Process and Productivity Improvements through Bottleneck Reduction and Design of Experiments

by

Lawrence R. Oliver

B.S. in Mechanical Engineering
United States Military Academy at West Point, NY (1986)

Submitted to the Departments of Mechanical Engineering and the Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Mechanical Engineering

and

Master of Science in Management

in conjunction with the

Leaders for Manufacturing Program
at the Massachusetts Institute of Technology

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Signature of Author

Sloan School of Management
Department of Mechanical Engineering
May 6, 1994

Certified by

David Hardt
Professor of Mechanical Engineering

Certified by

Stephen C. Graves
Professor of Management Sciences

Accepted by

Ain Sonin
Chairman, Department Committee
Department of Mechanical Engineering

Accepted by

Jeffrey A. Barks, Associate Dean
Sloan Master's and Bachelor's Programs
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Abstract

Productivity improvements are critical to the long-term manufacturing success of a company. Much attention has recently focused on improving U.S. manufacturing productivity by using the lean production techniques demonstrated in Japan. A competing technique using the theory of constraints to optimize production has also gained some acceptance in U.S. industry. The objects of both techniques is to maximize production by the application of simple decision rules designed to minimize waste and focus resources where they can have the biggest impact. Additionally, design of experiments has been gaining wider currency as a means of improving the quality of manufacturing while simultaneously achieving the productivity improvements.

This goal of this thesis was to evaluate the production operations of a large corporation engaged in the manufacture of a consumer durable product to search for ways to improve their productivity through the use of lean production, theory of constraints, and designed experimentation. One section of one plant was studied and implementation strategies designed and tested to study the application of these techniques in concert.

This thesis examines the practical effects of implementing lean production and the theory of constraints as well as the use of designed experimentation in a production environment. It seeks to simplify an outline for deciding what changes to pursue and give practical experience in the problems of change implementation. It also discusses the use of design of experiments which was used primarily to identify process control variables and secondarily to optimize the process itself. This is of particular interest since it quickly identified the most important areas of the process to focus the plant’s efforts to simultaneously improve both quality and productivity.

Thesis Advisors:

David Hardt, Professor of Mechanical Engineering
Stephen C. Graves, Professor of Management Sciences
Acknowledgment

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Chapter 1 -- Introduction

1.1 Corporate Background

United Technologies Carrier is adopting the principles generally called the Toyota Production System (TPS) or lean production, for improving the manufacturing productivity of its operations. George David, the new CEO of parent United Technologies Corporation (UTC) names productivity as one of three primary focus areas for UTC and lean production as the second priority behind technology development for the future of UTC. This thesis represents the efforts of a cross-functional team to improve the productivity of the heat exchanger coil production department in Carrier's air conditioning plant in Tyler, Texas by applying the principles of lean production.

1.2 Corporate Structure

United Technologies Corporation had revenues of almost $23 billion in 1993 split between two major sectors, Aerospace/Defense and Commercial applications. Two critical aspects of UTC's growth strategy are an increasing reliance on the commercial business units, of which Carrier is a part, and an increasing reliance on overseas markets.

![United Technologies Corporate Structure](image)

**Figure 1.1 United Technologies Corporate Structure**
Carrier is the world's largest producer of HVAC equipment; however, the next seven largest competitors are all Japanese companies. In order to realize the necessary growth, Carrier must meet tough, global competition and improve productivity and quality.

Carrier was purchased by UTC in 1979 as part of a diversification strategy to reduce reliance on military spending for revenue. Carrier is divided into six major divisions shown below. North American Operations (NAO) is the largest with almost 50% of sales. Europe (ETO), Latin America (LAO), and Asia Pacific (APO) are the other major divisions. Transicold makes refrigeration units for shipping containers and Carlyle Compressor makes compressors, as the name implies. Within NAO there are three major segments. Tyler is part of Commercial Unitary (CMU) which makes light duty commercial rooftop and residential air conditioners which contain the complete air conditioning system in one unified package. The Residential unit makes split systems for home use, and Commercial Applied (CAES) makes the chillers which would be a part of larger buildings.

![Carrier Corporate Structure](image)

**Figure 1.2 Carrier Corporate Structure**

1.3 Plant Background
Carrier has experienced below average returns relative to its sales volume for several years. The facility I interned at was part of the Commercial Unitary group and was experiencing the same problems with its product lines as the company as a whole. The plant volume was roughly 175,000 units annually. The plant first opened in 1946 as the Bryant Heater Company. Carrier acquired the facility in 1955 with the purchase of Affiliated Gas Equipment Co. In 1969, the plant was expanded to 505,000 sq. ft. (its current size) and the workforce began its affiliation with the International Sheet Metal Workers Union. In 1979, UTC purchased Carrier in a hostile takeover. Several generations of different products have been produced at the plant since its inception, from gas-fired heaters to food freezers to room air conditioners. The current product mix includes central air conditioning units with gas fired heat or heat pumps. In 1992 Carrier consolidated its NAO manufacturing operations from 12 sites to 7. Tyler absorbed the product from the City of Industry plant in California.

1.4 Plant Organization

The Tyler plant is operationally divided into two units. The two units are the SPP - Small Package Products and SRT - Small Rooftop Products and each consists of two assembly lines. A business unit manager, directly responsible to the plant manager, controls each unit and is responsible for all aspects of their operation. Air conditioners are produced at the plant in two phases. In the first phase, two coils and sheet metal parts are fabricated. These are then joined with purchased parts at the assembly lines where they are assembled into finished units. The sheet metal stamping departments are essentially co-located with the assembly lines and are part of the organization of the two business unit managers. The coil department is semi-autonomous since it supplies completed coils to all assembly lines and is not integrated into the organizational structure of any assembly line. It is, however, controlled by the SRT business unit manager.
1.5 Coil Production Problems

The coil department was a significant source of problems for the entire plant. The department was the single largest source of assembly line downtime for the plant, accounting for 31.5% of all downtime. One month, lack of coil availability accounted for 66% of all assembly line downtime. In addition to lack of coil availability, coil defects, chiefly coil leaks, accounted for the largest source of assembly line defects within the plant. The direct costs of the problem in both productivity and quality was running at an annual cost of approximately $1 million.

The productivity and quality problems of the coil shop are an obvious starting point for focusing attention. The question now becomes what within the coil shop can yield the greatest returns towards improving productivity and quality. Carrier is adopting lean production methods with its emphasis on standard work and kanbans for material flow. An alternate method has been proposed by Professor Eli Goldratt in several books including The Goal and The Haystack Syndrome. This method focuses attention on finding and then improving only production restricting operations. Using a hybrid of the two worked most effectively in the coil shop. The methodology of Prof. Goldratt was
most helpful to analyze the operation of the coil shop in order to find the bottleneck. Then, the techniques of lean production were used to analyze where improvements could be made to reduce the bottleneck.

From a quality perspective, the team attempted to first gain a thorough understanding of the basic processes involved in making a coil. Then target process parameters were compared with actual levels with the coil shop engineers to determine whether the process was within tolerance. Next, a design of experiments was proposed to find the optimal values for key process variables. Subsequently, a confirming experiment was run in order to ensure that the initial results could be duplicated. The emphasis in this phase was in ensuring that repeatable quality output could be attained by reducing the variation of the input factors to the brazing operation.

The emphasis throughout the research program was to focus on both identifying opportunities for improvement and then actually implementing change. The underlying reason for this emphasis on active change was the recognition that the pursuit of change requires both a champion and persistence. Change is always accompanied by unforeseen problems and resistance, and unless changes could be implemented during the research, it is unlikely proposed changes would ever be implemented. Beyond this was the goal to leave the organization more capable of recognizing and implementing change by itself.

1.6 Thesis Structure

The thesis consists of seven chapters. Chapter 2 is an orientation to both the air conditioner and the processes used in making the heat exchanger coils. It then provides a detailed analysis of the existing production problems within the coil shop. Chapter 3 discusses the steps proposed to reduce the bottleneck other than those related to quality. Chapter 4 is a detailed discussion of the physical heat transfer mechanism and of those factors which have a significant impact on the braze joint quality. Chapter 5 follows with the designed experiment performed to improve the brazing process and the results of the original and follow-up experiments. Chapter 6 is a reflection on the change process and the
opportunities and pitfalls associated with change implementation. Finally, Chapter 7 discusses the use of both the theory of constraints and lean production and the practical uses of designed experimentation.
Chapter 2 -- Air Conditioning and Coil Production

2.1 Chapter Overview

This chapter describes the basic steps involved in the air conditioning process. It also provides a description of the A/C components and includes a detailed breakdown of the components of the heat exchanger coils themselves. The manufacturing processes to make a coil are varied and range from press operations to brazing. The processes used to make the coils will first be described and then process flow within the coil department. Once the reader is familiar with the coil shop itself, the methodology used to determine which resource is the bottleneck within the department will be explored and then how solutions to the bottleneck were determined.

2.2 The Air Conditioning Process

![Diagram of the Air Conditioning Process]

**Figure 2.1 The Air Conditioning Process**

Air conditioning is basically a heat transfer process driven by movement of air and a temperature differential between two different points. An air conditioner consists primarily of two heat exchangers. The first transfers energy from the air inside the room to the
refrigerant and is called the evaporator coil. The second transfers energy from the refrigerant to the air outside and is called the condenser coil. The refrigerant is pumped by a compressor through the condenser coil to the evaporator coil. The refrigerant system is a closed system so that no refrigerant leaks occur to the atmosphere.

2.3 Coil Components

There are five major components to the heat exchanger coils used in the air conditioner. The two components that make up the bulk of the coil are the copper tubing (hairpins) which route the refrigerant through the coil and the aluminum fins that provide the heat transfer mechanism to/from the environment. In addition to these, there are two tube sheets that provide structure to the coil. They can be thought of as two slices of bread that sandwich the aluminum fins and protect them. The tube sheets are made of steel for strength. At the top of the coil are both return bends and headers. A return bend directly links two copper tube outlets and provides the flow path for the refrigerant from one circuit to another. The headers are refrigerant distribution manifolds that link the coil in
several places to either the compressor or to the other coil. There will generally be two headers per coil making from 6 to 25 joints with the coil while the number of return bend joints will vary from about 20 to 120.

2.4 Coil Production Processes

The production of coils consists of five primary operations and their flow is depicted below. The coil shop is divided into two separate departments, one for the fabrication of evaporator coils and one for the fabrication of condenser coils. Some of the process equipment is shared by the two departments.

![Diagram of Coil Production Process Flow](image)

**Figure 2.3** Coil Production Process Flow

The key processes are listed below with a brief description of the processing steps:

**Tube sheet press** - Purchased steel coils are processed through a press which produces the tube sheets by punching and extruding holes for the hairpins. The die also cuts the steel to the correct length.

**Hairpin bender** - Copper tubing is bent to $180^\circ$ and sized to the correct length for the coil.
Hairpin Bending Machine

Fin press - Aluminum sheet is processed through a press that cuts fins to be used in the coil. The aluminum is cut both laterally and to the proper length and holes are punched and extruded for the hairpins to pass through.

Expander Machine

Figure 2.4 Hairpin Bending Machine

Figure 2.5 Expander Machine
**Expander** - Aluminum fins are sandwiched between two steel tube sheets and hairpins are manually laced through the holes. They are then placed in the expander which plunges a rod or "bullet" through the copper tubing, expanding it to make positive contact with both the tube sheet and aluminum fins. This process also treats the exposed ends of the copper tubing for the return bends and headers to be seated.

**Brazer** - Copper return bends that complete hairpin circuits and headers that join circuits to each other for the even distribution of refrigerant are placed in the open ends of the coils. Each joint has a ring of brazing alloy which becomes the filler metal when the coils are sent down an automated brazing line. Heat is applied to all of the joints and the return bends and headers are brazed to the coil.
After the brazing process is complete, the coils are 100% tested and then placed into a storage area for transport to the assembly lines.

The layout of the evaporator shop is depicted above and the condenser shop is depicted below.

Figure 2.6 Condenser Shop Layout

The product flow within the department corresponds to the flows shown in figure 2.5 and 2.6 above. The tube sheets and some hairpins flow from one shop to another, however no other parts do. The production is done in batch quantities based upon a schedule, which is modified daily based upon the progress of the four main assembly lines within the plant.
The plant produced 14 different capacity air-conditioning units, although because of different efficiency ratings, the number of different coils was approximately 90. Because of the batch scheduling used on the assembly lines, the actual variety produced on any given day would vary from 8 to about 24. This variety directly drove the complexity within the coil shop. As would be expected, the brazers experienced the greatest number of changeovers since each set of brazers was supplying four assembly lines. The setup time at the brazer would average about 6 - 8 minutes and each shift would have to produce for an assembly line twice per shift. That meant that since two brazers would have to divide the 8 to 24 changeovers, over two shifts they would generally make between 8 and 24 changeovers each. Obviously, the number of changeovers would be influenced by the size of the batch and would vary from day to day. The expanders would have significantly fewer changeovers to complete. Since the plant had six expanders, each with two doors, there were 12 possible work stations. Each changeover at the expanders would take approximately 35-45 minutes and the doors averaged about one change per shift. This necessitated a fairly good size buffer stock to prevent frequent changeovers. Also, in recognition of the long changeover times, the plant used dedicated set-up men to perform the set-ups. The four hairpin bending machines supplied all 12 expander doors. Because of the design of the coils, many coils took a uniform length hairpin so the number of changeovers from the expanders to the hairpin benders was often reduced. Additionally, the setup time for the hairpin benders was generally 10 - 15 minutes and often less on the more advanced equipment.

The real effect of the changeover frequency and times was that a conscious effort was made to reduce the number of changeovers at the expanders, but nowhere else. The way this was managed was to have a relatively large buffer stock (on the order of 8 - 12 hours) of inventory between the expanders and the brazers. This allowed the expander operators to batch a complete shift’s and often a complete day’s worth of common coils into one production run, minimizing changeovers. The changeovers on the brazing lines
were a minor problem, but one which was essentially eliminated during the internship. I will specifically discuss the brazing line changeovers in a later chapter.

The daily scheduling process begins with a count of all finished coils and a count of all coil cores in inventory before the brazers. This physical count is then referenced against the assembly line schedule which is generated weekly by the MRP system a week prior to the schedule start date. The daily schedule usually takes between 6-8 man-hours to complete and is generally distributed about two hours after the first shift of the day has started. While the daily scheduling in the coil shop is tedious and perhaps redundant, the basic process is correct and does not cause significant problems.

2.4 Line Analysis

Based upon the large amount of downtime experienced by the assembly lines due to the shortage of coils, it was obvious that the coil shop must be a bottleneck relative to the assembly lines. This leads to the conclusion that relieving the bottleneck within the coil shop would have positive effects upon the plant production as a whole. Goldratt's emphasis on productivity improvement can be summed up in his five steps:

1. Identify the system's constraints
2. Decide how to exploit the system's constraints
3. Subordinate everything else to the above decision
4. Elevate the system's constraints
5. If, in the previous steps, a constraint has been broken, go back to step one[6]

The first step can be pursued in many different manners. The easiest would be to look at a section of the plant and the bottleneck operation should be the operation with inventory waiting to be processed, but no inventory in process after it. By simply looking at it this way, the bottleneck should be easily identifiable (if the correct quantities and styles of parts are being produced) with a visual inspection. There may be situations where this method
will not work well, but it did give the correct conclusion for the situation in the coil shop. However, a more rigorous approach was applied by the team in this situation.

Using the concept of TAKT time, which is the rate at which products are demanded by the customer in a lean production operation, it is quite easy to calculate what the required production through each process within the coil shop would have to be to satisfy the line requirements in an eight hour day. Using the assembly line production requirements to determine the coil shop TAKT time yields the simple equation:

$$\text{TAKT time} = \frac{\text{Available Time}}{\text{Customer Demand}}$$

The required coil production per shift was 400 units and available time was 460 minutes. This yields a TAKT time of 69 seconds. This TAKT time can then be measured against the cycle (actual) time of each operation to determine where the bottleneck operation is and if there are multiple operations preventing the plant from meeting customer demand.

There are several possible methods for determining the cycle time of the operations in the coil shop. I chose to vary the method based upon the operation in order to achieve a reasonable estimate with a minimum of work. I should caution that finding the cycle time is not important in and of itself. It is only important relative to finding the problem area in which to focus further attention to reduce the bottleneck. For the brazers, I decided that taking the average production over several days would be the most accurate method of finding the cycle time. For the hairpin benders, expanders, and tube sheet presses, we timed the actual operations and then added allowances for changeovers based upon the production standards which had been published for the operations. The rationale for taking the daily production for only the brazing lines was that the brazing operation is weakly affected by the size and mix of the coils relative to the upstream operations. For example, the brazing time is equal regardless of the height of the coil and varies only slightly with the width (one to four rows). Additionally, the test cycle time is independent of the coil type and is constant for each line. Every other operational cycle time depends to a great extent on the size of the coil and to some extent on the amount of set-up they require.
By conducting this analysis, the bottleneck operation was found to be the brazing operation. Figure 2.7 shows the coil shop cycle time vs. TAKT time.

Figure 2.7 Coil Shop Cycle Time vs. TAKT Time

It can be easily seen that the brazing line is much further out of balance compared to the TAKT time than any other process step. Additionally, the expander operation is above the TAKT time, but this is not of great significance for immediate improvement because it is not a limiting step in production. If fact, by just looking at the inventory levels within the shop, it would be evident that the brazers were the bottleneck. There was generally a large amount of inventory waiting in front of the brazers and generally little or no inventory after the brazing operation.

2.5 Bottleneck Reduction

The way we looked at the problem was to analyze the brazing line as another operation with three discrete steps and find which operation within the brazing line itself was the bottleneck of the brazing line. Figure 2.8 shows what the operational cycle time of value-
added work completed at each station. Each circle represents an operator and the time above the station represents the amount of time to complete their work on a given coil. The wide

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<th>80 - 175 sec</th>
<th>0 - 190 sec</th>
<th>80 - 90 sec</th>
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<td>Braze</td>
<td>Test</td>
<td></td>
</tr>
<tr>
<td>Prep</td>
<td>Touch-up</td>
<td>Test</td>
</tr>
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Figure 2.8 Brazing Line Layout

time bands represent the work differences possible from a small two row coil to a large four row coil. From the figure, it would appear that the bottleneck should be the preparation station since the average of the high and low cycle times is the highest, but when we observed the operation of the brazing line, the test station was actually the bottleneck most of the time.

Once the bottleneck was identified, the general technique for bottleneck reduction is to analyze everything that the bottleneck resource is doing and look for solution strategies. These strategies can usually be prioritized by their contribution to operating expense and throughput and their ease of implementation as:

1. **Eliminate non-value added work**
2. **Shift work to a non-constraint**
3. **Add resources (either people or machines)** [3]

In analyzing the bottleneck (test station) we took four shift's worth of data and documented all non-value added work being done by the test station. For this analysis we categorized the whole test cycle as value added work. This classification may be debated although one component of the test was a required burst test certification while the second part was a leak
check. For the purposes of finding what could be improved at the test station, our classification of the entire test cycle as value-added is sufficient. We then broke the data down into groups, and the three largest non-value added categories were rework and retesting, poor work methods, and changeovers. The changeover time was time that the test station was not being used due to a lack of coils from the upstream operations. This table documents only the largest assignable blocks of time. The spreads represent differences between brazing lines and they do not add to 100% since smaller blocks

<table>
<thead>
<tr>
<th>Percent of Non-Value Added Time</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>26-41%</td>
<td>Repair at test station</td>
</tr>
<tr>
<td>17-19%</td>
<td>Poor work methods</td>
</tr>
<tr>
<td>8-17%</td>
<td>Changeover</td>
</tr>
</tbody>
</table>

Table 2.1 Non-Value-Added Time at the Bottleneck

such as leaving the work station to discuss the next batch of coils, waits related to the movement of material and not changeovers, and simple mechanical problems with the test fixtures or machinery are not included.

Based upon the results of the analysis, the biggest opportunity was directly related to the poor quality of the initial brazing, even with a dedicated operator to perform touch-up. The second biggest problem was poor work methods which could then be broken down and attacked individually. Finally, the changeover problem would have to be addressed at the preparation station which is where the changeovers occurred.
Chapter 3 -- Bottleneck Reduction

3.1 Chapter Overview

This chapter examines the steps taken to improve the productivity of the coil shop by reducing the bottleneck. It explains the overall thrust of the improvement effort and then explain specific actions within the context of the bottleneck reduction and the generic reduction methods. Finally, it gives the results of the productivity improvements and contrasts the final state with that at the beginning of the internship.

3.2 Bottleneck Reduction Strategy

The generic bottleneck reduction strategies which were listed in Chapter 2 are:

1. *Eliminate non-value added work*
2. *Shift work to the non-constraint*
3. *Add resources (people or machines)*[3]

3.2.1 Historical Perspective

The management of the bottleneck at the start of the internship consisted almost entirely of adding resources by working overtime. For the first five months of the year, each shift averaged over 55 hours per week within the coil shop. That is over 35% extra production time each week when compared to the normal 40 hour week. However, this was still not enough time to produce the required output. For the first five months, the assembly lines were shut down for 4.5% of all available time due to coil non-availability. Additionally, the coil availability problem had grown worse over time because other departments were decreasing their downtime statistics which meant that there were fewer places for the coil shop to hide. (The way downtime was tracked, if the materials group ran out of compressors one unit before the coil shop ran out of coils, the entire downtime would be charged to the materials group. During the downtime, of course, the coil shop would build additional coils and could have a sufficient inventory before the assembly line started back up.) The productivity problem within the coil shop definitely needed to be
solved, and quickly for the plant to operate efficiently. In addition to the productivity bottleneck, quality problems relating to leaks on the coils were the greatest single quality defect on the assembly lines.

3.2.2 Alternative Solutions

Eliminating the bottleneck at the test station could be accomplished in two ways. The first would be to add additional repairmen upstream who would supposedly do a better job of screening the coils and finding leaks. Obviously, this should improve output, but it would not reduce the amount of non-value added work. The alternative would be to improve the brazing process to reduce the rework or eliminate the repairman. This would indeed eliminate non-value added work. A quick reminder of the layout of the line and the value-adding cycle times shows that if the repairman can be eliminated through process improvement, the bottleneck should become the preparation station. In fact, if the non-value added work can all be eliminated, the preparation station would need to shift work

![Brazing Line Schematic](image)

Figure 3.1 Brazing Line Schematic

or add resources to maintain production. The general solution methodology taken was to improve the quality of the brazing operation so that the touch-up man could be eliminated from the line. This operator could then be used at the preparation station to reduce the cycle time at that operation. In addition to reducing the cycle time of the preparation station, the
second prep station operator would also be able to work on making the changeovers more efficient since with two operators, the extra resources would be available to reduce the time to complete the changeovers.

3.3 Step 1 Eliminate Non-Value-Added Work

Given this general solution strategy, the challenge now was to implement the solution and maintain production. Given the immediacy of the problem, and having to do something before any real analysis of the problem was conducted, the first step taken was to add resources (people) to the brazing lines. Because of the lack of productivity of the brazing lines, and the immediate need to produce coils, adding another person to the brazing line was the quickest way to get results. The additional operator was initially added to the preparation station due to space limitations at the other stations. As could be expected, the addition of another person to the line only recovered some of the 8-17% that was being lost to changeovers. The time lost due to repair was still lost since the added person was unable to affect that portion of the non-value added time loss.

The eventual elimination of the touch-up operator was done concurrently with the designed experiment (DOE), but relied on some of the results of the DOE to improve the process enough to ensure that both the line operators and the supervisors in the department supported the change. The organizational change aspects of the move will be discussed in Chapter Six. While the change did not go smoothly at first, eventually, the change was made and the touch-up man was eliminated from all of the brazing lines.

A brief description of the test station operator’s work which cannot be changed is given below. The time to connect and disconnect the coil from the tester cannot be used for any other purpose. The time the test is running can be used to perform a wide range of additional work.
Table 3.1 Test Station Work

The internal work for this same test cycle before and after removal of the touch-up operator are given below. The extra work content could not consistently be performed in the internal test cycle time of the test machine if leaks had to be repaired. In practice, only a cursory inspection of the coil for leaks could be performed, focused on those joints that commonly displayed leaks. This inspection methodology was not precise and was highly dependent on the previous experience with leaks and the operator’s knowledge.

Table 3.2 Test Station Internal Work

Unfortunately, a majority of the coils straight out of the brazing furnace had at least one leak and required some immediate repair in order to pass the test machine. While some
small number of leaks would be acceptable, the goal was to eliminate all leaks, thus eliminating the non-value-added work which was contributing to the bottleneck.

It should be noted now that the theoretical capacity of the brazing lines staffed with three operators is well above the customer demand. Given a demand of one coil every 70 seconds and two brazing lines to supply those needs, the required TAKT time of each brazing line was 140 seconds. Given the average value added cycle time of the bottleneck station at approximately 85 seconds, this is well below the 140 second TAKT time of each line. The difference between the capacity and the TAKT time leaves about 35% excess capacity at the bottleneck, given no non-productive time. Even estimating that the machine can be used at 85% capacity leaves ample excess capacity. In fact, given the state of the operation at the start of the internship (line cycle times of 200 seconds), the machines were only running at 42.5% of capacity.

3.4 Step 2 Shift Work From Bottleneck

3.4.1 Eliminate Re-work

As mentioned several times previously, eliminating the non-value added repair work was the most important step in improving productivity and was directly related to quality. The second step was to shift work from the bottleneck resource either upstream or downstream. Because the brazing furnace was immediately before the test station, there was limited opportunity to shift work upstream. There were several opportunities for shifting work downstream though. The overriding principle for evaluating work at the test station was to try to ensure that as little time as possible was spent on work between the time a coil completes testing and the time the next coil can begin being tested. In other words, the goal is to keep the test machine working as much as possible. The first, and easiest change involved changing the test station layout. After a coil completed testing, plastic plugs were inserted in all orifices to prevent contamination during storage and transport. These were inserted by the test station operator. Because of the layout of the
station, these were often inserted while the coil was actually in the test booth instead of
outside of the booth during the test cycle of the next coil. This was a relatively minor task,
but usually took between five and ten seconds to complete. We moved the supply rack for
the plugs downstream of the test booth so that it was no longer possible to insert them
while the completed coil was in the test booth.

3.4.2 Handling

The second opportunity for shifting work was with the handling of the coils
themselves. The coils are stored in racks which hold approximately 20 coils at a time.
After a rack is full, the coils are tied off to prevent them from falling during movement to
the assembly lines. The test station operator almost always performed this work, which
could take from 1-2 minutes per rack. Given the typical brazing line would produce 200
coils/shift, this amounted to 10-20 minutes per shift each day for each line. A material
handler for the coil shop was responsible for the movement of the storage racks as well as
supplying most of the parts for the brazing line and maintaining the schedule. He could
have performed this work, at least on a primary basis which would have effectively shifted
the work off of the bottleneck resource. If the material handler were involved in some
other activity such as staging copper tubing or tube sheets, then the test station operator
could certainly perform the work. In addition to the work to complete the rack, there was
some preparation work to perform on the empty storage racks before they could be used to
store coils. A side rail had to be removed from the rack in order to safely insert the
completed coils. This was a lesser amount of work, but still measurable. This too could
have been transferred to the material handler on a primary basis.

We did not have much success in shifting this work from the test station operator to
the material handler. Because of the built-up prejudices of the operators as to what their
station's work entailed and the idea that it would be unfair to add additional work from one
operator to the other without a corresponding decrease somewhere else, this idea was
difficult to sell. Also, the shift supervisors didn't see the benefit of shifting the work
relative to the problems that implementing the change would have caused from the employee's perspective. Another factor which will be discussed more fully in Chapter 6 is the prejudices built by the former incentive system, most of which was still in place.

The last section of work which could be transferred was the actual movement of the coils from the brazing line to the storage rack itself. This was performed by the test station operator and obviously should be done while the next coil is undergoing the test cycle. Eliminating this work from the test station operator would allow him more time to check and repair the oncoming coils, hopefully finding and repairing more leaks before the coil starts the test cycle. It was not feasible to attempt to get the material handler to go this far up in the process where he would have work to perform every cycle. However, this concept was tested in the condenser shop. The preparation cycles are generally shorter in the condenser lines since the coils are only one and two rows wide. One person was designated as the take-off person for both condenser lines instead of assisting with preparation in touch-up as was usual. This operator was responsible for inserting the plastic plugs to prevent contamination, moving the coils to the storage rack, and for preparing the racks for movement to the assembly lines (mostly tying the coils down). This freed up more time for the test station operator to screen coils and repair leaks during the internal test cycle, making the entire test station more productive. This concept worked well for the condenser shop, however it would have necessitated the addition of another person in the evaporator shop due to the layout and longer preparation times. In the condenser shop, the trial showed an improvement of almost 10% greater output with the same number of workers. The lesson to be learned from this is that there are often many opportunities to shift work if you are creative and willing to look at unconventional strategies.

3.5 Step 3 Add Resources if Necessary

3.5.1 The Preparation Station
The third major contributor to non-productive time was problems related to changeovers. This problem was mostly addressed by using the third generic strategy of adding resources. Knowing that the prep station operator would never be able to meet the customer demands if the test station were to improve its operation, we moved the touch-up operator to the prep station. This had several benefits simultaneously. First, since the cycle time for the prep station was effectively reduced by about 50%, the problem of starving the bottleneck (test station) was eliminated. Second, there was far less time pressure on the prep station operators now, so more time could be taken in doing a quality job. As will be shown in Chapter 5, the care taken in properly seating the headers to the coil can be a critical determinant of the output quality of the brazing furnace. Since the operator now had "extra" time to spend on each coil, extra care could be taken when seating the headers and return bends. This helped the test operator because he now had fewer leaks to repair, thereby increasing the productivity of the entire line. Finally, the changeovers could go much more quickly since with two operators, there was extra time to pre-stage materials for the next runs while the current run was being worked on.

The work distribution for the two preparation station operators was split like this:

<table>
<thead>
<tr>
<th>First Operator</th>
<th>Second Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage cores for preparation</td>
<td>Seat return bends</td>
</tr>
<tr>
<td>Install all return bends</td>
<td>Install and seat headers</td>
</tr>
<tr>
<td>Move coil to brazing line conveyor</td>
<td>Install heat shields / Nitrogen purge</td>
</tr>
<tr>
<td></td>
<td>Release coil to furnace</td>
</tr>
<tr>
<td></td>
<td>Replenish header inventory as needed</td>
</tr>
</tbody>
</table>

Table 3.3 Preparation Station Work by Operator
Since the two operators could effectively outpace the test station under normal circumstances, they could effect a changeover from one coil to the next before the in-process inventory for the test station was depleted. Additionally, the first operator had the time to perform a quality check on the hairpins by checking the flaring of the tubing. If the tubing were under-flared, he had the time to manually adjust the flaring with a hand belling tool. Previously this quality check was generally not conducted. Underflared tubing allows the brazing alloy to run down the outside of the tubing rather than sealing the gap between the return bend and the tubing. Underflaring was especially a problem if the copper tubing was peglegged at the hairpin bender.

Several other improvements were implemented at the preparation station in addition to those mentioned above. Templates were already being used for the placement of return bends to ensure accuracy. There were about 40 different possible patterns which could be made for each brazer. The templates were stored on racks, but they weren’t color coded and were poorly labeled. When a changeover would take place, the operator would sometimes have to search through many of the templates to find the model corresponding to the coil he needed. The confusion was exacerbated because there was one set of templates for each shop so two crews on two shifts used each set of templates. The templates were color-coded by model type (6 types) and marked with the specific model number on the outside for ease of identification. This, of course, was a simple, yet effective way to reduce non-productive time during the changeovers.

Another improvement made was in the use of heat shields for the headers. Heat shields were used to prevent the overheating of joints on the headers which had already been brazed to prevent the reflow of the braze alloy. This was of special concern on the heat pump models because these headers were heavier, causing more joint stress. The preparation station was initially putting on several shields designed to protect the joints. A common shield was designed to replace the 3-5 separate shields. This common shield was easier and quicker to put on, was less likely to fall off during movement and therefore
offered better protection. And, most importantly, it took less time for the test station operator to take off the one common shield than the 3-5 separate shields. This streamlining of work offered several quality benefits while reducing the workload of the bottleneck resource.

3.6 Summary

The drive to improve the productivity of the bottleneck resource displays what can be done to improve productivity in general. All three generic strategies were employed to increase the output of the brazing lines. It should be reiterated that the major change was due to the improved quality of the brazing operation itself. This allowed a re-deployment of personnel away from non-value added work towards productive work. Some of the other steps taken to improve the productivity would seem to be self-evident, but in reality because the old ways had become such an accepted part of everyday operations, improvements weren’t always readily apparent. But strangely enough, most of the ideas were proposed by workers on the brazing lines themselves.

The final output of the brazing line was far better than the situation at the beginning

![Graph](image-url)  
**Figure 3.2** Final Cycle Times for Coil Department
of the internship. As can be seen above, the cycle time of the brazing line pair was reduced to 76 seconds from 100 seconds. While this is still above the TAKT time, the magnitude of the problem is greatly reduced and is much more manageable than before. Additionally, continuing improvement efforts focused on reducing the non-value-added work should help to further reduce the cycle time in the future. A synopsis of the efforts to reduce the bottleneck is outlined below.

<table>
<thead>
<tr>
<th>Eliminate Non-Value Added Work</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eliminate Touch-up Operator</td>
</tr>
<tr>
<td></td>
<td>Code and Organize Templates</td>
</tr>
<tr>
<td></td>
<td>Improve Heat Shields</td>
</tr>
<tr>
<td>Shift Work</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Move Shipping Plugs</td>
</tr>
<tr>
<td></td>
<td>Move Coil Handling Responsibility to Downstream Operator</td>
</tr>
<tr>
<td></td>
<td>Move Coil Rack Preparation Downstream</td>
</tr>
<tr>
<td>Add Resources</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Add set-up operator</td>
</tr>
</tbody>
</table>

Table 3.4  Productivity Improvement Initiatives
Chapter 4 -- The Brazing Process and Quality

4.1 Chapter Overview

The factors that affect the brazing quality are numerous and sometimes hard to measure. I will attempt to give a brief description of the brazing process and the factors that have a significant bearing on quality. The topic areas which will be defined are the heat input of the brazing furnace itself, some of the heat transfer characteristics of the joints and how that affects the brazing, the length of the hairpins and how variability affects the process, how the expansion process affects the joint quality and finally how oxidation can affect the process and the measures taken to prevent or reduce oxidation.

4.2 Overview of Brazing

Brazing is the same process as soldering except that it occurs at temperatures above 425°F while soldering occurs below 425°F. A heat source heats the base metal, the flux, and the brazing alloy. The flux dissolves surface contamination on the base metal which allows the braze alloy to contact the base metal directly. The alloy must wet the base metal and be able to displace the flux in order to form a strong metallic bond with the base metal. The proper flux and surface cleanliness are essential factors to effective brazing since in order to achieve a strong bond, the flux must decompose the surface oxides during the brazing process.[4] Increased temperatures generally enhance the flux cleaning of the surface and increase the speed of bonding. Also, in the particular application in the coil shop, the uniformity of the temperature of the joints is a significant factor due to the number and type of different joints that must be simultaneously brazed.

4.3 Brazing Furnace

The brazing furnace itself is probably the most critical factor within the entire process. It is also the least subject to change and once the furnace operating parameters are set, it requires little maintenance from coil to coil. The alignment of the burners in the
furnace is critical to getting uniform and adequate heat to the joints in order to get complete flow of the braze alloy. There are two ways to align the burners, first by distance from the joints and second by the angle of the burner which affects the height of the flame relative to the joint. One side of the furnace is fixed so the other side is aligned to match that distance in order to ensure uniform heating. Additionally, the angle is set so that one row of burners hits just below the joint and one row of burners hits just above the joint. This is designed to maximize the amount of heat at the joint without creating disturbances at the joint from the flame.

The brazer will give best results when the process is conducted in the least possible time. There are several reasons for this. First, the phosphorous flux in the braze rings will liquate (pre-melt and separate from the CuP alloy) and sublime (conversion directly from solid to gaseous form) when heated. Slow heating therefore results in a loss of phosphorus and drives brazing temperatures and times up. This can lead to structural damage as heat transfer away from the joints can lead to alloying of the tubes to the tubesheets or fins. Additionally longer heating times will increase both the grain growth and annealing of the
copper tubes that reduces its capability to meet burst strength requirements. Both of these considerations argue for keeping the actual brazing time as short as possible which means maximizing the heat input of the brazers.

While the heat transfer mechanism is integral to the brazing process, it is necessary only to understand the physical differences from coil to coil to see how the heat transfer is affecting the braze quality. First, the wall thickness of the return bends is .022" while the wall thickness of the header legs is .028". This immediately means the headers are a greater heat sink than the return bends because of the greater mass and will therefore require a longer time to reach the same temperature. Another difference occurs due to the physical differences in the configuration of the headers and return bends. The heat transfer progression can be approximated by the following equation:

\[
\text{distance} = \sqrt{\alpha \cdot \text{time}}
\]

\[\alpha \text{ for Copper} = .032 \text{ Ft}^2/\text{sec}\]

Since the brazing time is on the order of 10 - 15 seconds, the direct heat of the flame will propagate between 1.96 and 2.4 inches while the flame is still being applied in the furnace.
This allows the heat to transfer past the middle of the return bend, effectively limiting the heat transfer away from these joints. This causes them to become hotter than the header joints because the height of the headers (approximately 4 inches) doesn't limit the heat transfer during the brazing.

In contrast, the header legs are much longer (approx. 4") and have another heat sink at the top because of the distribution tube. Additionally, the end of the header tubes are swaged so that they extend down into the fin pack for additional strength. This also serves as another heat sink because they will transfer more energy down to the fin pack. The return bend legs end above the tube sheet so they will not transfer heat down into the fin pack as effectively as the header legs.

4.4 Alloys

The practical consequence of this situation is that the alloy used on the header legs will not be heated to as high a temperature as the alloy on the return bends. In order to compensate for this difference, a Copper-Phosphorous (Cu-P) alloy is used on the return bend legs and a Silver-Copper-Phosphorous (Ag-Cu-P) alloy is used on the header legs. The addition of the silver has the effect of lowering the flow temperature of the braze alloy. This is done in an attempt to equalize the amount of time it requires to flow the alloy at the header joints.

4.5 Hairpins

Another factor affecting the braze joint quality is the length of the hairpins used to make the coils. There are two dimensions of the length that are of interest. First is the difference in length between the two legs of one hairpin (pegleg). Second is the difference from one hairpin to the next.
in length, especially when different cut batches are used. A pegleg error is most damaging, because it cannot be compensated for while the mixed batch error, although easily fixed, often goes uncorrected.

If two legs of the hairpin are cut to different lengths (pegleg), the variation is displayed at the expander process. The key to note is that any variation in length is exhibited above the top tube sheet because once the expander bullet passes the top tube sheet, that dimension is set. The variation in the hairpin leg length affects the quantity of the heat input to the joint since the alloy ring will sit on top of the hairpin and will be either higher or lower than planned and changing the burner alignment. Consequently, this adds variability to the heat transfer process. Also, if some legs are too short, the belling tool of the expander will not flare the tubing, meaning it will not have a good "cup" to catch the alloy as it melts and flows down the tubing. Overflaring can cause too large a cup and splitting of the tubing. I will explain the flaring process later in this section.

The second variation is in length from one hairpin to the next. Due to the configuration of the hairpin forming machine, there is generally only slight variation from one hairpin to the next during any particular batch. However, there is an almost infinite variety of different cut lengths possible from one batch to the next. Since the variety of
hairpins drives changeovers, it is inevitable that for many runs, hairpins from different cut batches will be used for building a common coil. Two problems can exist here. First, if the lengths are different and there are multiple expander operators working out of multiple buckets of inventory, the expander may be "seeing" multiple cut lengths when it is only set for one. This condition would cause every core which is not equivalent to the setup hairpin length to be either over or under-flared. Alternatively, if batch integrity is maintained, the expander set-up may need to be adjusted when the batch changes. Obviously, if these two differences can be minimized, then the amount of variability at the expander can be minimized along with the need to revise the set-up on the expander.

4.6 Expansion

The expansion process is so named because a "bullet" is run through each of the hairpins to expand the diameter of the copper tubing to the size of the hole in the aluminum fins. This is done to improve the heat transfer characteristics of the coil. The expansion process also locks the fins and tube sheets in place, relative to the hairpins. At the end of the expansion process, a belling tool is used to treat the exposed end of the hairpins. The purpose of the belling tool is twofold. First, it oversizes the top section of the hairpin so that the return bends and header legs will fit inside of the hairpins. Second, after the bell is formed, a flare is put onto the top of the hairpins to form a

![Belling Tool and Hairpin Joint Illustration](image)

*Figure 4.4 Belling Tool and Hairpin Joint Illustration*
cup which will trap the alloy from the alloy ring as it melts and flows downward due to gravity. If the cup is too narrow (underflared) the alloy can easily flow outside of the joint, perhaps leaving insufficient alloy to seal the joint. If the cup is too wide, the copper tubing may split, sometimes at several places. This can cause problems, especially if the split runs below the depth of the bell where the end of the return bend seats. If this occurs, there will be a large gap which the alloy is unlikely to fill, causing a leak.

The cleanliness of the joint can also have a major impact on the integrity of the braze joint and several steps are taken to ensure that the joint is clean. First, all coils are purged with dry nitrogen prior to brazing so that oxygen which might break down the joint is eliminated from the coil. This is done just before the coil enters the brazing furnace. As in any brazing operation, flux is used to remove oxidation from the surface of the joint during brazing. The flux within the braze alloy is phosphorous. This is liberated and cleans the joint. In addition to the phosphorous, a gas flux is added to the natural gas mixture to reduce the oxidizing nature of the flame. The header legs were being brushed with metal brushes at the supplier's facility prior to being shipped to the coil shop in order to remove any oxidation which might have built-up during the storage and fabrication phase. They were then packaged in plastic, although they weren't packaged to be air tight. There was a time lag of between 2-4 days between the time the headers were packaged and when they were then used in production. The effectiveness of the brushing of the header legs will be addressed later in Chapter 5. Finally, the return bends were sealed in nitrogen-filled plastic packages to prevent oxidation of the return bends prior to use. In practice, each box of return bends would last about six hours, so the return bends would be exposed on average for about three hours - much less time than the headers were exposed.

4.7 Summary
Obviously, there are many more factors which will affect the joint quality other than those enumerated above. These are just the major factors upon which the limited scope of the research focused, due in part to the limited length of time available and the limited ability to test and affect other factors. As I mentioned earlier, while the furnace settings were most important to the braze joint quality, they were the most stable, and therefore, once set, afforded the least opportunity for change. Additionally, there had been much development work done when initially setting up the operating parameters of the brazers within the corporation. A quick review of the most important factors is listed below:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Affect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burner Alignment</td>
<td>Affects heat input to joint and peripheral heating</td>
</tr>
<tr>
<td>Heat Input</td>
<td>Maximum heat intensity improves the braze quality and reduces peripheral heating</td>
</tr>
<tr>
<td>Tubing Wall Thickness</td>
<td>Varying wall thicknesses change heating requirements</td>
</tr>
<tr>
<td>Alloy Composition</td>
<td>Can be changed to help equalize melting times</td>
</tr>
<tr>
<td>Hairpin Length (pegleg)</td>
<td>Varies heat input by changing the effective burner alignment. Also causes poor end-treatment of tubing for poor alloy collection.</td>
</tr>
<tr>
<td>Tube Height above Tube Sheet</td>
<td>Changes effective burner alignment and peripheral heating</td>
</tr>
<tr>
<td>Joint Flare</td>
<td>Affects alloy collection in joint</td>
</tr>
<tr>
<td>Joint Cleanliness</td>
<td>Affects joint strength and ability of alloy to wet base metal</td>
</tr>
</tbody>
</table>

Table 4.1 Brazing Factors and Their Affect on Joint Quality
Chapter 5 -- Designed Experiment Formulation and Results

5.1 Chapter Overview

This chapter looks at the genesis of the designed experiment to improve the quality of the brazing process. After examining the factor selection and design criteria, it explains the actual implementation of the experiment and the analysis of the experimental data. Next, it discusses the follow-up confirmatory experimental runs and the analysis of the data from them. Finally, it explains the conclusions drawn from the data and the implementation of specific actions taken to bring the coil production process into agreement with the optimal process parameters.

5.2 Factor Selection

The designed experiment was driven by a desire to improve the brazing process and the large number of factors which impact the brazing quality. The designed experiment can vary a number of the factors simultaneously to efficiently determine the importance of each factor. Another reason behind the designed experiment was the presence of many so called "wives tales" surrounding the brazing process. After many years of experience, anecdotes had arisen concerning the efficacy of different approaches to brazing. The designed experiment, it was hoped, would put a scientific basis back into the process improvement of the brazing itself. Finally, the experimental factors would have to require a minimum of interference in the process and be easy to maintain because of the desire to be able to maintain the results of the experiment and translate them into practical outcomes.

The starting point of the experimental factor selection was a series of experiments conducted in 1990 and 1991 at the Carrier plant in Collierville, TN. The brazing equipment was essentially the same as that in Tyler. There were two differences between the two plants that are worth mentioning. First, the Collierville plant brazes only return bends and not headers in their automatic process, that eliminates the problem of heterogeneous joints.
Secondly, the Collierville plant produces only condenser coils of which a majority are one row in width. The Tyler plant produces coils of from one to four rows in width. The initial Collierville experiment showed that the higher the copper tubing extends above the tube sheet, the better the brazing quality. The second experiment found that by extending the refractory board in past the tube sheet, the brazing quality could be improved (a refractory board is used on both sides of the autobrazers to prevent the flames from damaging the aluminum fins along the side of the coil and from overheating the transfer mechanism for the coil through the brazer). Tyler set the refractory boards at the outside of the tube sheet and Collierville set the refractory board to run on top of the tube sheet inside the outer edge.

Based on the Collierville experiments, we chose two factors: the tube height and the position of the refractory board. Another factor chosen was to test if brushing the oxides from the header legs at the supplier was a significant factor. This process was relatively new and there was debate over whether it was actually improving the joint quality. The copper was brushed between 2-4 days prior to its use in the brazing process. Additionally, only half of the products were being brushed, albeit the half that showed the lower leak rates. This was easy to test and would be easy to either implement or eliminate it across the board. Another factor which was a part of the Collierville operation, though not shown to be significant in their DOE was the use of an air cleaning station prior to placing return bends and headers in the coil. The expander process would often leave some debris in the tubing and it was hypothesized that this could interfere with the flow of alloy. This step was easy to add and could be easily monitored, although significant variation could be added. The final factor chosen was the use of two alloy rings on the header legs. Most of the leaks which could be identified on the brazing line itself appeared to be due to the alloy running through the joint and leaving a hole. The second alloy ring would be a response to that "run through" by doubling the amount of alloy available to fill the hole.
5.3 Experimental Design

Because of the discrete nature of the outcomes, e.g. there either is a leak or there isn't a leak, the experimental design chosen was a fractional factorial with two levels and eight runs. This allowed the use of 20 repetitions of each run, giving a relatively large number of runs at each design point. The experimental matrix is given below:

<table>
<thead>
<tr>
<th>Run</th>
<th>Refractory Board</th>
<th>Tube Height</th>
<th>Ref. Board x Tube Height</th>
<th># of Rings</th>
<th>Air Blow-off x # of Rings</th>
<th>Tube Height</th>
<th>Brushed Headers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>5</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>7</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>8</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
</tr>
</tbody>
</table>

Table 5.1 Experimental Design Matrix for Initial Experiment

The table above describes the experimental settings for each run. The +1 designates a “high” factor setting and the -1 designates a “low” factor setting. The experiment was designed to minimize the interactions of the main effects while maximizing the amount of information which could be gathered. The main effects which were tested are designated by the capital letters A - E above the columns. Because of the number of effects tested, second order effects are confounded with main effects. This isn't of great concern because of the nature of the factors, second order effects are unlikely. The two columns above without letters are the secondary effects which are not confounded with main effects. The experiments were conducted randomly within two “blocks”. The blocking was set up because the refractory board was difficult and time consuming to change between runs. Because of the problem with the refractory board, the blocks were set up with runs one...
thru four in the first block and five thru eight in the second. Each set of four runs was randomized by drawing numbers from a box. All 20 runs for each setting were then conducted sequentially.

The factor settings for the variables were chosen to be representative of those settings which were normally seen within the operating parameters of the current production processes or to experiment with parameters which we thought might have an effect on the process quality but there was no experimental data to show a positive correlation. The factor settings are given below:

<table>
<thead>
<tr>
<th>Variable</th>
<th>High Setting (+1)</th>
<th>Low Setting (-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractory Board</td>
<td>Inside tube sheet</td>
<td>Outside tube sheet</td>
</tr>
<tr>
<td>Tube height (in)</td>
<td>.550</td>
<td>.475</td>
</tr>
<tr>
<td># of alloy rings on headers</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Air cleaning</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Brushed header legs</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 5.2 Variable and Factor Settings for Designed Experiment

The coil chosen for the experimental runs was picked to be representative of the coils which were brazed at the plant. It was a three row coil with a total of 96 joints. There were two headers each with eight legs for a total of 16 header joints, leaving 80 return bend joints to be brazed. The header joints were classified into three groups, liquid line joints (8 joints all straight), suction line straight (5 joints), and suction line bent (3 joints). This designation was used to try and determine where the biggest problems were occurring and specifically because by observing the leaks, there appeared to be a higher incidence of leaks on the bent legs, especially legs which were both bent and hidden.
5.4 Experimental Results

During the experiment, after the first block of four runs, the refractory board was changed to ride over the tube sheet. After trying a couple of modifications, the coils still could not be made to run smoothly through the brazing machine. Because the coils were "hanging" on the board, the board was moved back to the "out" position, in effect eliminating the refractory board position as a factor. The remainder of the experiment went smoothly.

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td># Leaks</td>
<td>17</td>
<td>12</td>
<td>5</td>
<td>0</td>
<td>20</td>
<td>12</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.3 Initial DOE Results, Sep 9, 1993

Because the results are discrete, a transformation to a binomial probability is appropriate prior to conducting a linear regression to analyze factor effects. This is a simple exercise
done by dividing the number of leaks by the number of trials (e.g. for trial 1, 17/20 = .85). This will obviously eliminate almost all of the degrees of freedom because it translates 20 experiments into the equivalent of one, but is necessary to obtain accurate results from the regression. A second transformation is necessary to eliminate the mean dependency of the variance. In a binomial distribution, the variance is dependent on the mean where

\[
Mean = n * p
\]

and

\[
Variance = n * p * (1 - p)
\]

where \( n \) = number of trials

\( p \) = probability of success in any single trial

One method of ridding the variance of mean dependency is to use the following transform:

\[
sin(x) = \sqrt{p} \quad [1], [2]
\]

An example of the complete transformation for the first run is:

\[
\# \text{ of observed leaks} = 17
\]

\[
p = 17/20 = .85
\]

\[
x = \arcsin(\sqrt{p})
\]

\[
x = .785 \text{ (in radians)}
\]

The ANOVA using this transform is displayed below.
### Analysis of Variance

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>2</td>
<td>0.256</td>
<td>0.128</td>
<td>90.0</td>
</tr>
<tr>
<td>Residual</td>
<td>5</td>
<td>0.007</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>0.263</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 ANOVA for DOE Results

The ANOVA results show that the regression is significant to greater than the 99% level. The relevant F factor for a 99% significance level $F(0.01, 2, 5)$ is 13.27. This gives a high degree of confidence that the regression model is correct.

The subsequent linear regression based upon the experimental results is:

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Statistic</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.227</td>
<td>17.06</td>
<td>5.8E-07</td>
</tr>
<tr>
<td>HEIGHT</td>
<td>-0.165</td>
<td>-12.37</td>
<td>5.1E-06</td>
</tr>
<tr>
<td>RINGS</td>
<td>-0.069</td>
<td>-5.18</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

Table 5.5 Linear Regression of DOE Results

This final linear regression was obtained by modeling the linear regression with all four variables and then eliminating the least significant variables one at a time. We chose a 95% confidence interval just for ease of convention, although it should be noted that there was a large difference between the next most significant variable and the variables which are included in the final regression. This led to dropping the variables for air cleaning and brushing. The variables which are included in the final regression have a level of significance of the inverse of the P-value in the table above.
By transforming the coefficients of the linear regression back to percentages, the results show that the prediction equation to be of the form:

\[ \%LeakingCoils = .45 - .32x1 - .13x2 \]

\( x1 = 1 \) if the tube height is tall
\( x2 = 1 \) if two alloy rings are used

These results indicate that by setting both significant factors to their high setting, the leak rate could be reduced to essentially zero. This would mean having the tube height at the high setting and using two alloy rings on each header leg.

These results make sense from the data in the experiment since only one leak occurred between the combined two runs, four and eight. The two other factors varied between the two runs and seemingly had no effect on the results.

5.5 Initial Actions Following Experiment

At this point it should be noted that the leaks being classified are those coming immediately after the brazing furnace and being repaired either before or during the test cycle on the brazing line. The test station was still the bottleneck operation in the coil shop and to a large extent for the plant. For this reason, it was critical to reduce the number of coils which required repair since they slowed production considerably. It should also be noted that a small percentage of coils were exhibiting small leaks on the assembly line after successfully passing the leak test in the coil shop. The testing equipment on the assembly lines was approximately ten times more sensitive than the detection equipment in the coil shop, so it was expected that some number of leaks would be missed in the coil shop testing.
Based on the results of this initial designed experiment, we took immediate action to control the tube height in a more consistent manner. We implemented two process control steps which were being practiced at the Carrier plant in Collierville, TN. The first was to control the length of the hairpin since this can affect the ultimate tube height. We built stationary gauges for each hairpin bender operator which had a micrometer and set points for each hairpin length cut on that machine. This allowed the operator to measure and control not only the nominal length of the hairpins but also the variation from one leg to the next (pegleg). The second control step was a "go" - "no go" gauge which could be used to measure the height of the tube above the tube sheet after the expander process. The gauge had a minimum and maximum height measure which could be used to quickly check the tube height. It also incorporated a set gauge on one end which could be used as an aid when performing the changeover on the expander to quickly set the tube height close to the desired height.

Using the prediction equation above showed that if just the tube height were controlled, the leak rate could be reduced to 13% of coils. The vendor who supplied the headers did not like to use double rings. There were a host of problems for the vendor associated with using two alloy rings in the process, to include the added cost of the material, the labor cost to have the legs double-ringed, and the quality problem of ensuring all the legs are indeed double ringed. Because of these considerations and the thought that the test station operator had sufficient time to repair the expected number of leaking coils (13%) within the internal test cycle time of the test machine, we decided to do the confirming experimental run at the second best setting. We controlled the tube height to be over .55" but used only a single alloy ring without brushing the header legs and with no air cleaning station.

5.6 Confirming Experiments and Results
The results of the experiment were not encouraging. Of the sixty samples tested, we found 31 leaks for a leak rate of 52% versus the 13% prediction. At this point, we stepped back to see if there were any obvious process differences or other sources of variability which had crept into our experiment. When looking back to the processing, it appeared that essentially all the processes were controlled the same way as during the initial experiment. The only obvious difference was the operator at the preparation station for the brazing line itself. The first experiment had been conducted on the day shift and the second during the night shift. Because most of the leaks looked like they were caused by the alloy "running past" the joint, we hypothesized that the operator difference in the seating of the header to the coil could be a significant source of variability.

As a note, the preparation station operator first places all the return bends into their proper pattern and then seats them using a rubber mallet. He next places the headers into their place and seats them with a rubber mallet. The obvious problems which could differentiate the two processes are that the return bends have to mate with the coil in only two places. This allows a proper fit into each hairpin, regardless of minor differences in

![Figure 5.2 Properly and Improperly Seated Header Legs](image)

Figure 5.2  Properly and Improperly Seated Header Legs
the relative leg lengths. In contrast, the particular header tested had to mate with the coil in eight places at once. It is easy to seat one end while failing to seat the second end properly. This can cause problems with "run through" because the alloy would have a significantly larger area to seal than if the header is properly seated.

After the second experiment, we conducted two more confirming runs of 60 runs each. One was at the optimal point, tall tube height and double rings, and one was at the same point as the first confirming run. Both of these trials were conducted during the day shift to try and eliminate the variability between the first experiment and these trials due to the operator. The tabulated results of the three confirming runs are displayed below:

<table>
<thead>
<tr>
<th>Run #</th>
<th># of coils</th>
<th>Tube Height</th>
<th># of alloy rings</th>
<th>Pred. Leak Rate</th>
<th>Actual Leak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>.550&quot;</td>
<td>1</td>
<td>13%</td>
<td>51%</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>.550&quot;</td>
<td>2</td>
<td>0%</td>
<td>2%</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>.550&quot;</td>
<td>1</td>
<td>13%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 5.6 Confirming Experimental Run Results

These results show that the second and third confirming runs correlated closely with the initial experimental predictions.

Based on our findings, the first corrective action we took was to instruct all of the preparation station operators on the necessity of properly seating the headers across the entire length of the coil. If simple variation between the operators could induce an output quality difference of almost 40%, this was a vital area to concentrate on to improve quality. In addition to instructing the operators on the importance of proper header seating, we also devised several simple fixtures which could be used on a number of coil types to improve the seating consistency.
5.7 Summary

The designed experiment was very successful in finding those variables that could promote significant improvements in the final brazing quality. The two variables that were significant, tube height and number of alloy rings, provided a starting point for improvement. The subsequent confirming experiments then provided more insights into operator induced variability which was a significant factor in final quality. These insights would not have been found if the designed experiment had not stripped away the "wives tales" which had surrounded the brazing process.

The resulting change in quality was quite dramatic. While no direct measure of the number of leaks was taken at the brazing line test station, the leaks actually found during inspections on the assembly line dropped by 56% from their initial level to the time after all corrective actions were implemented (about three months). The productivity improvements on the brazing line were also due in large measure to the decrease in the number of leaks through the brazing furnace. The designed experiment was instrumental in making the quality improvements possible and led to possibilities for continuing to decrease the leak rate even further.
Chapter 6 -- Organizational Challenges

6.1 Chapter Overview

This chapter will attempt to explore some of the more salient organizational issues regarding the implementation of change. While it will not refer to too many theories of organizational change and culture, it will try to relay the experiences observed in the manufacturing environment encountered during the internship and then generalize where I believe appropriate.

6.2 Initial Attitude

One of the most passionate issues encountered centered around the issue of whether or not the employees felt that their contributions were valued, and whether they felt they were treated merely as another machine, albeit a machine which resided at the plant only for the shift. The Japanese have been able to harness the mindpower of their employees through quality improvement circles and other similar programs while many American firms have been unable to tap this valuable resource. Throughout the internship, but especially at the beginning, I asked many of the hourly workers for improvement suggestions. I was surprised by the rather bitter attitude they held, replying with statements like, "they (management) never do anything we ask for," and "we've been through those programs before and nothing ever changes". I decided very early to spend special attention on those requests received from the employees on the floor, even if they had no direct relation to improving the productivity or quality of the shop. While many employees at the Tyler plant would put me in the same category as "management", I believe that a substantial majority of the line workers felt that I would try to implement their suggestions or at least tell them why I wouldn't work on it. Over the course of the research, more and more people were willing to share ideas about improvement with me. From starting with rather mundane proposals like the need for a table for the break area or
adding an additional light to the line, several of the proposals we implemented like the
color-coding and labeling of the coil templates were the direct result of worker suggestions.

This is relevant for two reasons. First, change is inherently scary to both
management and the line workers. Most of the time, management is more willing to accept
change because they also have to accept the responsibility for improving the operation. The
line workers generally do not have to answer to the plant manager if the shop does not
produce the scheduled number of coils. Therefore, change only has the perceived
downside risk of making their jobs tougher (what manager is going to try and make their
job easier?) or add work content to their present job. If the suggestion actually comes from
the line rather than from management, then the change should be far less threatening
because they know both the intent and the expected outcome. This should allow the
management to expend far less energy in getting the change accepted and get more help
from the line in making modifications to the original plan if changes need to be made.

The second consideration is that only about 5% of the plant personnel actually work
as salaried people out on the plant floor versus about 90% of the overall workforce. That
means there are about 18 line workers for every supervisor, engineer, and other salaried
employee on the floor. In addition to this disparity in numbers, the line workers are the
people in the plant most intimately familiar with the actual work that they do. And perhaps
most importantly, the line workers are the people in the plant who can notice changes in the
process most quickly. For an organization to disregard or receive little input from that large
a share of its workers is literally to give up any chance for long-term sustainable
improvement. If a salaried employee must be responsible for noticing every change in the
process or for implementing every improvement (whether it requires getting a simple
fixture made or coming up with an idea that must be submitted on a work order) then the
number of improvements will be small. The salaried employees have many responsibilities
besides looking for improvement possibilities. Machines break, schedules change,
materials arrive late or in the wrong quantities, somebody is late to work or absent; these
are all examples of competing priorities. If the managers also have to observe every process looking for change opportunities, initiate the change, monitor its progress, modify the plan, initiate another work order to implement the modification, and continue to monitor the change to ensure it is adhered to, then there is little likelihood that substantial change will take place.

6.3 Communication

A second subject for organizational learning is communication. Much has been written about the need for communication and its positive effects. I will discuss worker to worker communication rather than manager to worker communication since it often receives less attention. The coil shop had some good communication and some poor communication existing within the same shop. The personnel in the coil shop all knew each other and for the most part were friendly with one another. There wasn't very much turnover since the pay grade was higher than most of the assembly line jobs. However, there was a lot of reticence towards giving feedback between some of the operations in the department. Two examples will illustrate the contrast. The first is between the hairpin benders and the expanders and the second between the expanders and the brazing lines.

6.3.1 Two Examples of Communication

The hairpin bending machine operators received a schedule based on the assembly line schedules, so theoretically, they wouldn't need to coordinate their production with the expander operators. In practice, though, they frequently moved from their machines to coordinate with the expander operators what types of hairpins would be needed for the production runs to ensure they were on track and had the proper number and length of hairpins cut. This exchange also became an informal feedback loop to the hairpin benders on the quality of their output and on how their production was affecting the quality of the expansion process. For example, due to variations in the copper tubing from different manufacturers, the shrinkage during the expansion process would sometimes vary. Based
on these discussions, cut lengths could be modified to ensure the hairpins compensated for different shrinkage. In contrast, between the expanders and the brazing lines, there was no reason for communication. The expander operators were given a schedule and told not to deviate from it because in the past there had been shortages that caused production problems. The expander operators strictly adhered to the schedule and when they completed a batch of coils, they simply put them in the inventory storage area and started work on the next scheduled batch. The brazing line operators never went back to the expander operators since they processed those coils which the material handler told them to work on. If the coils were in inventory, everything went smoothly, and if the coils weren't in inventory, they would skip to the next batch. In practice, because the brazing line was almost always the bottleneck resource, they rarely ran out of inventory. The situation required no interaction between the two groups and no professional contact occurred. At lunch and breaks, they would talk with each other, but if there were a quality problem during production, the brazing line operators wouldn't break from their routine to notify the expander operators of it. This lack of communication was highly detrimental to quality because small changes in the physical characteristics of the coils such as the tube height above the tube sheet, detailed in Chapter 5, could have a major impact upon the output quality of the brazers. Additionally, the brazing lines could have been a valuable source of feedback to monitor the work practices of the expanders. For example, if the braze line operators would have provided feedback on a continuing basis about the quality of the flaring, it is certain that the expander operators would have paid additional attention to their machine settings and would have monitored it more closely. This small but constant attention to detail would have been a source of improved quality for the coil shop.

6.3.2 Possible Solutions

There is no easy answer for how to foster the communication links between dependent processes in the workplace. Most of the methods have been enumerated in the literature but the key is in recognizing the need for better communication and then
implementing the proper actions. One method which was being tried in another section of the plant was a "Partners in Quality" program. This program's method was to have weekly meetings of an entire department to air quality problems and hopefully stimulate the production workers to come up with solutions to their own problems. This can be a useful method to at least get the quality problems out into the open if the internal dynamics of the situation don't lend themselves to continuous feedback. The key is to harness the energy of the 90% of the people who work with the processes. Another possible solution is to use cross-training as a means of improving communication between sub-groups. Cross-training is generally thought of as a means of improving management's flexibility by increasing the skills of the workforce. If it were used as a tool for getting expander operators more knowledgeable about the effect they have on the brazing operation by allowing them to see first-hand the effects, it could have the dual benefit of bringing quality issues to light. It could also be used in reverse by showing the brazing line operators what actual impact the expanders have on the physical characteristics of the coils. They would then be more knowledgeable about how to target their feedback to the expander operators and when issues might need to be brought to the attention of the engineers and supervisors.

The overall concept of communication's link to quality is clear. With about 18 hourly workers to every salaried person actually working on the shop floor, if the plant has to rely on the shop engineers and supervisors to detect and correct quality problems, the quality will always be poor because they cannot see every piece of production or know every time something has gone wrong. If the hourly workers are constantly monitoring quality, even if they don't solve every problem on their own but simply bring the problems to light instead of allowing them to pass, the quality will quickly improve and the incidence of problems in the future will decrease rapidly.

6.4 Management Attitude
I believe that the productivity of the workplace was adversely affected by the attitude of many of the supervisors in the plant. The plant had been a strictly piecework incentive shop prior to my arrival and was making a transition to a straight wage with a group incentive based on quality and assembly line production. However, the old system of tracking an individual’s performance against the standard continued. This would manifest itself in a supervisor counseling and perhaps threatening to discipline a worker if he did not make 100% of the standard. The practical effect of this was to discourage teamwork among the workers and especially between departments.

I will give two examples of what I mean. On the brazing lines, I tried to enlist support for having a flexible worker who would spend most of his time at the preparation station and would spend some time flexing to the touch-up position when work would back up. The hourly workers didn’t like the idea because they believed it was an attempt to make them do more work and because the idea of shifting between two work stations was contrary to everything they had done at the plant previously. I was more surprised that the supervisors in the department were against the idea. Their reasons were twofold. First, they believed that it would be too hard to implement because they felt the workers weren’t competent to decide for themselves where the bottleneck was and so would have to be micro-managed. Second, they said that it would be too hard to determine if the workers were actually working, rather than just goofing off. This last comment was generated because it would be impossible to measure their output against a standard since they would be performing two jobs and it would not be feasible to punch the clock every time they switched between the two. As I said earlier, there was no difference in pay received regardless of the output.

The second illustrative example deals with an unwillingness among line workers to give feedback. A particular example of this surfaced fairly near to the end of the internship. I had tried to enhance some of the communication between the sub-operations in the coil shop. I had started out by asking workers on the brazing lines to go back and commend
the expander operators on the quality of a particular run, feeling that it is always better to start with positive feedback. I encountered much surprise and some reluctance to do this. After a while, I picked a particularly off-spec batch and asked the operator to go upstream to a expander operator and ask them to come and see the results. This was not an attempt to assign blame since no specific operator or shift could be assigned responsibility for the poor quality, it was merely designed as a means to reinforce good quality in the future. I was surprised that not a single operator on the brazing line would go to the upstream operation to tell them of a quality problem. The comment I received was “That’s his job, he knows what to do, and if he doesn’t then I’ll just do my best to do my job.” The best I was able to accomplish was to get them to agree to tell the union shop coordinator for the brazing lines, so that he could tell the shop coordinator of the expander operation, so that he could tell the operators in the expander area. This is obviously not a long-term solution to a quality feedback loop.

The question though is what motivated the workers to refuse to give direct feedback. From my observations, it is a mixture of pride and the desire not to assign responsibility. The first is quite natural and should be harnessed to improve quality. The workers have pride in what they do and if someone were to tell them that there is a deficiency, then they would want to correct the problem. The problem arises though because to tell them that a problem exists downstream could lead to counseling if the supervisors think that they are not adhering to the published quality standards. Since the standards are published, just as the production rates, failing to adhere to them represents a disregard for authority. This was at least partially confirmed by the response of one supervisor when I brought up a different breach of the quality control process. His immediate response was that the worker should be “written up” for failing to comply with the directive. I believe this goes directly back to the assumption that the workers were just out for themselves and were only kept in line by the disciplinary control measures available.
to the management. This is the view that management's job was to control rather than to coach and improve the workforce.

6.5 Bottom Line

The bottom line is that the management and workers must be able to work together in order to become truly productive. While this is not a revelation, it is a truism which is still not recognized in many manufacturing companies despite the rhetoric affirming it. If the management cannot work with the factory floor workers, then they will never be able to achieve the type of productivity gains which will make them world-class manufacturers. Additionally they will be unable to continue to improve their operations at the pace necessary to keep up with companies which have been able to attain a true partnership with their workforce.

There is no single answer for how to fix the varied relationships between management and labor, but they all start with building mutual respect and trust. From this basis, a strong culture of both continuous improvement and innovation can be fostered which is capable of growing and changing to meet the changing needs of the customer. If labor and management are at odds with each other, the ability of the culture to adapt to the changing customer needs is limited and will restrict the ability of the company to succeed.
Chapter 7 -- Application in the Real World

7.1 Overview

This chapter addresses some useful observations on the use of both the theory of constraints and lean production and how they can be mixed for maximum advantage. It then will describe what I consider to be the primary use for designed experimentation in a factory setting and how it can supplement the move to more efficient production.

7.2 Theory of Constraints or Lean Production

While the literature on the two production methodologies doesn’t reference the other and some say that the two are incompatible, we found that they could both be useful in improving the productivity of the department. Using the concepts of the theory of constraints we located the bottleneck and focused resources to it. Secondly, we used many of the theories of lean production to reduce the bottleneck. While we didn’t attempt to fundamentally adopt any of the scheduling techniques of either system, many improvements were made and many are still possible.

There are strengths and weaknesses of both methodologies. For example, the strength of the theory of constraints is that it focuses attention squarely where it needs to be, on the bottleneck. Improvement at any other resource will yield only marginal gains when compared with improvements at the bottleneck. The theory of constraints contends that the true cost of the bottleneck resource is the cost of operating the entire factory. This method is proposed because if the resource truly is the bottleneck, then additional throughput can be achieved in the plant by merely adding throughput at the bottleneck. This is true since all the other resources in the plant can, by definition, increase output. When this understanding of the true costs of the time on the bottleneck are calculated, the urgency and attention of more resources can be brought to bear. The theory of constraints
doesn’t give any real practical guidance for how to improve the constraint, though and this is where the practical emphasis of lean production techniques can be used.

The lean production techniques developed by Taiichi Ohno while at Toyota, and enumerated in the book *Kanban*, focus on the reduction in the number of workers and the use of strictly enforced work methods to achieve productivity gains. The key is to notice when a work cell can eliminate an entire worker by a small improvement in methods and to focus attention on those areas. Over time, this method will work extremely well as Toyota has shown. The problem is that if there is a major problem in one specific area, it may not always serve to point out that problem as explicitly and quickly as the theory of constraints will.

Drawing upon the lean production techniques and the work reduction methods J. Costanza, we looked for ways to improve the productivity of the individual operators on the brazing line. This worked extremely well to show where there were opportunities for improvement and as an aid in communicating to both the line workers and the management where resources should be focused. As we improved and came closer to the goal of meeting production targets without the use of overtime (partial reduction of the bottleneck), the amount of attention from the plant management diminished and the emphasis on improving slowed.

The question of what type of material flow system to use within a factory is left open by this thesis. The theory of constraints proposes to schedule all material flow by the use of the bottleneck and lean production rests upon the use of a demand pull kanban system. It is this author’s opinion that the decision as to what type of system to use is really a question which should be addressed when the overall process flow is designed and can be divorced from the more local process improvement initiative. The material flow in the coil shop did not adhere to the requirements for either system, but was instead a combination of the demand pull and MRP scheduling system. In truth, it resembled a true MRP production system more than a kanban system.
In summary, I believe that both the theory of constraints and the lean production techniques are useful and compatible for conducting a process improvement program. The theory of constraints should be used to formally focus both the improvement team’s attention and the attention of the plant management. Once the effort begins, the concrete and practical process improvement implementation methodology of the lean production system should be used to direct specific improvement options at the bottleneck resource. The material flow system to use can be divorced from both systems and should be considered as part of a “re-engineering” or similar effort.

7.3 Design of Experiments

Much has been written about the efficacy of designed experimentation and probably no one would argue that designed experiments should not be used. However, I propose that even though they can be used to “optimize” a process they can be just as valuable as a tool to guide process improvement. By this I mean that it can be used as an iterative tool to help not only to determine if the variables in the designed experiment are significant to the process, but also as a tool to guide further research.

For a plant staff to be able to do designed experiments, they must initially be kept simple. Since the statistical training of most engineers doesn’t include designed experiments and most plant engineers haven’t had any formal statistical training in their use, designed experiments are considered foreign. Even if a course can be taught to the plant staff, it will only cover the basics of designed experimentation and cannot go into the nuances of advanced experimental designs. For these reasons, short, simple designed experiments should be stressed and are the most likely to be successful.

When we initially started examining the brazing process for ways to improve it, there were many suggestions as to what could be affecting it. These ranged from the ambient temperature changes (the plant was air conditioned and the temperature never varied more than about 100 F while the brazers were 2,000,000 Btu), to the humidity, to
the incoming variation of the copper coils. Strangely absent from the list were most of the variables we finally tested. What was apparent was that it seemed that the plant personnel thought that there were so many variables that were significant to the brazing process that any attempt to control the process was doomed to failure.

After the initial designed experiment covered in Chapter 5, we implemented targeted process control methods for both the hairpin benders and the expanders to attempt to control the tube height above the tube sheet. This was rather straightforward and should have been expected. However, the designed experiment also allowed us to find something which we never expected to find, namely that the variation between the operators seating of the headers was a major factor in the output quality. Without the designed experiment, it is doubtful that this discovery would have ever surfaced. This discovery aided our ability to influence the process by instructing the operators more thoroughly and by designing fixtures which would improve the seating consistency.

The designed experiment also had several other additional benefits which were not apparent when we started. After the designed experiment and confirming runs were taken, there were several additional observations we made which wouldn’t have been readily apparent before the designed experiment. First, the incidence of leaks at the straight legs was much higher on the liquid side than on the suction side. Once we began to look more closely at this phenomenon, it appeared that the warpage in the liquid lines was greater than on the suction side. The liquid header distribution tubing was only 1/2” versus 3/4” for the suction tubing so we assumed that the thermal and mechanical stresses of the header fabrication process were causing the additional warpage. This caused improper seating and generally either one end or the other of the liquid line would display a leak, not the middle portion. This discovery also would not have been made, or if it were, the direct link to the braze quality would not have been recognized.

The final outcome of the designed experiment was far better than anticipated because it had the many side benefits outlined above. If the designed experiment had not
been conducted, the root cause analysis and subsequent exploration would have been tremendously more difficult and time consuming. The DOE had the effect of quickly sifting through many of the extraneous variables and then allowing greater focus on those that were significant and gave a better idea of where to look for further causes.

In general, the DOE can be an effective tool for process improvement. I believe that simple experiments are much better and more likely to be grasped by the typical plant personnel, not because they are incapable of learning, but because they don’t have the time to devote to learning and setting up large and intricate experiments. The iteration of small experiments can be much less imposing and much less time intensive than the larger experiments too.

7.4 The Final Status of the Coil Shop

As shown in preceding chapters, the cycle time of the brazing lines was decreased from 100 seconds to 76 seconds and the assembly line quality defect rate was cut by 56%. These, by themselves, were a major achievement, and the cycle time reduction had a dramatic effect on reducing the operating expense of the coil shop by drastically reducing the need for overtime. However, there were several additional benefits spawned by the improvements in the coil shop.

Most importantly, the downtime for the assembly lines decreased from a high of 4.5% before the changes to a nearly constant level of less than .4%. This helped the factory run much more consistently, a key to high productivity and quality. Additionally, the reduction in coil leaks on the assembly lines reduced the amount of rework and number of units which had to be taken out of production order to be repaired. The total difference between the operating expense alone before and after the improvements were completed amounted to approximately $1 million annually. This doesn’t include any expenses associated with schedule changes or problems with quality and delivery.
This research displays the improvements which are possible by applying the simple production improvement techniques described above. Nothing contained in this thesis is so technically sophisticated that it cannot be applied due to a lack of intellect. All that is necessary is to have the ability to look critically at the operation, and the drive to implement the changes required to execute the basic strategies outlined in Chapter 3 and 5.
References


