39	16.39	16.39	268.60
			8.78	29.84	1231.08

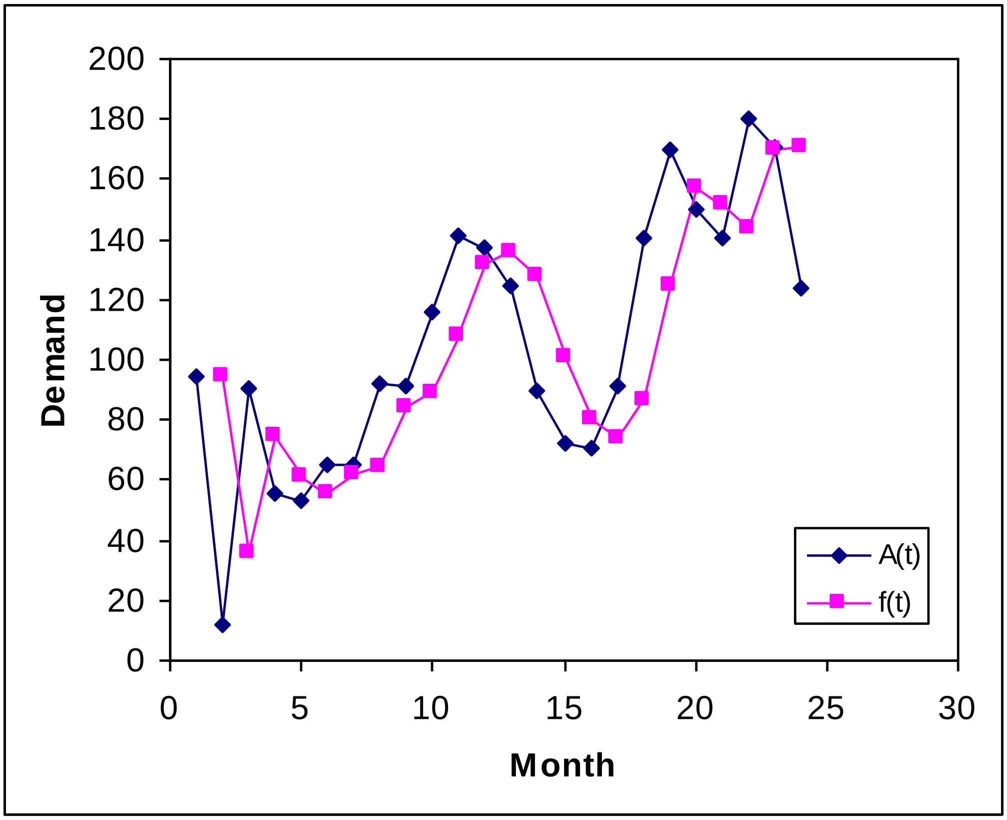


b) Interestingly, best fit occurs when trend is zero. This is due to high up-down variation, which makes having a trend overshoot and undershoot too much.

alpha	0.712218
beta	0

Month	A(t)	F(t)	T(t)	f(t)	f(t)-A(t)	|f(t)-A(t)|	(f(t)-

							A(t))^2
1	95	94.76	0.00	#N/A	#N/A	#N/A	#N/A
2	12	35.92	0.00	94.76	82.61	82.61	6824.06
3	90	74.64	0.00	35.92	-54.36	54.36	2954.49
4	56	61.21	0.00	74.64	18.86	18.86	355.67
5	54	55.75	0.00	61.21	7.66	7.66	58.72
6	65	62.19	0.00	55.75	-9.04	9.04	81.79
7	65	64.03	0.00	62.19	-2.59	2.59	6.72
8	92	84.22	0.00	64.03	-28.34	28.34	803.03
9	91	89.11	0.00	84.22	-6.87	6.87	47.24
10	116	108.05	0.00	89.11	-26.60	26.60	707.37
11	141	131.47	0.00	108.05	-32.88	32.88	1080.82
12	137	135.71	0.00	131.47	-5.95	5.95	35.39
13	124	127.70	0.00	135.71	11.24	11.24	126.39
14	90	100.85	0.00	127.70	37.70	37.70	1420.95
15	72	80.37	0.00	100.85	28.75	28.75	826.79
16	71	73.69	0.00	80.37	9.38	9.38	87.95
17	92	86.44	0.00	73.69	-17.90	17.90	320.33
18	140	124.83	0.00	86.44	-53.90	53.90	2905.57
19	170	156.88	0.00	124.83	-44.99	44.99	2024.37
20	150	151.94	0.00	156.88	6.94	6.94	48.12
21	141	143.93	0.00	151.94	11.24	11.24	126.24
22	180	169.95	0.00	143.93	-36.53	36.53	1334.10
23	171	170.48	0.00	169.95	-0.75	0.75	0.56
24	124	137.08	0.00	170.48	46.89	46.89	2198.74
					-2.58	25.30	1059.80
					bias	**MAD**	**MSD**

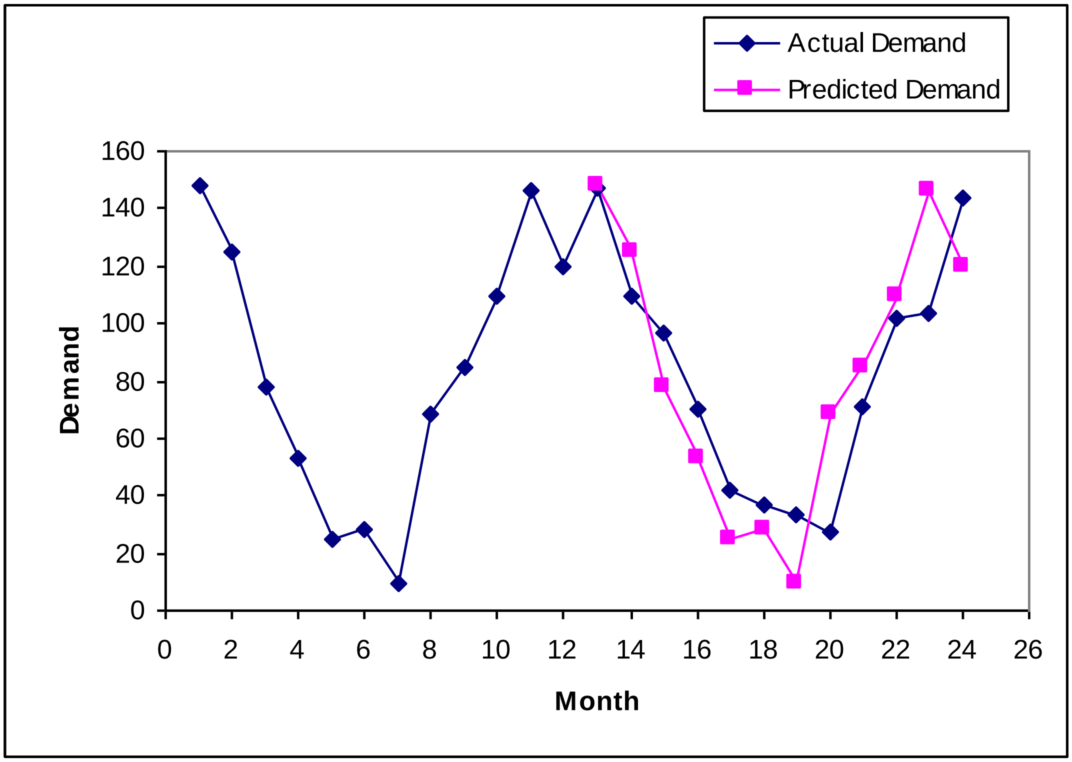


c) Seasonal model provides a good fit, although with only 2 years of data, the best fit occurs when α=0. This causes trend to be zero, so the prediction for year 2 is just demand from year 1.

alpha	0.000
betal	0.061
gamma	0.100

Month	**Actual Demand**	**Base Level**	**Trend**	**Seasonal Factor**	**Predicted Demand**
1	148	---	---	1.783	
2	125	---	---	1.512	
3	78	---	---	0.937	
4	53	---	---	0.636	
5	25	---	---	0.299	
6	29	---	---	0.344	
7	9	---	---	0.110	
8	68	---	---	0.823	
9	84	---	---	1.019	
10	110	---	---	1.322	
11	147	---	---	1.770	
12	120	82.87	0.00	1.446	
13	147	82.87	0.00	1.783	147.77
14	109	82.87	0.00	1.493	125.29
15	96	82.87	0.00	0.959	77.64
16	70	82.87	0.00	0.657	52.69

17	42	82.87	0.00	0.319	24.74
18	36	82.87	0.00	0.353	28.51
19	34	82.87	0.00	0.139	9.11
20	28	82.87	0.00	0.774	68.21
21	71	82.87	0.00	1.003	84.42
22	102	82.87	0.00	1.313	109.54
23	103	82.87	0.00	1.718	146.71
24	144	82.87	0.00	1.475	119.86
				MSD	516.41



6.

a) 10 days

b) (400 bicycles)/(50 bicycles/day) = 8 days

c) (500 + 50 bicycles)/(50 bicycles/day) + 10 = 21 days

Chapter 14

Study Questions

2. We have argued that system performance is relatively robust to changes in WIP level. Because of this the system will respond slowly to changes in WIP level and hence this is a poor option for varying capacity in response to demand changes. Better options are use of overtime, shifting workers from one part of the plant to another, or use of temporary workers.

4. If a normally fast downstream station experiences an extended failure it might tie up all the cards in the line and shut down the bottleneck. If we allow releases into the line above the WIP cap we can keep the bottleneck running and thereby not lose capacity that we can never recover. When the failed machine comes back up it will work off the excess queue and we can return to the WIP cap discipline. However, we must be careful not to do this too often or we will lose the benefits of a WIP cap by letting average WIP levels get too high. Also, we must set some kind of limit on how far above the WIP cap we will go or we may lose flexibility by releasing work into the system too early and exposing it to customer or engineering changes.

6.
   a) C
   b) P
   c) C
   d) K
   e) I

8. Figure 14.15 is symmetric because quota is set equal to mean capacity, while Figure 14.16 is asymmetric because quota is set below mean capacity. These charts give a visual demonstration of the increase in likelihood of meeting quota when some excess capacity is allowed. If the amount of production during regular time is symmetrically distributed (e.g., normal) then the probability of requiring overtime when quota is set at capacity is one half.

10. The standard deviation of periodic output can be used in the quota setting module and in due date quoting.

Problems

2.
   a) WIP will be fairly stable with 10 jobs of A and 20 of B, with the bottleneck alternating between A and B.
   b) WIP will fluctuate a great deal between A and B with the bottleneck running streams of A and then streams of B.
   c) If there are setups at the bottleneck, the sequence in (b) may be necessary.

4. $\mu = 2800, \sigma = 300, Q = 2500, R=40, t=20, n_{20} = 1000, x = n_t - Qt/R = -250.$

   a) The probability of missing quota given an overage of *-250* (a shortage of *250*) is given by:

$$P\{N_{R-t} \le Q - n_t\} = \Phi\left(\frac{(Q-\mu)(R-t)/R - x}{\sigma\sqrt{(R-t)/R}}\right)$$

$$= \Phi\left(\frac{(2500-2800)(40-20)/40 + 250}{300\sqrt{(40-20)/40}}\right) -$$

$$= \Phi(0.478) = 0.68$$

so the probability of making quota is only *1-0.68=0.32*.

b) To have a probability of missing quota equal to $\alpha = 0.1$ at *t=20* requires an overage level of

$$x = -(\mu - Q)(R-t)/R - z_{0.1}\sigma\sqrt{(R-t)/R}$$
$$= -(2800-2500)(40-20)/40 - (-1.28)(300)\sqrt{(40-20)/40}$$
$$= 122$$

So, the total number of toasters that must be completed by *t=20* is *Qt/R+x = 2500(20)/40+122 = 1372*.

c) Changing *Q* from *2500* to *2800* in the above changes *x* to *272* and hence the number of toasters we must have produced by hour *20* becomes *Qt/R+x = 2800(20)/40+272=1672*.

Chapter 15

Study Questions

2. Reducing cycle times helps to meet due dates, minimize WIP inventory, and keep quoted lead times short. It also reduces forecasting errors which is important in a make-to-stock environment and thereby helps to reduce inventory.

4. Average tardiness is the average of the lateness only when the job is late. Average lateness averages both positive lateness (late jobs) as well as negative lateness (early jobs). One could have an average lateness of zero with many early jobs canceling out many late jobs. This would not happen with average tardiness.

6. The "classic" assumptions of scheduling theory:

   I. All jobs are available at the start of the problem (i.e., no jobs arrive after processing begins). Valid in a system with "clearing" (e.g., airport) or in a sub-system (e.g., scheduling one process center for one shift).
   Invalid in most systems that have jobs arriving periodically.

   II. Process times are deterministic.
   Valid in some highly automated systems over short periods (i.e., without an outage). It is a reasonable model for the long-term production in a system with a periodic work quota using "make-up" time.
   Invalid in most situations over the short term when process times are *not* highly automated or when there are random outages for adjustment or repair.

   III. Process times do not depend on the schedule (i.e., there are no setups).
   Valid in situations of making one product or one family of products.
   Not valid when there are different products requiring a setup between product types.

   IV. Machines never break down.
   Valid in short term in many cases. Might be valid in highly labor intensive situations.
   Not valid in the long term.

   V. There is no preemption (i.e., once a job starts processing it must finish).
   Valid in most cases.
   Invalid in limited instances when jobs are quite long and can be started and stopped without interruption to the process.

   VI. There is no cancellation of jobs.
   Valid in most make-to-stock instances simply because no one *knows* that a job should be canceled (i.e., the demand is not known). May be valid in customer driven cases when cancellation is not allowed.
   Invalid when dealing closely with particular customers and cancellation is allowed.

8. The shortest process time (SPT) dispatching rule minimizes the average cycle time for a deterministic single machine when all ready times are zero. The earliest due date (EDD) rule minimizes the maximum tardiness (or lateness) for the same case. One can easily check to see if a schedule exists for which there are no tardy jobs by applying the EDD rule. If the maximum tardiness is zero, it is feasible. Again, this applies only to a single machine with deterministic process times and zero ready times for all jobs.

10. If anyone was ever able to solve one of the non-polynomial problems in the special class known as NP-complete, it would imply that all of the problems in the class NP-complete would have polynomial solutions. A lot of very smart people have been working for a long time on some of these problems (e.g., the traveling salesman problem) and have not been able to produce a polynomial solution.

12. Higher level problems include capacity setting, order acceptance, setting the product mix, and the like. The variables in the higher level problems include the capacity, the due dates, and the product mix. The constraints for the higher level problems are profitability constraints, cash flow requirements, etc. The variables in the higher level problems often become constraints for lower level problems such as due dates and capacity constraints. The problems are linked in that changing a higher level variable will change a lower level constraint.
For instance, at the high level we might decide to accept orders for 1000 units per month. When performing the detailed scheduling at the lower level this might prove impossible or, conversely, too easy. Such information must be fed back to the higher level so that adjustments can be made.

Problems

2.

a) A table of completion times under SPT at the first machine is shown below.

Job	p1	p2	C1
4	1	8	1
2	2	9	3
6	4	5	7
3	5	3	12
1	6	3	18
5	7	1	25
7	9	6	34

Time M2 is ready	Jobs in Q2 at ready time	Job to start	Completion time for M2
0	empty	none	1
1	4	4	9
9	6, 2	6	14
14	3, 2	3	17
17	2	2	26
26	5, 1	5	27
27	1	1	30
30	empty	none	34
34	7	7	40

The second machine is a bit more complex. We must determine which jobs are available when the second machine (M2) is ready. The job to be started is then the one that is available with the shortest process time. After choosing the job, the completion time for M2 can be computed. This then becomes the time when M2 is ready to start another. On two instances (at t=0 and t=30) no jobs were available. The result is shown in the table above. The time to complete all the jobs using SPT is 40 hours.

b) We now use Johnson's algorithm to minimize the makespan of these jobs. The sequence and the completion times for M1 are shown in the table below.

Job	p1	p2	C1
4	1	8	1
2	2	9	3
6	4	5	7
7	9	6	16
3	5	3	21
1	6	3	27
5	7	1	34

The same sequence is used at M2. The completion times are shown below. Note that the only time M2 is idle is at the very beginning. This sequence is optimal.

Time M2 is ready	Jobs in Q2 at ready time	Job to start	Completion time for M2
0	empty	none	1
1	4	4	9
9	2, 6	2	18
18	6, 7	6	23
23	7, 3	7	29
29	3, 1	3	32
32	1	1	35
35	5	5	36

c) The makespan has dropped from 40 to 36

4. The emergency position represents a backlog position of b = 150 while the end of the backlog is a backlog position of b = 1,400 parts. The current job is for 100 parts and there is 1,250 parts in the CONWIP line. Thus m = 2,750 for the end of the backlog or 1,500 for the emergency position. For a service level of 0.95, z = 1.645. Thus the equation for the lead time will be

$$L = \frac{m}{\mu} + \frac{z_s \sigma^2 \left(1 + \sqrt{\frac{4m\mu}{z_s^2 \sigma^2} + 1}\right)}{2\mu^2}$$

Plugging in values for the parameters yields

$$L = \frac{2750}{250} + \frac{(1.645)^2 (50^2)\left(1 + \sqrt{\frac{(4)(2750)(250)}{(1.645)^2 (50^2)} + 1}\right)}{(2)(250^2)} = 12.1$$

The table below covers the 4 cases for parts a) and b).

s =	0.95	0.95	0.99	0.99
z =	1.645	1.645	2.326	2.326
μ =	250	250	250	250
σ =	50	50	50	50
w =	1250	1250	1250	1250
b =	1400	150	1400	150
c =	100	100	100	100
m =	2750	1500	2750	1500
L =	12.1	6.9	12.7	7.3

c) A sequence with no tardiness can be found with trial and error.

Job	Family	Due Date	Comp Time	Tardiness
0	0	0	0	0
1	1	5	5	0
2	1	6	6	0
5	1	13	7	0
3	2	12	12	0
4	2	13	13	0
8	2	20	14	0
6	1	19	19	0
7	1	20	20	0
10	1	28	21	0
9	2	26	26	0
			Total Tardiness	0

6. We first compute the arrival rate of each product. The total time per month is
   (5 d/wk)(8 hr/d)(4.33 wk/mo) = 173.2 hr/mo
   Next we compute the SCV of the process times and the setup times. There is a lot of leeway in this so below is only one way that one might approach it. If the "time to process a lot does not vary more than 25 percent from the mean" then about two standard deviations would be equal to 25% of the mean, or

$$2\sigma = 0.25t$$

$$c_t^2 = \frac{\sigma^2}{t^2} = \left(\frac{0.25}{2}\right)^2 = 1/64$$

For the setup times, the mean (assuming a triangle distribution) is (2+4+8)/3 = 14.6667. The variance (using a triangle distribution) is 1.56**.** This leads to a SCV of 0.071.

a) The effective SCV has two components: the mean of the variances and the variance of the means. These are computed in the spreadsheet on the next page. The first six rows contain the problem data. The "batch arrival rate" is computed by dividing the monthly demand by the number of hours in a month and then dividing by the batch size. Notice that since all the batches are one month's demand, these values are all 1/173.2 = 0.0058. The "utilization without setups" is computed by multiplying monthly demand times the unit processing time divided by 173.2. "Probability of batch i" is the ratio of the batch arrival process divided by the sum of the batch arrival processes. The "mean time to do a batch" is given by the batch size times the unit process

$$\sigma_{\text{batch}}^2 = c_s^2 s^2 + k c_t^2 t^2$$

time plus the setup time. The "variance of a batch" is given by
The mean of the variances is obtained by summing the product of the probability of a batch and the variance of the batch. The "variance of the means" is simply the variance of the mean run lengths. The total variance is the sum of these variances.

The "effective batch process time" (t_e) is the sum of the products of the probability of a batch and the mean run length for the batch and is equal to 32.92 hours. Finally, the effective SCV is the ratio of the effective variance and the effective mean squared, or 0.5367. The component of variance due to the inherent variances of the process and setup times is relatively small, only 0.34

while the component due to the variance of the means is 581.53 hours squared.

monthly demand: D_i	50	170	45	80
unit process time: t_i	0.2	0.4	0.6	0.1
SCV unit proc time: c_ti^2	0.015625	0.015625	0.015625	0.015625
mean setup time: s_i	4.666667	4.666667	4.666667	4.666667
SCV setup time: c_si^2	0.071429	0.071429	0.071429	0.071429
Batch sizes	50	170	45	80
batch arrival rate d_i/k_i = b_i	0.0058	0.0058	0.0058	0.0058
utilization w/o setup: d_i * t_i	0.0577	0.3926	0.1559	0.0462
prob of batch i: π_i	0.2500	0.2500	0.2500	0.2500
mean time to do a batch	14.6667	72.6667	31.6667	12.6667
var of a batch	1.5868	1.9806	1.8087	1.5681
eff batch proc time: t_e	32.92	σ_e^2	582.92	
		mean vars	1.74	
		var means	581.19	
c_a^2	1.00	$\sigma_e^2/t_e^2=c_e^2$	***0.5380***	
(sum b_i) * t_e = u	0.7602			
(ca2+ce2)/2*u/(1-u)*te = CTqi	80.2454			
CTi = CTqi+mean batch time	94.9121	152.9121	111.9121	92.9121
CTi * π_i	23.7280	38.2280	27.9780	23.2280

b) The overall utilization is obtained by multiplying the sum of the batch arrival rates and the effective batch process time (t_e) and is 0.76. The SCV of arrivals is assumed to be 1.0. The expected queue time is then given by

$$\mathrm{CT_q} = \left(\frac{c_a^2 + c_e^2}{2}\right)\left(\frac{u}{1-u}\right)t_e = \left(\frac{1+0.5367}{2}\right)\left(\frac{0.76}{1-0.76}\right)32.92 = 80.1\,\mathrm{hr}$$

The average cycle time will be this queue time plus the average batch process time or, 90.1 + 32.92 = 113.0 hours. With 8 hours per day this is 14.1 days or almost three, five day weeks.

c) We can set batch sizes so as to minimize the variability of the means, i.e., such that the run lengths are all equal. The target utilization is given by

$$u^* = \sqrt{u_0} = \sqrt{0.6524} = 0.8077$$

Since all the setup times are equal, the batch size that makes all the run lengths equal is given by

$$k_i = \frac{u_0 s}{\left(u^* - u_0\right)t_i} = \frac{(0.6524)(14/3)}{(0.8077 - 0.6524)t_i} = 19.6/t_i$$

And the values are: 98.0, 49.0, 32.7, and 196.0. We round the third to 33 and compute the expected CT using the same procedure as above to be 75.3 hours or 9.41 days. A complete search reveals an optimal set of batch sizes of 91, 4, 30, and 182 yielding a cycle time of 74.88 hours.

8. This problem should be deleted from the 3ed Edition. However, it made it into the early printings so here is the solution.
   We can construct a spread sheet using the MRP-C computations. The first spreadsheet will be for Stage 0 that corresponds to process center (PC) 3 that feeds finished goods inventory. The second spreadsheet will be for Stage 1 or PC 2 while the third will be for Stage 2 or PC 1, the beginning of the line.
   The spreadsheets are constructed using the data given. The last process center (PC 3 feeding finished goods) is shown below. Note that we have a capacity infeasibility as indicated by the 40 units of "build-ahead" inventory in period 3 (equivalently the 40 units to start in period 0). However, before we can remedy these problems we should first determine what other problems are in the process

day	demand	WIP	Capacity	Prod	net WIP	Net Dmd	Bld-Ahd	Prod	Starts
t	Dt	wt	Ct	min{wt,Ct }	Nt	net Dt	Yt	Xt	St
0		450			450				40
1	80	95	100	95	465	0		95	100
2	80	95	100	95	480	0		95	100
3	80	100	100	100	500	0	40	100	100
4	80	0	100	0	420	0	140	100	100
5	80	0	100	0	340	0	240	100	100
6	130	0	100	0	210	0	340	100	100
7	150	0	100	0	60	0	440	100	100
8	180	0	100	0	-120	120	420	100	100
9	220	0	100	0	-340	220	300	100	100
10	240	0	100	0	-580	240	160	100	90
11	210	0	100	0	-790	210	50	100	80
12	150	0	100	0	-940	150	0	100	80
13	90	0	100	0	-1030	90	0	90	0
14	80	0	100	0	-1110	80	0	80	0
15	80	0	100	0	-1190	80	0	80	
16	0	0	100	0	-1190	0	0	0	
17	0	0	100	0	-1190	0	0	0	

centers feeding this one.

From this we see that we are 40 units short of capacity to make the schedule. We could change the demands, but we should first see what problems there are in the other process centers that feed this one.

The table below shows the MRP-C calculations for the middle process center. Note that the net WIP in period 4 is negative indicating a WIP infeasibility. There is also a 50 unit capacity infeasibility indicated by the build-ahead in period 4 (or the positive start quantity in period 0).

day	demand	WIP	Capacity	Prod	net WIP	Net Dmd	Bld-Ahd	Prod	Starts
t	Dt	wt	Ct	min{wt,Ct }	Nt	net Dt	Yt	Xt	St
0		35			35				50
1	100	90	90	90	25	0		90	90
2	100	90	90	90	15	0		90	90
3	100	90	90	90	5	0		90	90
4	100	90	90	90	-5	5	50	90	90
5	100	0	90	0	-105	100	40	90	90
6	100	0	90	0	-205	100	30	90	90
7	100	0	90	0	-305	100	20	90	80
8	100	0	90	0	-405	100	10	90	80
9	100	0	90	0	-505	100	0	90	0
10	90	0	90	0	-595	90	0	90	0
11	80	0	90	0	-675	80	0	80	0
12	80	0	90	0	-755	80	0	80	
13	0	0	90	0	-755	0	0	0	
14	0	0	90	0	-755	0	0	0	
15	0	0	90	0	-755	0	0	0	

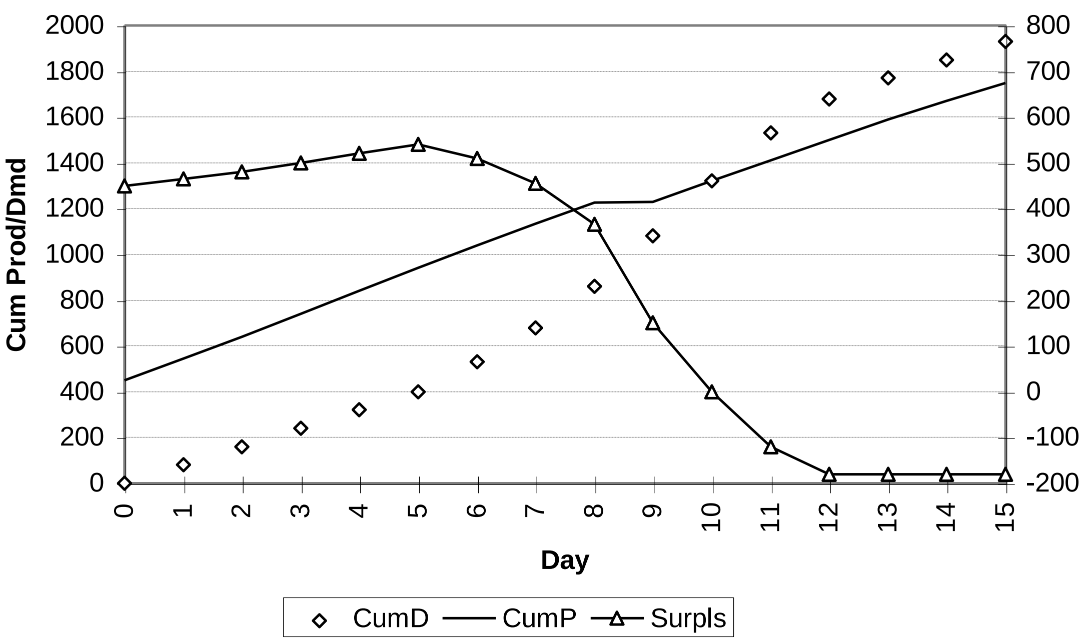
Finally, we consider the first process center in the line as shown below.

day	demand	WIP	Capacity	Prod	net WIP	Net Dmd	Bld-Ahd	Prod	Starts
t	Dt	wt	Ct	min{wt,Ct }	Nt	net Dt	Yt	Xt	St
0		0			0				0
1	90	95	100	95	5	0		95	90
2	90	0	100	0	-85	85		0	90
3	90	100	100	100	-75	90	0	100	90
4	90	0	100	0	-165	90	0	90	80
5	90	0	100	0	-255	90	0	90	80
6	90	0	100	0	-345	90	0	90	0
7	80	0	100	0	-425	80	0	80	0
8	80	0	100	0	-505	80	0	80	0
9	0	0	100	0	-505	0	0	0	0
10	0	0	100	0	-505	0	0	0	0
11	0	0	100	0	-505	0	0	0	0
12	0	0	100	0	-505	0	0	0	0
13	0	0	100	0	-505	0	0	0	
14	0	0	100	0	-505	0	0	0	
15	0	0	100	0	-505	0	0	0	

In this case there is a WIP infeasibility but no capacity infeasibility.
We see that there is no finished WIP in the process center (WIP = 0 at t=0) and that demand exceeds available WIP by period 2. Since this WIP has already been started in the line, no amount of extra capacity will remedy the problem. All we can do is reduce the demand. However, the demand is not

external but is needed to satisfy PC 2. The 90 units of demand in the above table at period 2 are from the 90 units scheduled to start at PC 2 in period 2 which are the result of the 90 units of production at PC 2 in period 6. We must constrain PC 2 to not demand more than 5 units in period 2. One way to do this is to reduce the capacity in PC 2 to 5 units in period

6.
This solves the problem for PC 1 but makes things worse for PC 2 which is now has 135 units short of capacity and 5 units of WIP infeasibility in period 4.
We fix the WIP infeasibility first. We are 5 units short in period 4 at PC 2. The demand generating these are from the starts in period 4 in PC 3 which are from the production in period 7 in PC 3. If we reduce the capacity in PC 3 from 100 to 95 in period 7 at PC 3, the WIP infeasibility is remedied. However, the capacity infeasibility in PC 2 just got worse.
The demands for periods 5 through 9 at PC 2 are all 100. The capacities are 90, 5 (after adjustment), 90, 90, 90, respectively. The difference between the demands and the capacities are 135, which is the value of the capacity shortage. These demands are from the starts in periods 5 through 9 at PC 3 which are from the production in periods 8 through 9 at PC 3. If we change the capacity in PC 3 for period 8 to 90, period 9 to 5, and periods 10 through 12 to 90, the capacity infeasibility at PC 2 is resolved.
Another way to look at it is to recognize that PC 2 is the bottleneck and that once the WIP buffer between PC 2 and PC 3 is exhausted, PC 3 cannot run faster than PC 2. For this reason, we change *all* the capacities in PC 3 past period 9 to 90.
We are now left with a capacity infeasibility of 180 in PC 3. This has grown from 40 because of all the reductions in capacity that we have done to remedy other infeasibilities. If we cannot add capacity we must push out demand.
Plotting cumulative capacity (including finished goods) versus cumulative demand reveals that demand can be met until period 11.



The demand for period 11 is 210 and the capacity is 90. Therefore we must move 120 units out. We move 10 units into period 14 (currently at 80), 10 into period 15 (currently at 80), 90 into period 16 (currently at zero), and the remaining 10 into period 17. We are now left with 60 units of excess build-ahead (i.e., capacity shortfall).

Period 12 has a demand of 150, 60 units over capacity (exactly the shortfall). We can move these 60 units into period 17 (currently at 10) and leave no capacity shortfall. Done!
The resulting tables are shown on the next pages.

MRP-C Computations for PC 3:

day t	demand Dt	WIP wt	Capacity Ct	Prod min{wt,Ct }	net WIP Nt	Net Dmd net Dt	BldAhd Yt	Prod Xt	Starts St
0		450			450				0
1	80	95	100	95	465	0		95	100
2	80	95	100	95	480	0		95	100
3	80	100	100	100	500	0	0	100	100
4	80	0	100	0	420	0	100	100	95
5	80	0	100	0	340	0	200	100	90
6	130	0	100	0	210	0	300	100	5
7	150	0	95	0	60	0	395	95	90
8	180	0	90	0	-120	120	365	90	90
9	220	0	5	0	-340	220	150	5	90
10	240	0	90	0	-580	240	0	90	90
11	90	0	90	0	-670	90	0	90	90
12	90	0	90	0	-760	90	0	90	90
13	90	0	90	0	-850	90	0	90	90
14	90	0	90	0	-940	90	0	90	70
15	90	0	90	0	-1030	90	0	90	
16	90	0	90	0	-1120	90	0	90	
17	70	0	90	0	-1190	70	0	70	

MRP-C Computations for PC 2:

day t	demand Dt	WIP wt	Capacity Ct	Prod min{wt,Ct }	net WIP Nt	Net Dmd net Dt	BldAhd Yt	Prod Xt	Starts St
0		35			35				0
1	100	90	90	90	25	0		90	90
2	100	90	90	90	15	0		90	5
3	100	90	90	90	5	0		90	90
4	95	90	90	90	0	0	0	90	90
5	90	0	90	0	-90	90	0	90	90
6	5	0	5	0	-95	5	0	5	90
7	90	0	90	0	-185	90	0	90	90
8	90	0	90	0	-275	90	0	90	90
9	90	0	90	0	-365	90	0	90	90
10	90	0	90	0	-455	90	0	90	70
11	90	0	90	0	-545	90	0	90	0
12	90	0	90	0	-635	90	0	90	
13	90	0	90	0	-725	90	0	90	
14	70	0	90	0	-795	70	0	70	
15	0	0	90	0	-795	0	0	0	

MRP-C Computations for PC 1:

day t	demand Dt	WIP wt	Capacity Ct	Prod min{wt,Ct }	net WIP Nt	Net Dmd net Dt	BldAhd Yt	Prod Xt	Starts St
0		0			0				0
1	90	95	100	95	5	0		95	80
2	5	0	100	0	0	0		0	90
3	90	100	100	100	10	0	0	100	90
4	90	0	100	0	-80	80	0	80	90
5	90	0	100	0	-170	90	0	90	90
6	90	0	100	0	-260	90	0	90	90
7	90	0	100	0	-350	90	0	90	70
8	90	0	100	0	-440	90	0	90	0
9	90	0	100	0	-530	90	0	90	0
10	70	0	100	0	-600	70	0	70	0
11	0	0	100	0	-600	0	0	0	0
12	0	0	100	0	-600	0	0	0	0
13	0	0	100	0	-600	0	0	0	
14	0	0	100	0	-600	0	0	0	
15	0	0	100	0	-600	0	0	0	

Chapter 16

Study Questions

2. Planned production and planned staffing are closely tied and both problems are amenable to similar models (e.g., linear programs).

4. *Optimal decision variables* give the planned production quantities in each period. *Optimal objective function* gives maximal production (including revenue and any costs explicitly modeled, such as inventory costs, backorder costs, etc.; note that unless fixed costs, such as overhead, are added to the model, that this profit is not identical to actual profit of the plant). *Tight constraints* indicate which resources determine capacity and are therefore likely to be bottlenecks. *Slack constraints* indicate resources that do not constrain capacity and are therefore non-bottleneck resources. *Shadow prices* indicate how much the objective can be improved per unit increase in a resource constraint (e.g., how much profit could be increased if the number of hours on a particular machine were increased).

Problems

2.

$$\max \sum_{t=1}^{\bar{t}} \{r_i S_{it} - h_i I_{it}^{+} - \pi I_{it}^{-} - l' O_t\}$$

subject to:

$$\underline{d}_{it} \le S_{it} \le \bar{d}_{it}, \forall i,t$$

$$\sum_{i=1}^{m} a_{ij} X_{it} \le c_{jt} + O_t, \forall j,t$$

$$I_{it} = I_{it-1} + X_{it} - S_{it}, \forall i,t$$

$$I_{it} = I_{it}^{+} - I_{it}^{-}, \forall i,t$$

$$X_{it}, S_{it}, I_{it}^{+}, I_{it,}^{-} O_t \ge 0, \forall i,t$$

Notice that we have used O_t to represent overtime on all machines, so *l'* represents the cost per hour of overtime for the plant. If we could use different amounts of overtime for different resources, but resources *a* and *b* were required to have overtime scheduled together, then we would define a variable O_{abt} representing the number of hours of overtime on these two stations, include it in the objective with cost l_{ab} and write the constraints

$$\sum_{i=1}^{m} a_{ia} X_{it} \le c_{at} + O_{abt}$$

$$\sum_{i=1}^{m} a_{ib} X_{it} \le c_{bt} + O_{abt}$$

4.

a)

$$\max 12(X_{H1}+X_{H2}+X_{H3})+10(X_{S1}+X_{S2}+X_{S3})+7(X_{E1}+X_{E2}+X_{E3})$$

subject to:

$$X_{H1}+X_{H2}+X_{H3}\le 700$$
$$X_{S1}+X_{S2}+X_{S3}\le 900$$
$$X_{E1}+X_{E2}+X_{E3}\le 450$$
$$21X_{H1}+17X_{S1}+14X_{E1}\le 10000$$
$$21X_{H2}+17X_{S2}+14X_{E2}\le 7000$$
$$21X_{H3}+17X_{S3}+14X_{E3}\le 4200$$
$$X_{H1}+X_{S1}+X_{E1}\le 550$$
$$X_{H2}+X_{S2}+X_{E2}\le 750$$
$$X_{H3}+X_{S3}+X_{E3}\le 225$$
$$X_{ij}\ge 0,\ i=H,S,E;\ j=1,2,3$$

b) Replace the capacity constraints (the last three constraints not counting non-negativity) with the following (note that *F* represents the fraction of capacity at each plant):

$$X_{H1}+X_{S1}+S_{E1}=550F$$
$$X_{H2}+X_{S2}+S_{E2}=750F$$
$$X_{H3}+X_{S3}+S_{E3}=225F$$
$$0\le F\le 1$$

c) To ensure at least 50% heavy duty batteries, we want

$$\frac{X_{H1}+X_{H2}+X_{H3}}{X_{H1}+X_{H2}+X_{H3}+X_{S1}+X_{S2}+X_{S3}+X_{E1}+X_{E2}+X_{E3}}\ge 0.5$$

With a bit of algebra, we can convert this to the following linear constraint, which can be added to the formulation of part (a).

$$X_{H1}+X_{H2}+X_{H3}-X_{S1}-X_{S2}-X_{S3}-X_{E1}-X_{E2}-X_{E3}\ge 0$$

6.

a)

$$Y_j=\begin{cases}1, & \text{if we lease machine } j\\ 0, & \text{if we don't}\end{cases}$$

$$\max \quad 150(X_{A1}+X_{A2}+X_{A3})+225(X_{B1}+X_{B2}+X_{B3})-20{,}000Y_1-22{,}000Y_2-18{,}000Y_3$$

subject to:

$$X_{A1}+X_{A2}+X_{A3}\le 200$$
$$X_{B1}+X_{B2}+X_{B3}\le 100$$
$$0.5X_{A1}+1.2X_{B1}\le 80Y_1$$
$$0.4X_{A2}+1.2X_{B2}\le 80Y_2$$
$$0.6X_{A3}+0.8X_{B3}\le 80Y_3$$
$$X_{Aj},X_{Bj}\ge 0, \qquad j=1,2,3$$
$$Y_j\in\{0,1\}, \qquad j=1,2,3$$

b) Simply add constraint $Y_1+Y_2\le 1$.

8.

a) MAX 50 SA1 + 50 SA2 + 50 SA3 + 50 SA4 + 65 SB1 + 65 SB2 + 65 SB3 + 65 SB4 + 70 SC1 + 70 SC2 + 70 SC3 + 70 SC4 - 5 IPA1 - 5 IPA2 - 5 IPA3 - 5 IPA4 - 5 IPB1 - 5 IPB2 - 5 IPB3 - 5 IPB4 - 5 IPC1 - 5 IPC2 - 5 IPC3 - 5 IPC4 - 10 IMA1 - 10 IMA2 - 10 IMA3 - 10 IMA4 - 10 IMB1 - 10 IMB2 - 10 IMB3 - 10 IMB4 - 10 IMC1 - 10 IMC2 - 10 IMC3 - 10 IMC4

SUBJECT TO

2) SA1 <= 100
3) SA2 <= 50
4) SA3 <= 50
5) SA4 <= 75
6) SB1 <= 100
7) SB2 <= 100
8) SB3 <= 100
9) SB4 <= 100
10) SC1 <= 300
11) SC2 <= 250
12) SC3 <= 250
13) SC4 <= 400
14) SA1 >= 0
15) SA2 >= 0
16) SA3 >= 0
17) SA4 >= 0
18) SB1 >= 20
19) SB2 >= 20
20) SB3 >= 20
21) SB4 >= 25
22) SC1 >= 0
23) SC2 >= 0
24) SC3 >= 0
25) SC4 >= 50
26) 2.4 XA1 + 2 XB1 + 0.9 XC1 <= 640
27) 2.4 XA2 + 2 XB2 + 0.9 XC2 <= 640
28) 2.4 XA3 + 2 XB3 + 0.9 XC3 <= 1280
29) 2.4 XA4 + 2 XB4 + 0.9 XC4 <= 1280
34) 0.8 XA1 + 1.2 XB1 + XC1 <= 1920
35) 0.8 XA2 + 1.2 XB2 + XC2 <= 1920
36) 0.8 XA3 + 1.2 XB3 + XC3 <= 1920
37) 0.8 XA4 + 1.2 XB4 + XC4 <= 1920
38) 3 XA1 + 2.1 XB1 + 2.5 XC1 <= 1280
39) 3 XA2 + 2.1 XB2 + 2.5 XC2 <= 1280
40) 3 XA3 + 2.1 XB3 + 2.5 XC3 <= 1280
41) 3 XA4 + 2.1 XB4 + 2.5 XC4 <= 2560
42) SA1 - XA1 + IA1 = 0
43) SB1 - XB1 + IB1 = 0
44) SC1 - XC1 + IC1 = 0
45) SA2 - XA2 - IA1 + IA2 = 0
46) SB2 - XB2 - IB1 + IB2 = 0
47) SC2 - XC2 - IC1 + IC2 = 0
48) SA3 - XA3 - IA2 + IA3 = 0
49) SB3 - XB3 - IB2 + IB3 = 0
50) SC3 - XC3 - IC2 + IC3 = 0
51) SA4 - XA4 - IA3 + IA4 = 0
52) SB4 - XB4 - IB3 + IB4 = 0
53) SC4 - XC4 - IC3 + IC4 = 0
54) - IPA1 + IMA1 + IA1 = 0
55) - IPB1 + IMB1 + IB1 = 0
56) - IPC1 + IMC1 + IC1 = 0
57) - IPA2 + IMA2 + IA2 = 0
58) - IPB2 + IMB2 + IB2 = 0
59) - IPC2 + IMC2 + IC2 = 0
60) - IPA3 + IMA3 + IA3 = 0
61) - IPB3 + IMB3 + IB3 = 0

30)	1.1 XA1 + 2.2 XB1 + 0.9 XC1 <= 640	62) -	IPC3 + IMC3 + IC3 = 0
31)	1.1 XA2 + 2.2 XB2 + 0.9 XC2 <= 640	63) -	IPA4 + IMA4 + IA4 = 0
32)	1.1 XA3 + 2.2 XB3 + 0.9 XC3 <= 640	64) -	IPB4 + IMB4 + IB4 = 0
33)	1.1 XA4 + 2.2 XB4 + 0.9 XC4 <= 640	65) -	IPC4 + IMC4 + IC4 = 0

b) The solution is given below. Constraints (3)-(13) are tight sales constraints. Two machine constraints are tight: constraint (26) is the machine capacity constraint on machine 1 in quarter 1; constraint (33) is the machine capacity constraint on machine 2 in quarter 4.

OBJECTIVE FUNCTION VALUE

1) 122240.50

VARIABLE	VALUE	REDUCED COST
SA1	70.833340	.000000
SA2	50.000000	.000000
SA3	50.000000	.000000
SA4	75.000000	.000000
SB1	100.000000	.000000
SB2	100.000000	.000000
SB3	100.000000	.000000
SB4	100.000000	.000000
SC1	300.000000	.000000
SC2	250.000000	.000000
SC3	250.000000	.000000
SC4	400.000000	.000000
IPA1	.000000	.000000
IPA2	.000000	.000000
IPA3	.000000	.000000
IPA4	.000000	.000000
IPB1	.000000	.000000
IPB2	.000000	.000000
IPB3	10.227270	.000000
IPB4	.000000	.000000
IPC1	.000000	.000000
IPC2	.000000	.000000
IPC3	.000000	.000000
IPC4	.000000	.000000
IMA1	.000000	15.000000
IMA2	.000000	15.000000
IMA3	.000000	15.000000
IMA4	.000000	15.000000
IMB1	.000000	15.000000
IMB2	.000000	15.000000
IMB3	.000000	15.000000
IMB4	.000000	15.000000
IMC1	.000000	15.000000
IMC2	.000000	15.000000
IMC3	.000000	15.000000
IMC4	.000000	15.000000
XA1	70.833340	.000000
XB1	100.000000	.000000
XC1	300.000000	.000000
XA2	50.000000	.000000
XB2	100.000000	.000000
XC2	250.000000	.000000
XA3	50.000000	.000000
XB3	110.227300	.000000
XC3	250.000000	.000000
XA4	75.000000	.000000
XB4	89.772730	.000000
XC4	400.000000	.000000
IA1	.000000	55.000000
IB1	.000000	46.666660
IC1	.000000	23.750000
IA2	.000000	5.000000
IB2	.000000	5.000000
IC2	.000000	5.000000
IA3	.000000	2.500000
IB3	10.227270	.000000
IC3	.000000	2.954545
IA4	.000000	7.500000
IB4	.000000	10.000000
IC4	.000000	7.045455

ROW	SLACK OR SURPLUS	DUAL PRICES	ROW	SLACK OR SURPLUS	DUAL PRICES
2)	29.16667	.000000	35)	1510.000000	.000000
3)	.000000	50.000000	36)	1497.727000	.000000
4)	.000000	50.000000	37)	1352.273000	.000000
5)	.000000	47.500000	38)	107.500000	.000000
6)	.000000	23.333340	39)	295.000000	.000000
7)	.000000	65.000000	40)	273.522700	.000000
8)	.000000	65.000000	41)	1146.477000	.000000
9)	.000000	60.000000	42)	.000000	50.000000
10)	.000000	51.250000	43)	.000000	41.666660
11)	.000000	70.000000	44)	.000000	18.750000
12)	.000000	70.000000	45)	.000000	.000000
13)	.000000	67.954540	46)	.000000	.000000
14)	70.833340	.000000	47)	.000000	.000000
15)	50.000000	.000000	48)	.000000	.000000
16)	50.000000	.000000	49)	.000000	.000000
17)	75.000000	.000000	50)	.000000	.000000
18)	80.000000	.000000	51)	.000000	2.500000
19)	80.000000	.000000	52)	.000000	5.000000
20)	80.000000	.000000	53)	.000000	2.045455
21)	75.000000	.000000	54)	.000000	5.000000
22)	300.000000	.000000	55)	.000000	5.000000
23)	250.000000	.000000	56)	.000000	5.000000
24)	250.000000	.000000	57)	.000000	5.000000
25)	350.000000	.000000	58)	.000000	5.000000
26)	.000000	20.833330	59)	.000000	5.000000
27)	95.000000	.000000	60)	.000000	5.000000
28)	714.545500	.000000	61)	.000000	5.000000
29)	560.454500	.000000	62)	.000000	5.000000
30)	72.083340	.000000	63)	.000000	5.000000
31)	140.000000	.000000	64)	.000000	5.000000
32)	117.500000	.000000	65)	.000000	5.000000
33)	.000000	2.272727			

c) We must either divide the process times on machines 1 and 2 by 0.8 or multiply the available hours on machines 1 and 2 by 0.8 to account for the extra time that will be spent reprocessing parts.

10.

a) Any cost accounting scheme will rank order the products according to profitability, and so would lead us to first cover minimum demand constraints, then produce as much as possible of the most profitable product (subject to maximum demand constraints), then move to the next most profitable product, and so on. We consider a few possibilities below.

Here is a solution that produces as much X-100 as possible. Note that Test is the constraint. Note also that this loses $69,500!

	Plant Produces Three Models of Cannister Vacuum Cleaners							
	Motor Ass	Final Ass	Test	Mat Cost	Price	Min Dem	Max Dem	Prod Quant
Product	(min/unit)	(min/unit)	(min/unit)	($/unit)	($/unit)	(unit/mo)	(unit/mo)	(unit/mo)
X-100	8	9	12	80	350	750	1500	1500
X-200	14	12	7	150	500	0	500	0
X-300	20	16	14	160	620	0	300	0
Solution			Labor Cost			Material Cost		Overhead Cost
Profit	($69,500)		$/hr	20				
			$/min	0.33				
Mach Time			$/mo	$14,500		$120,000		$460,000
Mot Assem	12000							
Fin Assem	13500							
Test	18000							

Here is a solution that produces as much X-200 as possible and then uses up the rest of capacity (Test again) with X-100. This makes $23,722.

	Plant Produces Three Models of Cannister Vacuum Cleaners							
	Motor Ass	Final Ass	Test	Mat Cost	Price	Min Dem	Max Dem	Prod Quant
Product	(min/unit)	(min/unit)	(min/unit)	($/unit)	($/unit)	(unit/mo)	(unit/mo)	(unit/mo)
X-100	8	9	12	80	350	750	1500	1207
X-200	14	12	7	150	500	0	500	500
X-300	20	16	14	160	620	0	300	0
Solution			Labor Cost			Material Cost		Overhead Cost
Profit	$23,722		$/hr	20				
			$/min	0.33				
Mach Time			$/mo	$17,168		$171,560		$460,000
Mot Assem	16656							
Fin Assem	16863							
Test	17984							

Here is a solution that produces as much X-300 as possible, covers the minimum demand for X-100 and then uses up capacity (Motor Assembly is the constraint) with X-200. It only makes $13,342.

	Plant Produces Three Models of Cannister Vacuum Cleaners							
	Motor Ass	Final Ass	Test	Mat Cost	Price	Min Dem	Max Dem	Prod Quant
Product	(min/unit)	(min/unit)	(min/unit)	($/unit)	($/unit)	(unit/mo)	(unit/mo)	(unit/mo)
X-100	8	9	12	80	350	750	1500	750
X-200	14	12	7	150	500	0	500	428
X-300	20	16	14	160	620	0	300	300
Solution			Labor Cost			Material Cost		Overhead Cost
Profit	$13,342		$/hr	20				
			$/min	0.33				
Mach Time			$/mo	$16,958		$172,200		$460,000
Mot Assem	17992							
Fin Assem	16686							
Test	16196							

Finally, here is a solution that maximizes profit subject to capacity constraints (found by using the LP Solver in Excel). Note that it makes $41,521, which is more than the others.

	Plant Produces Three Models of Cannister Vacuum Cleaners							
	Motor Assembly	Final Assembly	Test	Material Cost	Price	Min Demand	Max Demand	Production Quantities
Product	(min/unit)	(min/unit)	(min/unit)	($/unit)	($/unit)	(unit/mo)	(unit/mo)	(unit/mo)
X-100	8	9	12	80	350	750	1500	1062.5
X-200	14	12	7	150	500	0	500	500
X-300	20	16	14	160	620	0	300	125
LP Solution			Direct Labor Cost		Direct Material Cost			Overhead Cost
Profit	$41,521		$/hr	20				
			$/min	0.33				
Mach Time Constraints			$/mo	$17,854		$180,000		$460,000
Mot Assem	18000							
Fin Assem	17562.5							
Test	18000							

b) The LP solution has X-200 production set at maximum demand, but neither X-100 nor X-300 are set at their maximum demand. Therefore, there is no rank ordering that could have led to this solution. Since the true cost of a product depends on the product mix, it is not possible to use an *a priori* accounting scheme to plan production quantities.

Chapter 17

Study Questions

2. Cycle time reduction can reduce:

   - *WIP*: automatically by Little's law.

   - *Raw Materials*: by improving the accuracy of purchasing (i.e., since the further in advance purchases of raw materials must be made, the more errors will occur).

   - *FGI*: by reducing reliance on forecasts (i.e., whenever production in response to a forecast does not match demand the remnant goes into FGI).

4. Inventories of unmatched parts at assembly operations are caused by lack of synchronization, which can be the result of variability in the fabrication lines, uneven batching policies in different lines, or release/control policies that allow lines feeding an assembly to get out of sync. Remedies include variability reduction (e.g., reducing MTTR, reducing setup times, training to improve worker skillfulness, etc.), rationalizing batching (e.g., using common batch sizes or batch sizes that are powers of two of a common base size), and modifying the shop floor control system to maintain synchronization (e.g., use CONWIP with FISFO within the fabrication lines to tie them to the final assembly schedule).

6. Using approximations for fill rate and backorder level enable us to get simple expressions for Q and r. But, if we were to use these approximations to evaluate performance, we could wind up with solutions that do not meet performance targets. Therefore, even though we use expressions based on approximations of performance measures, we use the actual performance measures to see how good the resulting solution is.

8. Many retail distribution systems and spare parts systems are examples of arborescent multi-echelon inventory systems. An example of a reverse aborescent system is an assembly system in which many raw material producers supply several component plants which in turn supply a single final assembly plant.

10. Bookstore chains are examples of systems that can make use of a system where most of the inventory is held in the stores and lateral transshipments are used. If the book you want is not available at your local store, the clerks can check the computer to see if it is available at another store and have it sent over. Other retail establishments (department stores, appliance stores, furniture stores, etc.) can make use of similar strategies. The rise of integrated information systems seems to be making these practices more prevalent.

Problems

2.

(a,b)	c_i	D_i	l_i	θ_i	σ_i	Q_i	r_i	F_i	S_i	B_i	I_i
i	($/unit)	(units/yr)	(months)	(units)	(units)	(units)	(units)	(order freq)	(fill rate)	(backorder)	(inventory)
Rivets	0.1	24000	0.5	1000	31.6	1000.0	1000.0	24.0	0.987	0.250	$ 50.03
Screws	0.1	6000	0.5	250	15.8	1000.0	1000.0	6.0	1.000	0.000	$ 125.00
		30000						15.000	98.99%	0.250	$ 175.03

(c)	c_i	D_i	l_i	θ_i	σ_i	Q_i	r_i	F_i	S_i	B_i	I_i
i	($/unit)	(units/yr)	(months)	(units)	(units)	(units)	(units)	(order freq)	(fill rate)	(backorder)	(inventory)
Rivets	0.1	24000	0.5	1000	31.6	1000.0	1000.0	24.0	0.987	0.250	$ 50.03
Screws	0.1	6000	0.5	250	15.8	250.0	250.0	24.0	0.975	0.250	$ 12.53
		30000						24.000	98.49%	0.500	$ 62.55

Service falls a little, inventory a lot

(d)	c_i	D_i	l_i	θ_i	σ_i	Q_i	r_i	F_i	S_i	B_i	I_i
i	($/unit)	(units/yr)	(months)	(units)	(units)	(units)	(units)	(order freq)	(fill rate)	(backorder)	(inventory)
Rivets	0.1	24000	0.5	1000	31.6	1250.0	1250.0	19.2	1.000	0.000	$ 87.50
Screws	0.1	6000	0.5	250	15.8	312.5	312.5	19.2	1.000	0.000	$ 21.88
		30000						19.200	99.99999%	0.000	$ 109.38

Better service and inventory than (a)

Constraints		**Costs**	
F (orders/year)	15.000	Fixed setup cost (A)	$ 1.83
S (service level)	8.991%	Stockout Cost (k)	$ 250.00
		Holding rate (h)	100%

(e)	c_i	D_i	l_i	θ_i	σ_i	Q_i	k_iD_i / (kiDi+hiQi)	r_i	F_i	S_i	B_i	I_i
i	($/unit)	(units/yr)	(months)	(units)	(units)	(units)	(unitless)	(units)	(order freq)	(fill rate)	(backorder)	(inventory)
1	0.1	24000	0.5	1000.0	31.6	937.5	1.000	1131.6	25.6	1.000	0.000	$ 60.04
5	0.1	6000	0.5	250.0	15.8	468.7	1.000	313.3	12.8	1.000	0.000	$ 29.77
		30000							19.200	99.99999%	0.000	$ 89.81

An optimized (Q,r) policy (using stockout formulation because we are concerned with fill rate) achieves the same order frequency and fill rate as (c) with less inventory.

4.

Warehouse

Parameters	
Annual Demand (D)	20
Replenishment lead time in days (l)	30.4167
Mean lead time demand (θ)	1.667
Lead time standard deviation (σ_L)	0
Average daily demand (d)	0.055
Standard deviation of daily demand (σ_D)	0.234
σ adjusted	1.291

Facility

Parameters	
Annual Demand (D)	10
Replenishment lead time in days (l)	0.5
Adjusted lead time (l + W) in days	1.1741
Mean lead time demand (θ)	0.0322
Lead time standard deviation (σ_L) in days	2.1666
Average daily demand (d)	0.0274
Standard deviation of daily demand (σ_D)	0.1655
σ adjusted	0.1889

Decision Variables

Q	0.92
r	2.794

Performance Measures	Normal	Poisson
F(Q,r)	21.7391	21.7391
S(Q,r)	0.8857	0.9117
B(Q,r)	0.0733	0.0369
I(Q,r)	1.6606	2.3703
W = B(Q,r)/D (in years)	0.00366	0.00185

Decision Variables

Q	1
R	1

Performance Measures	Normal	Poisson
F(Q,r)	10	10
S(Q,r)	1.0000	0.9995
B(Q,r)	0.0000	0.0000
I(Q,r)	1.4678	1.9678

a) Expected backorder level at warehouse = 0.0733
b) Effective lead time to facility = 1.1741 days
c) Minimum reorder point required for 99% service is r=1

6.

Warehouse

Parameters	
Annual Demand (D)	365
Replenishment lead time in days (l)	60
Mean lead time demand (θ)	60.000
Lead time standard deviation (σ_L)	0
Average daily demand (d)	1.000
Standard deviation of daily demand (σ_D)	1.000
σ adjusted	7.746

Decision Variables

Q	30
r	60

Facility

Parameters	
Annual Demand (D)	365
Replenishment lead time in days (l)	7
Adjusted lead time (l + W) in days	7.4657
Mean lead time demand (θ)	7.4657
Lead time standard deviation (σ_L) in days	1.3755
Average daily demand (d)	1.0000
Standard deviation of daily demand (σ_D)	1.0000
σ adjusted	3.0590

Decision Variables

Q	1
R	10

Performance Measures	Normal	Poisson
F(Q,r)	12.1667	12.1667
S(Q,r)	0.8970	0.8971
B(Q,r)	0.5000	0.4657
I(Q,r)	15.5000	15.9657
W = B(Q,r)/D (in years)	0.00137	0.00128

Performance Measures	Normal	Poisson
F(Q,r)	365	365
S(Q,r)	0.8383	0.8652
B(Q,r)	0.2621	0.1569
I(Q,r)	3.2964	3.6912

a) Mean lead time demand considering supplier delays is 7.4657

b) Standard deviation of lead time demand is 3.059, which is greater than $\sqrt{7.4657} = 2.7323$ (i.e., what it would be if demand were Poisson)

c) The fill rate assuming Poisson demand for r=10 is 86.52%. Actual service will be lower than this because variability of demand is greater than that of the Poisson.

Chapter 18

Study Questions

2. Facilities needed to support production increase less than linearly with the amount of capacity. This is particularly true with regard to overhead and support functions. Thus, a plant with twice the capacity might only cost 70 percent more than the plant with less.

   However, this economy of scale does not consider the cost of complexity and the difficulty to manage larger enterprises. This diseconomy of scale is known as bureaucratization. Another diseconomy of scale results from distribution considerations when many smaller plants over a larger area might reduce distribution costs enough to significantly affect unit costs.

4. A more specific problem statement might be:

   maximize throughput
   subject to:
      budget constraint
      cycle time constraint
      product mix constraint(s)
      marketing constraints (min and max demands)
      etc.

6. The conveyor time, *c*, should be greater than the maximum time assigned to any station to make sure that all stations are able to finish their task before the part is moved to the next station. If this were not the case, parts would move before they were completed and would disrupt the flow of the entire line.

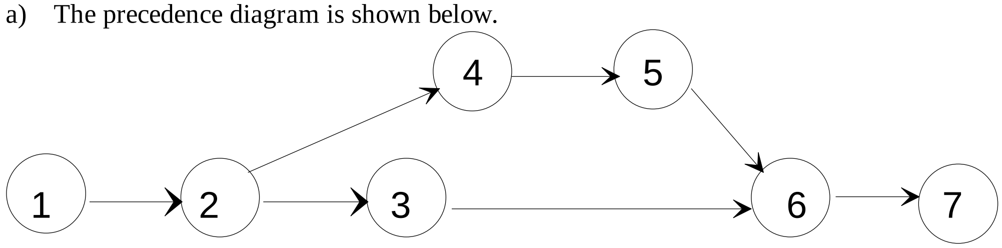
Problems

2. This looks like deja vu all over again. See solution to problem 9.14.

4. The information for the problem is summarized below.

Task Number	Operation	Time Required	Predecessors
1	Chassis	2 min	none
2	Board 1	3 min	1
3	Compts 1	3 min	2
4	Board 2	4 min	2
5	Compts 2	2 min	4
6	Yoke	3 min	2, 3, 4, 5
7	Test	5 min	6

a) The precedence diagram is shown below.



b) The total time is 22 minutes. This factors into 11 and 2. The minimum factor that is greater than the maximum single time is 11 minutes.

c) The conveyor time will be 22/0.85 = 25.88 minutes. This yields 2.32 monitors per hour.

d) We use the algorithm presented with two stations and 11 minutes per station. The first station performs tasks 1, 2, 4, and 5. The second station performs 3, 6, and 7. Both stations require exactly 11 minutes so the balance delay is zero.