Constraint Management at UniCo:
Analyzing “The Goal” as Fictional Case Study

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Abstract

Eliyahu Goldratt’s novel about manufacturing, “The Goal: A Process of Continuous Improvement,” is probably the best-selling operations management book of all-time. As a fictional case study, it presents a constraint-focused approach to production management, but in a very non-quantitative way. However, a fair amount of data about the plant is available, spread throughout the book. We collect and analyze the data for a greater understanding of the impact of the improvements.

Keywords: Production, The Goal, Theory of Constraints

Introduction: The Goal as Fictional Case Study

Eliyahu Goldratt’s manufacturing novel The Goal: A Process of Continuous Improvement has inspired countless professionals in production (and many other fields (Whitford, 2004)) to embark on their own efforts of continuous improvement. As Rand (1986) writes, “It’s a novel, but it’s also a manufacturing text-book, and it’s good on both accounts.” Many reviewers have agreed The Goal is an easy-to read way to get an introduction to production realities (Belis, 1994, The Economist 1995, Dani 2006, Rand 1986). However, no one has taken a hard look at the numbers presented in the book as a fictional case study. In this paper, we analyze the data presented during the course of the story. In so doing, we have several objectives:
1. To discover how complete an understanding we can gain of the plant’s operations from the details scattered throughout the book,

2. To see what additional insights we can gain from the characters’ actions in the book from the detailed analysis, and finally

3. To see if all of the details discovered do add up to form a cohesive view of the plant.

_The Goal_ is easy to read and understand, which has made it popular with practitioners. Because it puts the reader in the middle of Alex Rogo’s chaotic life at UniCo, the reader can see how all of the realities of production life affect a person’s abilities to make the “right” decisions. For this reason, it is a very powerful way to help people without production experience understand these realities. With an appeal like that, it is easy to understand why the third revised edition says “Over 3 million copies sold” (Goldratt and Fox, 2004).

Because most undergraduate students have not experienced a production environment first-hand, the book has been used in many universities, as I have in my advanced production course for the past dozen years. As I read the book more times, I began to notice more of the details about the plant’s capacity sprinkled throughout the book, and collected the information to analyze it and present it to my students. A detailed look at the changes in the book helped me and the students get a much clearer understanding of their impact in the plant. For the dedicated production manager / consultant / professor who takes the time to study the book’s problems and solutions, a careful examination of the data in the book can yield some interesting new insights.

In a few cases the data unfortunately, do not quite add up. Because this book has become the best-known book in the field, those of us who devote our energies to production details deserve that such a book have consistent technical details. Because the subtitle of the book is “A
Process of Ongoing Improvement,” hopefully the author will listen to the suggestions made here and further strengthen the book and its message.

After a disclaimer about what this paper will not cover, we will discuss the impact of *The Goal*, and give a brief summary of the book. Before we begin a detailed discussion of events in the book, we deal with some ambiguities in the timeline of events in the book. We then look at the performance of the plant, and estimates of its capacity, before focusing on the capacity improvements made on the two main bottlenecks in the plant, the plant’s inventory consumption, and finally lead time improvements. All page citations are from the third revised edition.

**What this Paper is Not**

A lot of time has passed since the book was written. The characters in the book do not use an ERP system, cell phones, pagers, email, voice mail, or even answering machines. This paper not concerned about such minor technological dressings. It would be easy to write things like that into the book, but by the same token, their absence does not in any way diminish the conclusions reached in the book. The same could be said of other changes in society, like the fact that today no one would consider smoking a cigar in a conference room, or that you can’t go down the airport jetway unless you have a boarding pass for the flight. If anything, they remind the reader of how long ago the book was written, and how timeless many of its lessons are.

If the book were set in the first decade of the 21st century, the characters would likely find management more willing to embark on a process of ongoing improvement. Management at many companies is more willing to change than it was 20 or more years ago. Many of the other ideas presented in the book are far more widely held today, at least in part, because of the ubiquity of the book.
There are some inconsistencies in the book that could affect our analysis, such as the fact that the number of heat treat furnaces is seems to change from being given as two ovens (p. 146, 147, 192) to one (p. 147,148). There are other inconsistencies that are not important, like the fact that the division controller’s name changes from Ethan Frost (pp. 25, 55, 249) to Nathan Frost (pp. 261-2, 268, 319). Or, one afternoon, Alex says “I happen to know the plant is only about fifteen years old,”(p. 37) but something doesn’t quite add up when he says that Lou the controller came to the plant “from corporate about twenty years ago,” (p. 44) and Bob Donovan the production supervisor says “Hell, I’ve been at this plant for more than twenty years.”(p. 143). These mistakes may be confusing, but do not lead to confusion about operational details.

What we will be focusing on the production details of the book. However, this will not be an attempt to determine whether Goldratt’s drum-buffer-rope methods are superior to other methods or whether the methods presented are the ideal way to run a plant or not.

**Impact of The Goal**

In 1995, *The Economist* (1995) wrote, “The most successful attempt at management-as-fiction is still ‘The Goal.’ ” At that point, the book had been translated into 18 languages. *The Economist* also says that a study of British managers found that although they bought books by many management authors, *The Goal* was the only one they had read cover-to-cover. Writing in *Forbes*, Belis (1994) writes, “The Goal offers a far more palatable way to absorb such simple but important home truths than most of the nonfiction management manuals out there.”

The drum-buffer-rope approach and Goldratt’s “theory of constraints” approach which both appear in “The Goal” have inspired a fair amount of discussion within the operations research literature, as Kouvelis et al. (2005) note. Spearman (1997) described a number of benefits and shortcomings of the approach. Atwater and Chakravorty (2002) considered a
question raised by Spearman (1997), namely the proper level of utilization for the bottleneck. Silver, Pyke and Peterson (1998) list some of the other papers that compare the production scheduling approach presented in “The Goal” with other, similar approaches. The ideas in “The Goal” have been widely-enough discussed in industry that they are often discussed in other textbooks like and Chase (2004), Hopp and Spearman (2001), Vollmann (2005).

**Central Points of the Book**

For the reader whose knowledge of the book needs refreshing, a brief synopsis follows. Alex Rogo is the manager of the fictitious UniCo plant. His Division Vice President, Bill Peach, tells him that because his plant is losing so much money and has so many late shipments, it will be shut down in three months, unless Alex can dramatically turn things around. Later that same week, Alex’s wife Julie leaves him, in large part because he has been spending so many long hours at work. Alex remembers a chance airport encounter with his Jonah, his old college physics professor who has become a manufacturing consultant, and enlists his aid. With Jonah’s guidance, Alex and his staff discover the plant’s bottlenecks, figure out how to increase the bottlenecks’ capacity, and how to ultimately use the bottlenecks’ production schedule to control the release of material into the plant. With a newfound emphasis on shipping late orders first, they clear their backlog, and go in search of new business. The plant is such a roaring success, overall, that the plant is saved, and Alex is promoted to run the whole division. He also discovers family life again and saves his marriage.

All of the in-plant action of the book centers around the two bottleneck workstations in the plant. Through Jonah’s prodding, Alex and his staff discover that their most expensive numerically controlled (n/c) machine, the NCX-10, (which Alex describes as “a sexy-looking machine” (p. 14)) is one bottleneck, and that heat-treat, (“It’s dirty. It’s hot. It’s ugly. It’s
dull.” (p. 146)) is the other. They spend the rest of the book figuring out how to increase the productivity of these bottlenecks, and how to allow the bottlenecks to dictate the pace of the rest of the plant. These two workcenters, and their throughput rates, are by far, the most important things in the plant, and most of our analysis will involve these two workcenters.

**Timeline Continuity Issues**

The book does not carefully signal the timing of events, which can be confusing for the reader. For example, at the end of a month, the plant has set a record for shipments, but it’s not immediately clear to the reader whether it was the first or second month of the plant’s probation. Because many things happen in a short amount of time in some parts of the book, the reader can be left confused about what is happening when. To take a detailed look at the book, as we will do, it is important to be able to know fairly accurately when things happened.

The first 16 chapters take place in what must surely be one of the worst weeks, both professionally and personally, a person could imagine: the plant Alex runs is threatened with closure if it doesn’t improve in three months, and Alex’s wife, Julie, leaves him.

Chapter 17 begins the next Monday, which continues into ch. 18, where the second Tuesday starts, and Alex’s staff begins trying to identify the bottlenecks. “A few days later” (p. 141) database manager Ralph Nakamura admits that he can’t find the bottlenecks using the MRP routings. Much later, Ralph says that it took him four days to realize that he couldn’t find the bottlenecks (p. 280). If he started Tuesday and tried for four days, that could mean he admitted defeat on Friday, or Monday of the next week. It seems to make more sense for this to be Monday, as we will see.

When Ralph admits defeat, Alex tells his team they’ve “only got ten weeks now to make something happen.” If they had 12 weeks to begin with, which seems like a reasonable
assumption, that’s true. But ch. 19 continues “that evening” when he picks up Jonah at the airport and tells him “We’ve only got two months left.” (p. 150). Two weeks apparently evaporated in one afternoon, but it seems more consistent to assume this is really still Monday of week 3. Chapter 20 starts with the morning after Jonah’s first visit, apparently Tuesday of week 3. Ch. 21 starts with that night and the next morning, which must be Wednesday. If the “few days” above ended with a Friday, this day would be Sunday, and they would have worked through the weekend, which was not mentioned, and seems unlikely.

In the “early afternoon,” on the Wednesday after Jonah’s visit, (p. 173) Alex discovers that the NCX-10 is idle. “A few days pass” (p. 176) while they develop the red and green tag system. “But at eight o’clock on Friday morning,” Alex is in the cafeteria explaining the new system to the employees. Apparently, Thursday lasts “a few days” at the UniCo plant.

Chapter 22 is Monday, and “a week has passed” since the tag system went in place, so it is Monday of week 5, and ch. 23 is apparently a Wednesday morning of week 6. Chapter 24 fast forwards to the Friday at the end of the month, which must be the second probation month and therefore week 8, and continues to Monday of week 9. Ch. 25 begins with Jonah arriving on Tuesday morning, and ch. 26 continues to Wednesday. Chapter 27 says “May has ended.” “Two months ago” the threat came, and they have a month to go, so apparently Peach’s threat came at the end of March or beginning of April.

The third month passes in chs. 27-30. In chapter 28, they halved the batch sizes on non-bottlenecks at the very start of month 3, and went to look for more sales. Chapter 29 takes place “two weeks” from the end of the month, which must be Monday of week 11. In this chapter, they halved batch sizes again and accepted a huge order from Bucky Burnside, and the first of four shipments were to ship in 2 weeks. Chapter 30 jumps two weeks to the end of May, and the
three months are up. The first Burnside order has shipped, on time, in week 13. “The following week,” week 14, some creative accounting they used was discovered (p. 248). Two days later, an audit team arrives. “For a week,” Alex waits for fallout from headquarters, which puts the time at roughly the end of week 15. All of Burnside’s orders have shipped, even though we wouldn’t have expected the last one to ship until week 16.

In Ch 31, Alex learns that the plant is safe, and he has two months to prepare for his big promotion, time which passes quickly, while he enlists his team’s help in preparing for the next stage of his career. Without Jonah, that next stage would have involved searching for a new job. Thanks to Jonah’s guidance, he saved his plant, and kept his job. (Alex also of course saved his marriage, but it’s not clear how critical Jonah was to that success.)

**Plant Performance and Costs**

Bill Peach threatened the plant with closure because it “is losing money” (p. 5). The plant was “a loser” when Alex started six months ago, and Alex admitted “it’s gotten worse instead of better” since he came (p. 6). The plant has added new robots fairly recently, apparently within the last year (p. 68), and since that time, the plant has had a harder time shipping orders to customers on time (p. 29) as overdue orders grew rapidly in the last nine months (p. 69), and inventories have increased significantly (pp. 29, 67). At the end of the previous third quarter, which was just six months ago, they discovered that the new robots were not being used as heavily as they needed to be to justify their purchase, so a lot more material was sent to them (p. 70), which is ultimately discovered to be a big part of the plant’s problem.

Aside from the statement about losing money, how the plant is doing financially is not given but we can make an estimate. The plant controller says the plant has “total operating expense” of $1.6m per month (p. 158). An estimate of “total operating expense” may or may not
include material costs, depending on the accounting practices of the company. As we will see, it would make more sense if this number did include materials costs.

The plant controller estimates that the selling price of a typical unit is $1,000 (pp. 156, 158). Johnny Jons, the sales manager, told Alex that Bucky Burnside wanted to buy “a thousand units,” of the popular Model 12, and says “a thousand units means a little over a million dollars in sales to us” (p. 242), which would put the sales price at just over $1,000. However, later Johnny says that UniCo sells the Model 12 to Burnside for $827 (p. 312). Clearly Johnny is confused about his pricing, but because $1,000 is given several times as the average sales price of a unit, we will use that number.

The materials cost of the popular Model 12 is $344.07 (p. 312). With monthly expenses of $1.6m, the plant would have to produce 1,600 units per month to break even. If the Model 12 material costs are typical, that would mean material costs would be approximately $550k. Since the plant was in fact losing money, they must have been shipping less than 1,600 units, and material costs may have been lower than this. On the other hand, because the plant was building inventory, the plant may have been bringing in more than $550k worth of material each month.

In 1984, the average hourly wage for a U.S. manufacturing worker producing durable goods was $9.74 (Statistical Abstract of the United States, 1986, p. 412.), which would be an annual salary of $20,259. The median weekly wage for a machinist was about $395 (Occupational Outlook Handbook, 1986, p. 424), which computes to $20,500 per year.

If “total operating expense” includes material costs, this would mean that total labor, depreciation and utilities would cost $1.05m per month. There are 400 people on the day shift at UniCo (p. 36), and 600 people work at the plant (p. 17). If depreciation and utilities costs were zero, this would mean an average annual salary of nearly $21,000, just slightly above average. If
the estimate of “total operating cost” did not include materials, and the full $1.6 were for labor, UniCo would be paying its people 50% above the national average. However, if we allow for the fact that the plant must have utilities and depreciation (for all of those new robots), its average salaries would come out somewhere below the national average, perhaps significantly so. This makes it easy to believe when Bob Donovan says “we can’t seem to attract anybody good with the wages we offer” (p. 146).

Before the improvements in the plant, the old record for shipments in a month was 31 orders worth “about two million dollars” (p. 195). If the record shipments for one month were $2 million, typical shipments must have been somewhere below that, and if the plant costs $1.6 million to run, it is not difficult to see why Alex’s plant has not been profitable lately. Also, the plant has already laid off 600 workers (p. 17), some of them just three months before the book starts (p. 4). Operating expenses must have been much higher than $1.6m before, and yet the record for shipments was only $2m. It would be very hard to see how the plant could have possibly been profitable before the layoffs.

**Improvement Required to Save the Plant**

When Alex came to the plant, it was losing money, and he was put in charge of it because Bill Peach thought Alex could “change this plant from a loser to…well, a small winner at least” (p. 6). Peach said in three months he needs to “turn this plant around” (p. 6). Exactly what had to be accomplished was not specified. In the second month, the plant achieved profitability and was the best-performing plant in the division (p. 220). But that was not enough to take away the threat of closure. Bill Peach thought that Alex may have only done so well because of the large backlog he was able to ship, and Bill wanted to see better proof of a long-term improvement. He told Alex “It’s going to take a ten or fifteen percent reduction in operating expense to make the
plant profitable for the long term” (p. 222). Alex asked how much improvement he needed to achieve, and Bill shifted the criteria from cost reduction to profit improvement and said “Just give me fifteen percent more on the bottom line than you did this month” (p. 223).

When the plant increases shipment by increasing production, labor costs are unchanged, and only materials costs go up, which gives Alex a marginal profit per unit of $656, assuming material costs of $344 (p. 312). But when he sells an item from inventory, he is selling an asset, which was valued at full cost of approximately $700 (p. 312), and profit per unit is only $300.

In month 2, the plant increased the production of the bottlenecks and shipped $3 million in orders. Labor costs were unchanged, so labor, depreciation and utility costs should remain constant at $1.05m. For 3,000 units, raw material costs would be $1.03m, so total expenses were $2.08m, and net profits were $0.92m on sales of $3 million. Peach told Alex to increase these profits by 15%, which would be an additional $0.135m. If material costs are $344 per unit, and a $1,000 sales price, an additional 208 units would be sufficient to reach the target.

However, in the book, Alex increases production by a 1,000 units, but the plant will not reach the target, so the controller suggests using a burden calculation based on the last two months instead of the last year (p. 239). After changing the burden, the profit increase comes out to 17%. (p. 247). If sales increased by 1,000, profits should increase by $656k, which should have been a 70% increase. In the end, the original burden is used and they record a 12.8% increase (p. 250). Since throughput in month three is twice the old plant record, compared to the last year, the burden should have been cut roughly in half, and a larger increase difference between the two profit calculations would be expected.

But it is hard to see how the discussion of burden is relevant to the plant’s profit improvement. Burden is used to calculate a profit per unit, but actual monthly profits should be
determined by actual expenses and revenues. Using burden to compute a unit cost shows a profit per unit of $300. Suppose the plant shipped 1,500 units in the month before the book began. Using the standard cost, Bill Peach would have said Alex had profits of $450k for the month. But Bill Peach was clearly using actual revenues and expenses to conclude the plant was losing money. Using actual costs and revenues, the plant clearly exceeded the 15% target by a huge amount, and it is hard to see how the figures given in the book could be correct.

**Estimates of Plant Capacity**

We know that the plant’s old record month for production was $2m, which represents roughly 2,000 units. After making changes to increase bottleneck capacity, during the second month of the book, the plant ships 57 orders worth “in round numbers, we’ll call it a cool three million” dollars (p. 195), approximately 3,000 units. Apparently, the changes made in the plant have allowed them to ship 50% more units than ever before. Given the layoffs the plant has experienced, this new record is especially impressive. Unfortunately, Alex is confused about the plant’s output, because in week 9, he says that volumes have only increased by 20% (p. 211).

When Alex is considering a large potential order from Bucky Burnside in week 11, it has been calculated that the bottlenecks can turn out 100 units of Model 12’s per day, which would give a monthly capacity of 3,000 units (p. 243). At the end of the book, Alex says that their efforts on the bottlenecks have allowed them to “squeeze almost twice as much out of them as before” (p. 334). When they were losing money before the book began, they were producing less than 1,600 units per month, so almost doubling capacity would mean 3,000 units per month.

Additionally, in Ch. 37, which is not long after the three months have ended, Alex discovers that Stacey Potazenek, the inventory control manager, was putting an extra work into the system to avoid unused bottleneck capacity. This unnecessary work represents “roughly
20%” of the bottlenecks’ capacity (p. 308). To use this capacity, he needs to find more than $10m more in sales (p. 309), assumably per year. If $10m is 20% of capacity, the plant’s total capacity has been increased to $50m per year, or 50,000 units per year. Since the plant is already producing at this level, it is producing around 4,167 units per month, and Alex is hoping to find additional sales of roughly 833 units per month.

At that point, Alex is prepared to accept an offer of 10% below cost (p. 311), and he agrees to an offer of $701 per unit. From the Johnny Jons’ comments, it appears that this offer is at or below the standard cost, but there is no way to know exactly how it compares to the standard cost. For the sake of argument, we’ll assume it is exactly at cost. The material cost is $344.07 (p. 312). If the standard cost is $701, the labor and burden must be $356.93. Alex explains to Julie that for his plant, burden is calculated as about three times labor cost (p. 240), so labor is one fourth of the labor and burden total, or $89.23. In 1984, manufacturing wages in the U.S. averaged $9.74 per hour (U.S. Department of Commerce, 1986). This means that a typical product would have 9.2 hours of labor content.

If all 600 workers in the plant were directly involved in production (which is unlikely), there would be 600*40*4.3 = 102,857 production hours available per month. There are 400 workers on the day shift (p. 36), so there are 200 workers total between the second and third shifts. The day shift probably has more than 200 production workers, but if we assumed 200 of the daytime workers were in managerial or administrative positions, this would give 400*40*4.3 = 68,800 production hours available per month.

If an average product has 9.2 hours of labor content, the plant would be able to produce almost 7,500 units per month, assuming 100% availability of 400 production workers. This is almost double the highest estimate of plant capacity. As Alex and his plant realize, workers on
the bottlenecks need to be activated 100% of the time, but non-bottleneck workers need to be activated less. Also, some workers are not directly involved in production. However, this particular analysis does not appear to agree with the other estimates of plant capacity.

The old plant record was 2,000 units in a month. Before the story starts, the plant must have been producing less than that. By some estimates, the plant capacity is 3,000 units per month, by others it is 4,000 units per month. Is it possible that total plant capacity could have been raised by 50%, or 100%? Below, we will look at the capacity increases in the bottleneck processes, to answer that question.

**Capacity Increases on Both Bottlenecks**

The plant undertakes a number of different measures to increase the capacities of their two bottleneck (BN) processes. The following changes apply to both bottlenecks.

- First, they moved quality control inspection (QC) to be in front of the bottlenecks, to make sure the capacity was not wasted on parts that would later turn out to be defective.
- They made an administrative decision to only work on parts that were needed for waiting customer orders, and not waste BN time making parts to be sold “someday.”
- Worker schedules were changed so that the BNs would not sit idle during workers’ lunch breaks; if a break came during a setup, workers would finish the setup before breaking.
- The BN workers were typically working at several different stations, and when a run finished, the BNs would sit idle, sometimes for hours, until personnel came. Dedicated crews were placed at each station, to make sure no time was lost to worker unavailability.
- To make sure that the work was done as quickly and as well as possible, only the best people were put to work on the BNs (p. 191).
• Red tags were placed on each part that would go through a BN, to make sure the BN parts progressed rapidly to the BNs. This ensured a significant queue in front of the BNs, so they would never run out of material to work on. However, before they realized they needed to restrict the flow of material into the plant by having the BNs control the flow, so many red tags flooded the upstream workstations that the other parts, with green tags, sat in some cases for weeks before a gap in red tags allowed them to be produced.

• Yellow tags were placed on parts that had gone through the BN, to make sure the capacity would not be wasted by preventable errors downstream from the BNs.

These changes had similar, but not identical benefits at the two bottlenecks, and additional steps were taken at the two stations. Also, lot sizes on non-BN machines were cut in half not once (p. 233), but twice (p. 244). The plant found that this gave an increase in throughput (p. 244) because sometimes a large batch would take so long to leave a workstation that it would cause a non-bottleneck to wait so long that it would lose enough capacity that it would become a temporary bottleneck (p. 238).

**Capacity of the NCX-10 is a Fraction of Previous Capacity**

The NCX-10 does jobs formerly done by a series of three machines. Production supervisor Bob Donovan tells us that in one “typical instance,” (p. 145) part process times would be 2 minutes on the first machine, 8 minutes on the second machine, and 4 minutes on the third machine, for a total of 14 minutes of processing time. The NCX-10 takes 10 minutes per part, a savings of 4 minutes per part. But the savings would appear to be even greater. The old machines each required an operator to run them continually. The NCX-10 only needs operators who load the machine, and then go do something else, only to come back later. Instead of 3 full
time people being dedicated to the process, the plant was using two people on a very part-time basis, which represents a significant labor savings.

With the old machines, the first machine produced a part every 2 minutes (cycle time = 2 min), so its throughput (TH) is 30 parts per hour (pph). The second machine had CT (cycle time) = 8 minutes, or 7.5 pph. The third machine had CT = 4 min, so TH = 15 pph. The bottleneck of the three is clearly the second machine, which can produce 7.5 pph, so the three machines together could produce only 7.5 pph.

\[
\begin{align*}
\text{CT} &= 2 \text{ min/part} \\
\text{TH} &= 60/2 = 30/\text{hr} \\
\text{CT} &= 8 \text{ min/part} \\
\text{TH} &= 60/8 = 7.5/\text{hr} \\
\text{CT} &= 4 \text{ min/part} \\
\text{TH} &= 60/4 = 15/\text{hr}
\end{align*}
\]

Figure 1: Throughput of Old Machines

The NCX-10 has CT = 10 min, so TH = 6 pph. It would appear that capacity on these operations went down by 20% when the NCX was brought in, from 7.5 to 6.0. This seems believable, because at the time, because no one realized how important capacity on these processes was. Once Alex and company discover that the NCX-10 is the bottleneck, it seems that buying the NCX-10 looks like a bad decision.

\[
\begin{align*}
\text{CT} &= 10 \text{ min/part} \\
\text{TH} &= 60/10 = 6/\text{hr}
\end{align*}
\]

Figure 2: Throughput of NCX-10

But the NCX-10 actually represented a much larger reduction in capacity. Bob said, “We had two of the first type, five of the second type, and three of the third type” (p. 145). This means the two part-time workers for the NCX-10 represent an even greater labor savings,
compared to 10 full time workers. However, this also means that the first station had capacity of
2 * 30 pph = 60 pph. The second station had capacity of 5 * 7.5 pph = 37.5 pph, and the third
station could produce 3 * 15 pph = 45 pph. So the second station is still the bottleneck, but total
output is 37.5 pph. The NCX-10 only does 6 pph! It is only capable of 16% as much production
as the older machines. The plant needs more capacity than it has, and less than it had with all of
the old machines, but it is very hard to believe that any company would have reduced any work
center’s capacity by 84%.

\[ \text{TH} = 15/\text{hr} \times 3 \]
\[ = 45/\text{hr} \]

\[ \text{TH} = 7.5/\text{hr} \times 5 \]
\[ = 37.5/\text{hr} \]

\[ \text{TH} = 30/\text{hr} \times 2 \]
\[ = 60/\text{hr} \]

Figure 3: Throughput of Old Workcenters

Even if we were to assume that the NCX-10 runs “24/7” (24 hours a day, 7 days a week),
and the old machines only ran one shift per week, the NCX-10 can produce a maximum of
7*24*6 = 1,008 parts per week (ppw), (which is consistent with the estimate when considering
the Burnside order) where the old machines produced 37.5 * 40 = 1500 ppw. In this case, the
new machine reduced capacity by 32%.

As Alex discovers, the NCX-10 is not running 24/7. A lot of time is lost to breaks and
other losses. Its uptime is 585 hours per month (p. 153), out of the possible 24 * 30 = 720 hours
in a typical month. But if we assume that the three old machines would have had similar uptime
percentages, the fact would remain unchanged that the NCX-10 has represents a capacity loss of one third. If those old machines ran 24/7 with a similar uptime ratio, the capacity lost would be the huge 84% seen above. The old machines may have a slightly higher defect rate (p. 184), but it’s hard to imagine that even the most obtuse company would reduce capacity of any process as drastically as this plant did.

**Re-Activated Old Machines Have Lost Capacity**

When Jonah asks if they have the machines that the NCX-10 replaced, Bob says “Some of them we do” (p. 153). But then he says that they “got rid of an entire class of machine that we’d need to supplement the NCX-10” (p. 154). The old machines from one of the stations were sold off to make room for more work in process (p. 154, 184), but Bob gets one of them back, an old “Zmegma” (pp. 183-4). He also says that combined with a “Screwmeister” and “that other machine off in the corner, together they can do all the things the NCX-10 can do” (p. 183). So the plant has its original Screwmeisters and Other Machines (as I’ll call them), and one new-to-them Zmegma.

Because these are the same three machines from before, they have capacities, like before, of 30, 7.5, and 15 pph, per machine, for a combined throughput of 7.5 pph. If they run the three old machines one shift per day, we should realize 8 hrs * 7.5 pph = 60 additional units per day. The NCX-10 is working 585 hours per month, or an average of 19.5 hours per day. With a rate of 6 pph, that is 119 per day. The re-activated machines represent an increase of slightly over 50%. Since experienced veteran machinists will be running each machine (p. 190), we would expect them to be operating at least at the standard rate, and since they will be dedicated to the machines, they will not be wandering off doing other things and ignoring these machines.
Yet, Bob estimates running them one shift per day will increase capacity 18% (p. 190). It seems that the machines will not improve capacity nearly as much as would be expected, only improving capacity by one-third of what would be expected. An 18% increase over 119 units would be 21 units, a rate of 2.6 pph, roughly 34% of the past capacity.

There are a few possible ways to explain this. First, some small amount of time will be lost to breaks. Second, maybe the machines are old and just don’t run as well as they used to. The Zmegma appears to be from 1942 (p. 183). But the NCX-10 is only 2 years old (p. 145), so the two machines recently re-introduced into service were being used in this same plant only 2 years ago. It seems reasonable that they would have chosen the most operational machines from those remaining, and any parts that were in poor condition could have been cannibalized from the other machines in the plant.

If the Screwmeister and Other Machine are capable of operating at approximately their old production levels, maybe the Zmegma is the bottleneck machine, and the one they got is just barely operational, capable of only a fraction of the 7.5 pph it should produce. However, since Bob’s “buddy” had “a couple of these sitting around he’d have no problem parting with” (p. 184), it seems reasonable to expect Bob would have looked them over and chosen the better one, and made sure all of the pieces seemed to be there, maybe cannibalizing parts from the other. Since he’s been the production manager in the plant for 9 years (p. 8), and worked in the plant for over 20 years (p. 143), he likely knew the machines well in the past, and it’s unlikely he’d bring back and suggest the plant start using a machine in such terrible condition.

Another way to look at this issue is that an 18% increase in production would be 21 units (117 * 18%). If the BN of them produces 7.5 units per hour, when running, that would represent
2.8 hours worth of production per 8 hour shift, which would represent a 35% uptime, which seems highly unlikely, if, as just explained, we assume reasonably soundly-working machines.

**Capacity Increase at the NCX-10**

Putting QC in front of the NCX-10 increased the plant’s effective capacity. About 5% of the parts coming into the NCX-10 were defective. After the move, 5% fewer parts flow through it. Where they used to produce 100 parts, they now need only produce 95, which meant the plant could produce 5.3% more finished goods.

We do not know how many parts that went through the NCX-10 would later become defective, but placing the gold tape on the parts that had gone through it is assumed to have had some reduction in defects occurring after the NCX-10. If the NCX-10 were in the middle of the process, and if the stages after the NCX-10 had the same defect rate as the steps before it, the savings from the yellow tags could potentially be as high as 5%.

In the first chapter, a setup on the NCX-10 took an hour and a half (p. 2). We are not told that this is a typical setup time; on the other hand, we are not told that this was an exceptionally long setup time, so we will assume that 1.5 hours is a typical setup time. The machine has typically run 585 hours a month, out of 720 hours per month. In the second month, the plant shipped 57 overdue customer orders (p. 195). We know that 90% of the overdue orders were waiting for parts from one of the bottlenecks (p. 171). If we assume they all went through the NCX-10, that would be 51 jobs. At 1.5 hours per setup, that would require 76.5 hours, which would leave 58.5 hours for the month for maintenance, or were hours the machine spent idle.

Adding the dedicated crew must certainly have taken away any idle time lost due to a lack of personnel. Before a dedicated crew was put on the NCX-10, it would still frequently sit idle for 20-40 minutes each time a job finished, because the crew needed to tend to it was
working at another station (p. 189). If approximately 50 jobs per month pass through the machine, these time losses would represent 25 hours of lost bottleneck time. Because the machine is only available 585 hours a month, taking away this idle time represents an effective increase in capacity of just over 4%. If closer to 58.5 hours were regained from the dedicated crew, that would be an increase of 10%.

If 4-10% more capacity was gained by the dedicated crews, 5% was gained from moving QC, and 5% was gained from the yellow tags, multiplying the benefits (1.04 * 1.05 * 1.05), the increase should be 15%-22%. Adding the old machines added 18% more capacity than what they had before. Together, total NCX-10 capacity has increased 33%-40%, which does not appear to be enough to support a doubling of demand.

However, if demand has increased to 4,000 units per month, it seems that after the improvements, capacity should be sufficient to meet the demand. If the NCX-10 was running 585 hours per month, and if it can produce 6 pph, it could produce 3,510 parts per month (ppm). This full capacity was not being realized, because of defective parts being sent through the machine, or its output becoming defective later. If the yellow tags and moving QC drove defects to zero, 3,510 good units could be produced in 585 hours. The percentage of jobs waiting for a part from at least one of the bottlenecks is given as 90% (p. 171) or 80% (p. 208). If the long-term average of products waiting for parts from the NCX-10 is 90%, 3,600 good parts would be enough to support sales of 4,000 units per month. By reducing the defective parts before and after the NCX-10, the plant would almost have enough capacity to satisfy all of its demand.

If 25-60 hours of productive time are gained by the dedicated crews, this would represent an additional 150-360 units per month. The old machines added 18% more capacity, or 632
parts per month (18% of 3,510). Together, these improvements raised total capacity to 4,292-4,502 units per month, more than enough to support monthly production of 4,000 units.

Although not mentioned, the increase in NCX-10 capacity may have been greater. Since the plant appreciates the need to avoid downtime on the machine, people would have reason to perform the setups more quickly, further increasing the machine’s productive capacity. Such improvements were made at heat treat, and similar efforts may have been made at the NCX-10.

**Capacity Increase at Heat-Treat**

Unlike the NCX-10, which requires a constant amount of time for each part, heat-treat (HT) requires a certain amount of time for a batch to stay in the ovens, regardless of the number of pieces in the oven. Because we do not know how large the ovens are or how many parts will fit in at one time, we cannot directly compute the number of units they can produce in a period of time. We can, however, compute the percentage increase in capacity.

About 7% of parts going to HT were defective. Not allowing breaks to interrupt a setup had an impact of unknown size, because they don’t know how much capacity was being lost by people taking breaks mid-setup. The red tags increased the size of the buffers at the BNs, so they would not run out of work. The first week that these improvements were in place, the plant shipped 12 orders. Ralph had estimated that 18-20 would be shipped (p.187), and the reason fewer were shipped was because jobs were being left in the heat-treat ovens much longer than they needed to be, because no personnel were near the machine to take them out (p. 188). If Ralph’s estimate of shipping 18-20 orders instead of 12 is correct, then the subsequent decision to put a full-time crew at heat-treat should have increased capacity of HT by 50-67%. A significant impact could have been expected, because Ted Spencer, the HT supervisor, has three other centers he is responsible for, in addition to HT (p. 186).
After a full-time crew was stationed at HT, the night shift foreman, Mike Haley, had found a way to reduce the setup time. He was having his workers stack up parts so they are ready to be placed onto the tables that will roll into the heat-treat oven as soon as the previous batch comes out and cools down from 1200 degrees. He was also combining multiple parts, to fill up the ovens, instead of only running one part at a time, which is the standard policy (p. 192). These innovations allowed Mike to produce 10% more than the other heat-treat supervisors (p. 191). The conventional wisdom was that “most of the time these furnaces are running half empty” (p. 146) so unfortunately, these improvements did not lead to that great of an improvement, but they did lead to significant throughput increases, and these improvements were disseminated to the other heat treat foremen.

Mike also proposed another way to significantly reduce the changeover time. He suggested building an extra table so that they would not have to wait for the parts to cool down as a part of the setup; the extra table would be stacked up while the other one is in the furnace, and as one came out, the other would be immediately put in. Mike said that it currently “takes anywhere up to an hour or so to change a furnace load using the crane or doing it by hand. We could cut that down to a couple of minutes” (p. 192) if they built extra tables for each oven. Since parts typically need to be heat treated for 6-8 hours (p. 188), he estimates the tables might save “a couple of hours a day,” which means “we can do an extra heat of parts over the course of a week (p. 193). Using these estimates, a typical heat is 8 hours, with a one hour setup, so in a 168-hour week, each oven can do $168/9 = 18.7$ heats per week. If the setup time were reduced to 15 minutes, total CT would be reduced to 8.25 hours; each oven could do 20.4 heats per week, an increase of 9%. 


Adding a full-time crew to HT, they increased throughput by 50-67%. Mike Haley’s job splitting and setup reductions increased capacity by an additional 10% and 9%, respectively. Since these later increases were cumulative, if we assume the full-time crew had an impact of 50%, total capacity has been increased by a factor of $1.5 \times 1.1 \times 1.09 = 1.80$, or 80%. If we assume a 67% increase from the full-time crew, the increase is 99.8%, a doubling of capacity. In the short term, to quickly reduce the size of the queue at HT, some work was sent to an outside vendor (pp. 190-1), but this was not going to be a long-term policy.

Finally, Bob discovered that many of the parts that went through HT only did so because the plant was trying to be more efficient at a non-bottleneck machining center, and was taking larger bites out of the steel in each pass than required by engineering. The larger bites required the steel to be heat treated. Going back to smaller bites meant the parts did not need to be heat treated, and reduced the load on HT by 20% (p. 194). This reduction was on top of the 7% reduction gained from moving QC. Together, these mean that the flow of parts coming into HT has been reduced by 25.6% $(1 - 0.93 \times 0.8)$ from the previous levels. For every 100 parts previously coming through HT, the flow has been reduced to 74.4, and the capacity increased to 180-200. The result is that the plant can now take orders for 140%-170% more units than before. This is well beyond the 100% increase that would be needed to increase production from 2,000 units per month to 4,000. Thanks to these improvements, they should easily have enough capacity going into the future.

**Bottleneck Buffer Stock**

As a part of the plant’s efforts to increase sales, a much shorter lead time was promised to customers. Just before the book began, the plant was promising a four lead time and taking six months to deliver (p. 235). In the end, they are willing to promise a three week lead time (p.
In order to reduce lead times this significantly, the plant needed to significantly reduce the amount of work in process (WIP) in the plant.

When Alex discovered that the NCX-10 was a bottleneck, it had a huge pile of inventory in front of it, which was estimated to hold “weeks” of inventory (p. 144). After all of their improvement efforts including the red and green tags, overall work in process was reduced by 12% (p. 195). However, at the bottlenecks, “the piles of inventory in front of them have grown” (p. 180) and are “even bigger than before.” Alex describes the inventory pile as “not just a mountain, but a mountain with many peaks” (p. 204). The buffers are estimated to be “at least a month or more” (pp. 204-5), and ultimately estimated to be 5 or 6 weeks worth (p. 216).

In the same conversation that the 5-6 week conversation is made, Jonah helps Ralph discover how he could schedule the release of all of the materials so that the bottlenecks are driving the production plans for the plant. Ralph has estimated that it takes parts two weeks to reach the bottleneck queues. He is so confident of this estimate that he believes holding three days’ worth of inventory in front of the BNs will be enough to protect them against any variability in production by upstream processes (p. 217).

Only a couple of days later, Alex tells his staff that he is going to promise a lead time of three weeks to the sales manager Johnny Jons, apparently based on the assumption of parts reaching the bottlenecks in two weeks, waiting in the buffer 3 days, and reaching final assembly and being ready to ship in 4 days. He tells Johnny Jons he can deliver in 4 weeks, and Jons tells the salespeople to quote a lead time of 6 weeks. Unfortunately there is no way that in two days the BNs could have worked their 5 or 6 week queues down to three days in two days. If they stopped releasing any new orders into the plant, (instead of actively getting more orders), it would have taken more than a month to produce the first order with a 3 or 4 week lead time. At
heat treat, some of the backlog was sent to an outside vendor earlier and maybe they did that again here (although it’s not mentioned), but at the NCX-10, there was no such option.

By the end of the three months, the time it takes parts to reach the BN buffers has been reduced to one week from two (p. 324), and they have reduced total work in process by fifty percent (p. 272). Because the largest piles of WIP were in front of the bottlenecks, if the buffers in front of them have been slashed from more than a month to a few days, it is easy to see how orders could flow through the plant in two weeks. However, the estimate of 5-6 weeks’ worth of inventory was made at the start of the second month, and there is no way that this backlog could have been worked through the bottlenecks in the 4 weeks of the last month.

**Plant Finished Goods Consumption**

It’s not clear how much finished goods inventory (FGI) the plant has at the beginning of the story. At the beginning of the book, Alex says the plant has $20m in finished goods inventory (p. 40). However, during Jonah’s second visit, Alex thinks to himself that there are 1,500 units in stock, which would give them $1.5m in inventory (p.209). Of that, they are lucky to sell 10 a month, which would be $10,000 (p. 209), which means that their finished goods inventory is indeed very slow-moving. All of the competitive products ship as soon as they’re done, so the FGI is made up of non-competitive products. It is hard to see how this inventory could quickly be drained down, even with a special effort by marketing.

When the inventory control manager realized that BN capacity had increased to the point that it exceeded market demand, she built inventory with the excess 20% of the BN capacity, which represented over 800 units a month. She built a supply that reflected their customer demands, which the plant should not have any difficulty in selling. At the end of month 3 she revealed that she had been doing this. In month 2, the plant shipped the last of its backordered
items and started producing new incoming orders as they came. This means that her fictitious orders could have been part of the production plan for at most a month, and at most could have represented $0.8m worth of easily sold inventory.

It is hard to imagine how any significant reductions could have been made in their inventories of obsolete or uncompetitive products. However, the plant was able to significantly reduce its levels of finished goods inventories. At the end of the third month, Alex says “inventories are about 40% of what they were three months ago,” (p. 247), which would mean total WIP plus FGI has been reduced by 60%. However, a few days later, the controller says that 50% of the WIP has been removed from the plant and 25% of FGI (p. 272). Clearly, both estimates cannot be correct.

A 60% reduction of $20m in finished goods would mean $12m in shipments out of inventory. In the first month, sales were below $2m, in month they were $3m, and in month three they appear to have been $4m, for total sales of $9m. Clearly $12m in shipments from inventory cannot have happened. If we assume the other extremes, a 25% reduction from $1.5m in finished goods would be $375,000, which seems much more likely. However, in light of the $0.8m inventory build caused by Stacey, for a net 25% reduction, they would have to have shipped $1.175m out of finished goods inventory, which does not seem possible, given that it appears that each month capacity was sufficient to meet demand.

The conclusion we can draw is that because the plant increased production capacity significantly, there does not seem to be any way that it could have possibly reduced finished goods inventory as much as is claimed.
Summary and Conclusions

“The Goal” has been a huge success, and began a series of successful management books for Eliyahu Goldratt. At a time when many people did not think that operations were “important,” The Goal helped operations personnel help other people understand the difficulties of the task they face. It is easy to read, which makes it easy for non-production people to understand the difficulties of production. It also is a very easy way to help them appreciate some of the possible solutions. For these reasons, all production personnel should be thankful for this book and what it has done.

By looking at the production details presented in the book, we have discovered that many detailed calculations can be done using the data presented in the book. The book provides a good deal of detail that can be used to construct a very full picture of the plant’s bottleneck operations. As we have seen, the picture that we can construct from these details is in many ways quite consistent. Unfortunately, in a number of ways, the facts of the book do not go together to form a consistent picture.

A major theme of the book is the importance of mastering important details, so it seems only appropriate that we as readers ask for the authors to have done the same. It is unfortunate that the most-widely read, best-known operations management book of all time has technical details that just do not stand up to close scrutiny. Significant changes in the book have been made between past editions of the book. Hopefully, in future editions, the shortcomings addressed in the paper can be addressed.
References


