

# RAPID QUALITY FEEDBACK THROUGH LEAN MANUFACTURING

by  
Brian G. Sullivan

B.S. Mechanical Engineering  
GMI Engineering & Management Institute

Submitted to the Sloan School of Management and the  
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and  
**Master of Business Administration**  
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Signature of Author \_\_\_\_\_  
Department of Mechanical Engineering  
MIT Sloan School of Management  
May 9, 1996

Certified by \_\_\_\_\_  
Stanley B. Gershwin  
Senior Research Scientist  
Department of Mechanical Engineering

Certified by \_\_\_\_\_  
Charles H. Fine  
Associate Professor  
MIT Sloan School of Management

Accepted by \_\_\_\_\_  
Alan A. Sonin  
Chairman, Department of Mechanical Engineering Graduate Committee

Accepted by \_\_\_\_\_  
Jeffrey A. Barks  
Associate Dean, Sloan Master's and Bachelor's Programs

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## **Abstract**

This thesis presents a methodology of improving quality through the use of feedback and lean manufacturing to streamline the process of feedback. As customers' expectations and competition increase, so does pressure to improve quality and reduce manufacturing costs. This thesis examines an approach which improves quality, thereby reducing manufacturing costs. This is accomplished without negative effects on other manufacturing measurables and without large capital expenditures. An informational feedback loop is used to relay quality (and defect) information to upstream operations within a manufacturing process. A lean manufacturing tool of process mapping is then used to reduce the delay of this information through the process.

This thesis also examines the implementation of this approach within a component's manufacturing and assembly process. Process mapping is used to improve operations within a retest and repair area. Waste and delays identified in the process map are reduced or eliminated to improve the rate and accuracy of defect detection. Information regarding specific defects is then fed to upstream operations to make improvements in the manufacturing process.

Results of the implementation include 95% reduction in lead time through the area, 95% reduction in area inventory, and 90% reduction in total time from defect occurrence to detection. A 50% decrease in scrap cost was observed in only four weeks, and an 80% decrease has been accomplished to date.

The implementation approach is directly applicable to many manufacturing systems, and the general approach is applicable to any process in which the quality of output is important. Implementation across a wide variety of industries and processes is possible.

Thesis supervisors:

Stanley Gershwin, Senior Research Scientist  
Charles H. Fine, Associate Professor



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# 1. Introduction

This thesis is the result of several months of research at a major US auto company (Acme Motor Company) through the Leaders for Manufacturing Program at MIT. The general problem facing the Acme manufacturing line studied was an unacceptable quality level. This thesis presents a methodology of improving quality through the use of feedback and lean manufacturing to streamline the process of feedback. The methodology is implemented in the component assembly line, in which annual scrap costs are approximately \$1.6 million. (A sister line contributes an additional \$0.8 million annually.) The results of implementation include an observed 50% reduction in the scrap cost in 4 weeks, and an 80% reduction to date.

Using process mapping and waste reduction, changes were made in the process which generates quality information to be fed back to upstream operations. Inventory in this area has been reduced by 95%. The lead time through the process has been reduced by 95%, resulting in a 90% reduction in time from defect occurrence to detection. The changes also had a noticeable positive effect on the operator's job satisfaction.

The implementation approach is directly applicable to many manufacturing systems, and the general approach is applicable to any process in which the quality of output is important. Implementation across a wide variety of industries could result in millions of dollars in material and labor savings through defect reduction.

The purpose of this thesis is to present this methodology of quality improvement through the use of feedback and lean manufacturing. Information about the status of a system and its output is essential to make improvements in the system. Feedback results when this information is used by upstream operations, or by support employees (such as manufacturing engineers) to identify the need for improvement, or to see the effect of a change made in the system. Lean manufacturing is used to improve the process of collecting this information. Process mapping identifies opportunities to reduce delays

and waste in the process, resulting in a reduced lead time. The quality information is obtained more rapidly, and becomes more relevant and useful when fed to upstream operations. The goal of this thesis is to present the key components of the methodology, discuss their importance, and provide a real-world example of implementation. While this approach is not the only method of improving quality, the results of implementation will show that it can be an effective one.

After this introduction, Chapter 2 presents background information and a description of the manufacturing system studied. The methodology of quality improvement is discussed in Chapter 3, with implementation details and results in Chapter 4. Chapter 5 presents conclusions and recommendations for future action.

## **2. Background & System Studied**

This chapter presents relevant background information and describes the manufacturing system studied. A description of the product and its requirements is given, followed by a description of the supply chain for this product. The in-house production process and the Retest/Repair/Scrap process are described, including a general physical layout of operations in the respective processes. An examination of the organization and flow of information is also presented<sup>1</sup>. The chapter concludes with an examination of the status of the system at the onset of the project.

### **2.1 Product**

The product discussed in this thesis is a windshield wiper motor used in all vehicles assembled by Acme Motor Company in North America. The motor is electrically powered, and is connected through a mechanical linkage to the windshield wiper arms. One motor is used on each vehicle. In addition to the requirement that the motor be very durable, there are various performance requirements for each motor. These include torque requirements, speed ranges at specified torque levels, maximum current draws, and park angles. These requirements vary from vehicle to vehicle depending on the wiper blade size used, the sweep angle of the blades, and generic target market desires. These different performance requirements is a contributing factor to model complexity. There are approximately 33 different windshield wiper motors produced for Acme North American vehicles.

In the past several years, passenger vehicle customers have demanded lower in-cabin noise levels. Companies have responded to this customer need by establishing noise/vibration/harshness departments, and have used lower noise levels as part of their marketing campaigns. The windshield wipers are a large contributor to in-cabin

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<sup>1</sup> The description given is of the system as it existed during this project. Although organizational changes have been made since completion of this project, they are not described here.

noise and vibration levels, and are a common source of customer complaints. Although customers normally hear wiper blade noises first, the wiper motor often contributes more to the overall in-cabin noise level. Noises reach the passenger area of the vehicle both directly from the wiper motor, and indirectly through other components of the vehicle. An example of the latter is through the vehicle's windshield. The vibrating motor may be attached to the vehicle's cowl, which transmits the vibration to the windshield, which acts like a large speaker directly in front of the passengers. Therefore, not only is a motor's sound output important, but its vibration characteristics are equally important in determining the vehicle's in-cabin noise levels.

## 2.2 Supply Chain

A simplified diagram of the supply chain for this product is shown in Figure 1.

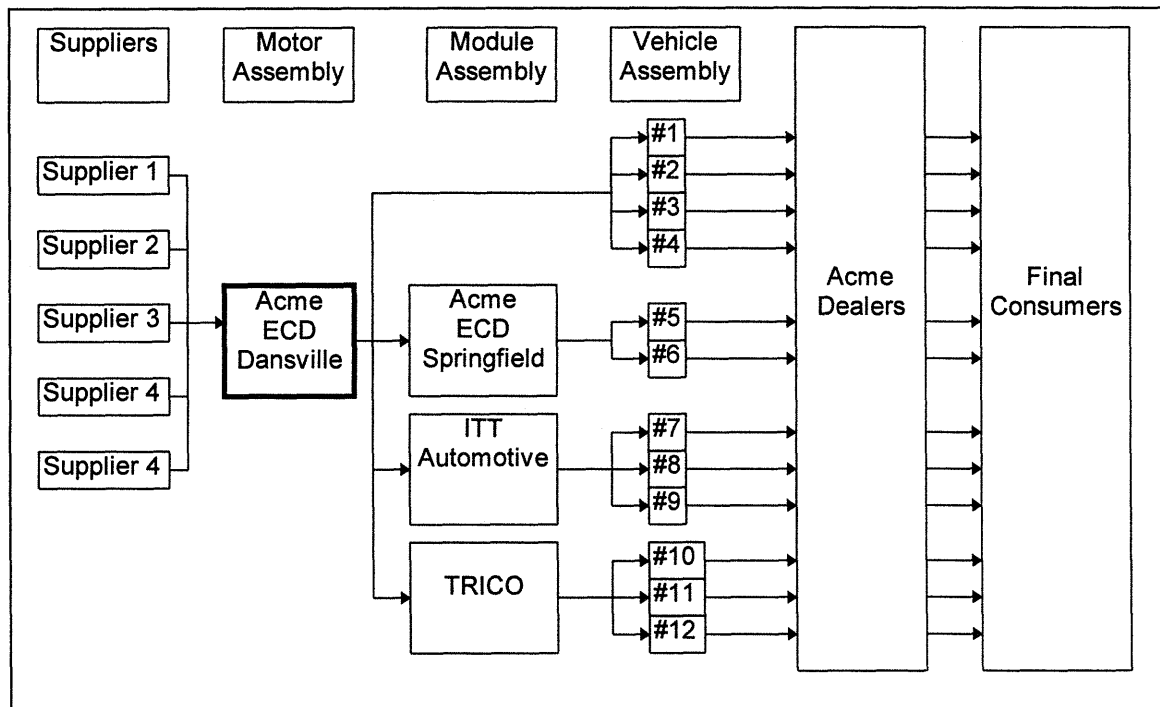


Figure 1 - Supply Chain

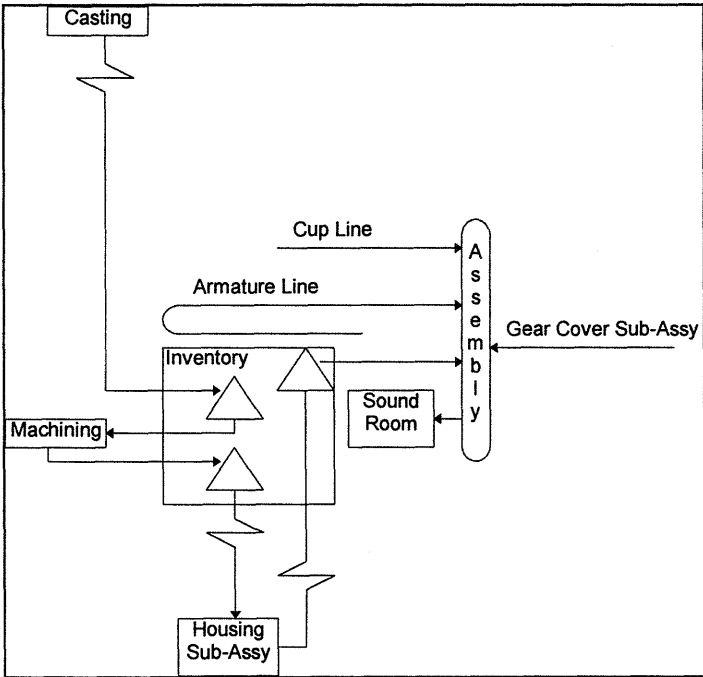
The wiper motor assembly function (shown above in the highlighted box) is performed solely at Acme's Electrical Components Division's (ECD's) Dansville plant. Parts arrive at the assembly operation from both external (bearings, magnets, etc.) and internal (casting, armature winding, subassembly, etc.) suppliers. After assembly and testing at Dansville, the motor is shipped to one of three general locations. The first is ECD's Springfield plant. Springfield attaches the motor to a wiper module, which is delivered to the vehicle assembly plant. The second direct customer of the motor is one of several external companies, who also attach the motor to a wiper module which they supply back to Acme assembly plants. Many of these companies also manufacture wiper motors for other vehicle manufacturers, and are therefore competitors as well as customers and suppliers to different parts of Acme Motor Company. The motor can also be shipped directly to assembly plants for vehicles which do not have modular wiper system designs. The assembled vehicles are then shipped to dealers for eventual sale to the consumer.

The different product paths create a certain level of complexity of information (as well as product) exchange. There are three distinctly different direct customers of the product, with three different methods of communication. The first customer is within the same division of the corporation. They are much more likely to share information, and work together to satisfy the subsequent customer. The second customer is an external company, which also supplies other vehicle manufacturers. This company is also a competitor, both to the internal module manufacturer, and in most cases, to the motor manufacturer. The relationship here is much more like the traditional supplier/customer relationship, except that the additional pressures of being a direct competitor exist. Information sharing is much more formal and cautionary here. The final customer type is within the same corporation, but in a different division. The level and type of communication here lies somewhere between the first two.

### 2.3 In-house Production Process

The in-house production process is centered around the final assembly of the motor, which is fully automated. The run length or batch size of a particular model is generally 5 to 10 hours of production. The 33 different models are a result of the varying vehicle requirements described in Section 2.1. To meet these different requirements (or in an effort to reduce cost), several operations in the manufacturing and assembly process have different components to select from<sup>2</sup>. It is the combination of these selections that leads to the 33 different models. The number of different components within each operation will be referred to in this thesis as model complexity.

Four “satellite” production processes flow into the final assembly, each of which have varying levels of automation. These processes will be referred to within this thesis as Housing Sub-assembly, Armature Line, Cup Line, and Gear Cover Sub-assembly. A general layout of the area is shown in Figure 2.



**Figure 2 - Assembly Area**

<sup>2</sup> For example, 3 different bearings are used. This is done in an effort to tradeoff cost and performance. Since the low friction bearings are more expensive, higher friction bearings are used when possible.

The first satellite process is that of Housing Sub-assembly. This process begins with the casting of the housings at the front of the plant (indicated in Figure 2 by the broken line). Casting operations are performed here for several products and assembly areas of the plant. The housings are then transported in batches to the machining area. The machining area is located adjacent to final assembly, but is separated by a large housing inventory area. Castings are stored here in steel tubs holding between 800 and 1000 castings each (approximately 1.5 hours of production). There are three different housings at this point in the process, distinguished by the length of the output shaft area. Castings are then machined and automatically off-loaded through a chute into steel tubs and returned to the housing inventory area. These housing are stored in separate rows in the inventory area, so as to not mix dissimilar components. Model complexity remains at 3. Total housing inventory in this area has been observed to vary between 1 and 2 weeks of production. The next step in this process is the insertion of bearings and bushings into the housing. This is done in batches on the automated "Housing Dial". Housings are manually loaded onto a rotating table, which indexes after each operation is performed. Finished housings are automatically off-loaded into plastic containers or steel tubs, and are transported to a storage area adjacent to the final assembly area. The housings are eventually manually placed on pallets on the Housing Conveyor to be fed to the final assembly line. This conveyor will hold a few minutes of inventory. Although three different bearings are inserted into the housings (allowing for a possible complexity of nine), only 6 combinations are used.

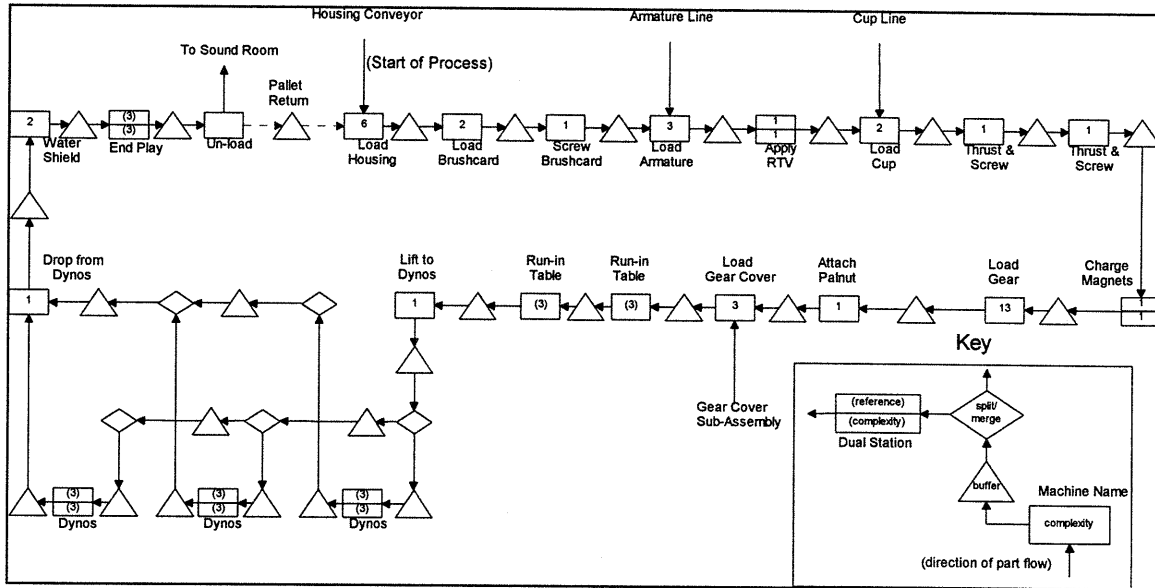
The second satellite process is the Armature Line. This process is fully automated, with the exception of the manual operation of unloading the finished armature. The line is composed of two segments, one which begins near the housing storage area and runs in a direction away from the final assembly line, and a second which runs toward final assembly. The two segments are separated by an in-line decoupler, which may hold as much as one hour of inventory. The first segment has a complexity of one, while the second segment has a complexity of three. The first operation in the second segment is armature winding. It is through the use of different windings that the complexity is

generated. After being transported through several more automated operations, the finished armature is manually unloaded from the conveyor. If the conveyor leading to the final assembly line is not full, the armature is placed on it. If the conveyor is full, the armature is placed in a plastic container to be placed in a storage rack, which is used as an off-line buffer. The total amount of work-in-process on the armature line (not including the off-line area) ranges from one to three hours of production. There is room for several hours of inventory in the off-line storage area, and the conveyor leading to the final line contains approximately 30 minutes of inventory.

The third satellite process is the Cup Line. This line is a straight shot feeding into the final assembly line, and is fully automated. A conveyor transports parts through several automated operations, and has a complexity of two. Once the cup is finished, it is automatically placed on a conveyor which feeds the final motor assembly line. The operator maintains an off-line buffer of cups at this location, to be used only when the cup line is down and the final line is starved for parts. The final operation on the cup line is part identification. The date, time and part number is printed on the cup before it is placed on the final assembly line. This part number serves to identify the entire motor, not just the cup. Therefore, changeover of this machine must be coordinated with other changeovers, even if the part itself does not change. The parts conveyor holds a few minutes of inventory.

The final satellite process is Gear Cover Sub-assembly. This process takes place on the opposite side of the final assembly line. An automated machine performs assembly and attachment operations on the gear cover, and places the cover on a gravity fed chute which holds a few minutes of inventory. The gear cover is then automatically loaded onto a pallet which is fed via conveyor to a gasket application operation. The cover is then transported via conveyor to the final assembly line, where it is placed on the motor assembly. The only source of model complexity here is the very first operation, with a complexity of three. Total work-in-process inventory here is a few minutes of production.

Final assembly of the motor is performed on a fully automated, recirculating pallet assembly line. A process flow of the line is shown in Figure 3.



**Figure 3 - Final Assembly Process**

The process begins at the Load Housing operation where housings are lifted from the Housing Conveyor, and placed on the final line pallets. In addition to the four satellite processes feeding it, there are six stations where purchased parts are placed on the assembly (with complexities of 2,1,1,13,1,2). Five more stations perform additional operations (driving screws, applying RTV, charging magnets, and running-in the motor). There is a performance testing area near the end of the line, where pallets (and parts) are lifted off of the main line and transported via a series of conveyors to one of three dynamometer stations for testing. Although these stations do not cause any additional part complexity, one of three setups is required, depending upon the model being produced. This is represented by “reference complexities” in parentheses in Figure 3. All pallets are then returned to the main assembly line to finish the process. The final operation is the automatic unloading of the motor onto a conveyor. Empty pallets then return to the beginning of the process. A total of 20 machines are used in this process,

not including the relatively simple parts handling machines. Total work-in-process on the final line is approximately four minutes.

If a part has passed all tests on the final assembly line, the automatic unloader places the motor on a conveyor which transports the part into the sound room. A motor which failed any one of the in-process tests is placed on the rejection conveyor, and enters the Retest/Repair/Scrap process. Once in the sound room, each motor is tested for noise and vibration characteristics. This is a manual operation performed by two operators, one on each side of the conveyor. The operator removes the motor from the conveyor and attaches a power connector to the motor. The power supply automatically runs the motor at both high and low speeds and parks the motor<sup>3</sup>. The operator listens for any unusual noise, and holds the motor through the test cycle to detect any unusual vibration. Examples of common defects and good motors are nearby for reference. A motor which has any unusual characteristics is placed in a box in the corner of the room. A normal motor is placed back on the conveyor, and transported to the packing area. Because of the repetitive motion and vibration associated with this testing operation, operators rotate with the packing operators every hour. Acceptable motors are packed in racks, and transported out of the final assembly area.

## **2.4 Retest/Repair/Scrap Process**

Motors that have failed any in-process check (generally performance testing) are placed on the reject conveyor. There is no marking or other indication of why a particular motor has been rejected. The parts are transported into the Off-line Dyno area, located directly adjacent to the end of the assembly line, as shown in Figure 4 . The Off-line Dyno operator removes the motor from the conveyor and connects it to one of four power connectors. The motor is run for three to five minutes, disconnected, and retested on the dynamometer. Often, the motor will pass this test, and is placed on the “accepted” conveyor. Motors that fail are generally reconnected to the power supply

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<sup>3</sup> The motor parks when returning the wiper blades to the bottom of the windshield after use.

and retested. Once the operator has decided that the motor is defective, the motor is manually marked with a rejection code displayed on the dynamometer. The defective motor is then placed in a reject box. Once eight defective motors have accumulated, the reject box is placed in the reject area, just outside of the dyno room.

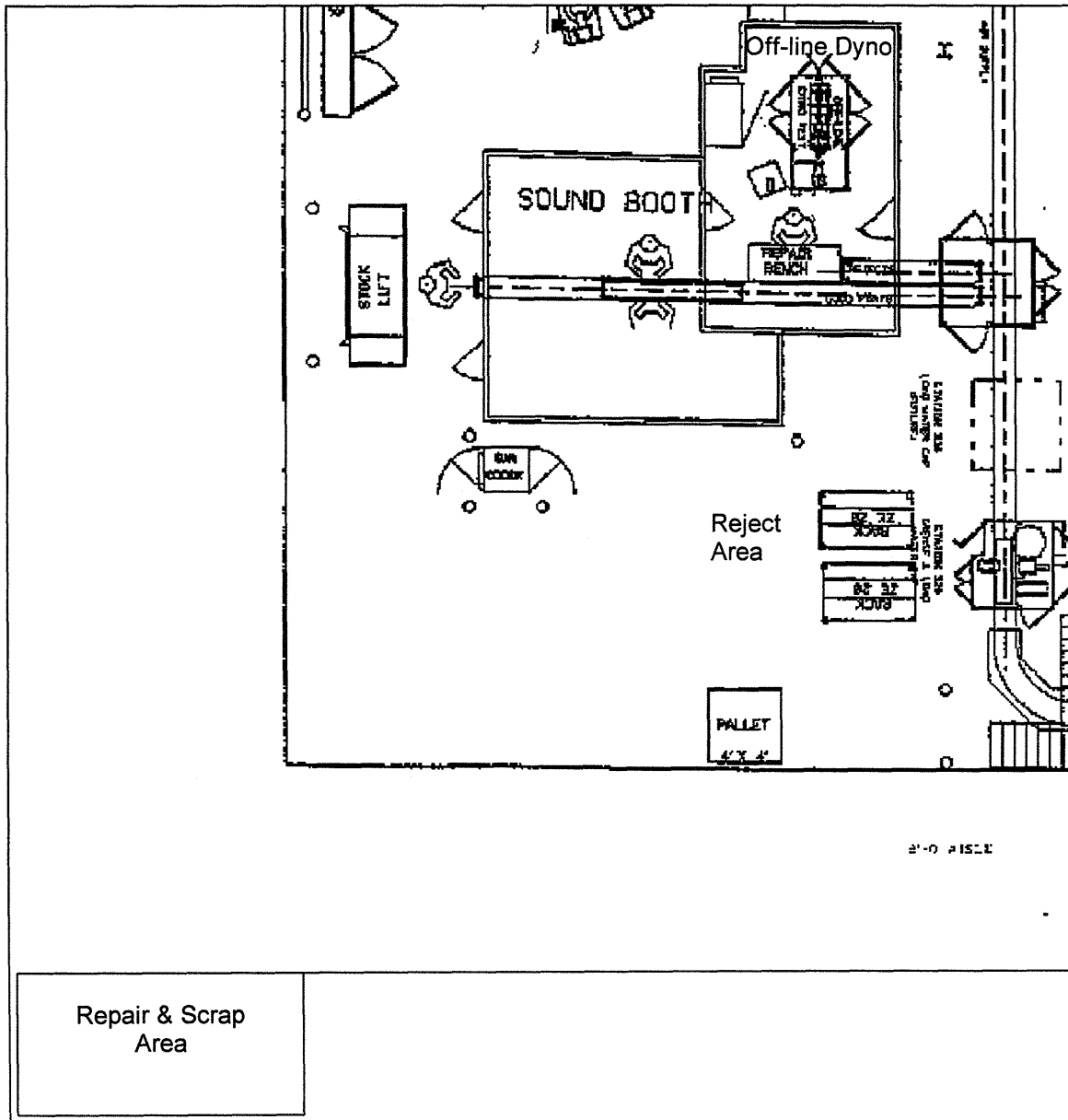


Figure 4 - Retest and Reject Area

Defective motors are manually transported to the repair area to be evaluated by the teardown operator. There is generally a large inventory of rejected motors awaiting disposition. The teardown operator connects the motor to a power supply to observe the motor in operation (or lack thereof), and determines a probable defect cause. This determination is made based upon the observation of the motor, the defect code, the recent history of past defects, and most importantly the operator's experience. The motor is then disassembled, and the defect cause is verified or corrected. The cause is recorded on a tally sheet, and the motor is scrapped or set aside for repair (few defects are repairable). The operator then moves on to the next motor.

Motors which have unusual noise or vibration characteristics accumulate in the corner of the sound room. The teardown operator periodically (usually twice per day) retrieves these motors and transports them to an evaluation booth which he shares with a teardown operator in another area. A transport vehicle is required since there are usually around 100 motors in each batch and the evaluation booth is 300 feet from the sound room. The teardown operator evaluates each motor by repeating the noise/vibration test, but for a longer period of time. The evaluation generally takes between 45 and 120 seconds per motor. Based on the operator's experience and the results of the evaluation, he sorts the motors into "acceptable" and "unacceptable". Acceptable motors are transported back to the final assembly area, and are available for shipment (a model changeover has usually occurred, so the motors are stored until the next time that particular model is run). The unacceptable motors are transported back to the repair area, where they join the performance defect motors. The cause of the defect is determined (if possible) and tallied on the scrap sheet.

## **2.5 Organization and Information Flow**

The physical layout, process characteristics, inventory levels, and organizational structure present some boundaries to the flow of information both within and between processes. As shown in Figure 2 and Figure 4, there are consecutive operations within processes that are separated by large distances. There are also physical barriers, such

as satellite assembly lines, located between operators that are in close proximity to each other. Additionally, noise levels are sufficiently high that verbal communication requires the parties to be standing next to each other. Therefore, communication with other operators either upstream or downstream requires some significant physical effort.

Since the process is highly automated and high volume (700 parts per hour), no one sees every part being processed at any operation. That is, each operator generally has responsibility for several machines which are each processing parts simultaneously at cycle times in the order of 4 seconds. The operator, therefore, only catches a defect if a machine points it out. Machines only detect defects if someone has programmed them to look for specific characteristics. These are generally missing parts, or no-build situations. Additionally, due to the product design and the performance requirements, many defects can only be detected after the assembly is completed and tested. This provides less than perfect information that is usually delayed a significant amount of time. This time delay increases rapidly with the inventory levels, the length of the process, and the frequency of model runs.

The organization of the operators and departments within the plant also provides some barriers to information flow. Although the operators on the final line are all part of one workteam, the operators on the satellite processes are members of a different workteam. The casting operation is in a completely separate production area, and is almost viewed as an outside supplier. Therefore, communication between these areas usually only happens when there is a no-build situation or when there is a part shortage. Although final assembly operators generally know what the day's production count is, scrap data<sup>4</sup> generally only flows upwards in the reporting hierarchy. Satellite processes are run as separate departments with little information exchange at the plant floor level. Once again, information from the satellite processes generally only flows upwards. Scrap information is aggregated on a weekly basis, and communicated to salary employees (including production supervision, engineers, and management) in a weekly scrap meeting held in the office area during production. If and when this information

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<sup>4</sup> Test reject information is collected automatically, but is not reported.

makes it to the operators, it has been aggregated and delayed to the point that it is not very useful for making improvements.

## **2.6 Status of System**

The performance of the system at the onset of the project is below desired and even acceptable levels. Although all customers have sufficient supply to continue their own manufacturing operations, it is not without cost to the Dansville plant. There is less than the desired level of finished goods inventory (therefore risking part shortage), and expedited shipments are not uncommon. High levels of overtime are required to meet demand, and the perceived stress and fatigue levels are high.

The area is also performing at much lower than desired quality levels. The reject rate from the automated performance testers averages 6%, but can run as high as 12%. The projected annual scrap cost for the area is \$1.6 million (10% above last year). There is an inventory of 6295 motors (31 days worth of rejects) awaiting repair or retesting. Because the system does not process these parts in a first-in-first-out (FIFO) fashion, the inventory consists of motors that were manufactured as much as 9 months prior.

The combination of the low quality, high costs, and trend toward outsourcing results in great pressure to improve performance. The structure of the supply chain, described above, increases this pressure as a growing number of the direct customers also manufacture competitive products. These companies would like to vertically integrate and use their own motors in the assemblies they supply to Acme, rather than the motor supplied by Acme's component division. The pressure is on the Dansville plant from all directions to reduce cost and improve quality.

### **3. Solution Technique**

This chapter discusses a method of driving quality improvement through the incorporation of feedback loops to operations upstream in the manufacturing process. Information regarding the quality of the output of the process is used to make adjustments or changes to operations within that process. This information needs to be both rapid and accurate, so that the correct changes can be made before the status of the system significantly changes. The lean manufacturing tool of process mapping is a method which can be used to increase the rate and accuracy of the information which is fed back. This detailed process map is then used to identify and reduce (or eliminate) waste and delays in the process, thereby increasing the accuracy and timeliness of the feedback.

#### **3.1 Quality Improvement**

Among virtually every manufacturer's goals for improvement is that of quality<sup>5</sup>. Those who are producing at very high quality levels see this as a competitive advantage, and strive to improve so that they maintain the edge over the competitors. Those who produce at lower quality levels strive for improvement to catch the leaders. Even manufacturers who have low cost strategies work to constantly improve quality, or risk losing their market to the increasing number of competitors. The goal of quality improvement, however, is but one of many goals for most manufacturers. Other improvement goals include those of increasing throughput, lowering cost, increasing service levels, etc. The problem is that these goals are perceived as being in conflict with each other. Most manufacturers think that increasing throughput will sacrifice quality (running a machine faster produces more scrap) and/or require capital expenditures (which increases cost). It is also generally thought that increasing quality costs money. While there certainly are cases in which these assertions are true, they are by no means universal truths.

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<sup>5</sup> Although "quality" can describe many things, it is used here to refer to the lack of defects.

Often times, incremental and even radical improvements in quality and throughput can be obtained without large capital expenditures or increased unit costs. In fact, simple low-cost improvements in a process can actually improve all three of these measurables. Additionally, while it may be true that running a milling machine at twice its designed speed may sacrifice the quality of the output, it is also true that an improvement in the quality of the parts processed may result in more dependable machines, and therefore increase throughput.

The process of manufacturing a high quality product extends through the product's entire life-cycle. The design of the product must not only focus on functionality and performance, but it must also be manufacturable. The design of the manufacturing process must not only consider yearly volumes and desired costs, but must also have the capability to produce quality parts. The operation of the equipment within the manufacturing process must also have a quality focus, so as to not deteriorate from obtained quality levels. The development of a high quality product, therefore, is very broad in scope and can be very costly. The incremental improvement in quality of an existing product, however, can take place after the product has been in production for even lengthy periods of time, and can be done with limited resources.

While vast financial resources are not generally required for defect reduction, capable people with available time are required. Capability here generally means technical competence and knowledge of the product and the manufacturing process. This technical competence and knowledge, combined with problem solving skills, results in the capability to make improvements. While many workers possess these attributes, what they generally do not possess is a great deal of time or the direction of what problems to fix. There are several methods to provide this direction (including Pareto analysis, root cause analysis, etc.), but all require information and data regarding the status of the system. If the system is a dynamic one (as most are), the information must be obtained and acted upon rapidly enough such that the status of the system has not radically changed. The methodology described in this chapter concentrates on

obtaining this information as quickly and accurately as possible, so that effective changes in the manufacturing process can be made to improve quality.

### 3.2 Feedback Loops

Feedback loops exist, in general, whenever output from a system is used to regulate the operation of the system. Although the physical output may be used for this purpose, it is more common that *information* about the physical output be used. This is not to say that the physical product cannot be used to relay this information in an effective and convincing matter, but that it is the information about the output that is important. In many manufacturing processes, it is not possible to reintroduce the physical product into upstream operations, and physical transport of the product may be impractical. Additionally, the information may not be observable on the physical product, or may change over time. Examples of this would be the hardness of a material, or the temperature of the product at the end of the process. The result is that most feedback is composed of information about the output, and display of the physical output is used only for explanation or clarification of this information.

The three general types of feedback are shown in Figure 5. The manufacturing process shown is a very simple one, consisting of three serial operations depicted by rectangles.

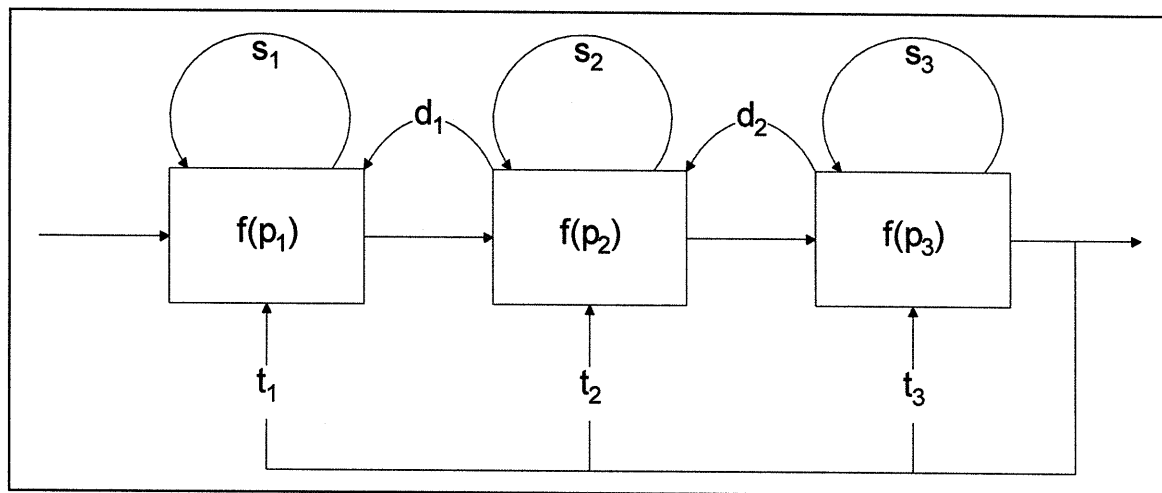


Figure 5 - Types of Feedback

The first type of feedback is depicted in the diagram by the loops labeled  $s_1$ ,  $s_2$ , and  $s_3$ . Each operation collects data pertaining to the operation being performed. This may be in the form of processing parameters (such as tool force required), or the result of inspections or checks being performed (such as determining if a component is present). This information is immediately fed back to the operation, and any problems are resolved. In the case of automated machinery, the part may be automatically rejected or the machine may stop processing and alert an operator. The operator may choose to reject the part or repeat the operation. In either case, the information regarding this defect should be used to make improvements in the operation<sup>6</sup>. This type of feedback will be referred to as “self” feedback.

The second type of feedback is depicted in the diagram by the loops labeled  $d_1$  and  $d_2$ . Each operation checks that the previous operation was performed correctly. This type of check is usually verification that a component is present, but can also include other types of inspections. Any problems are immediately communicated to the upstream operation. The part may also be transported to the upstream operation for re-processing, or may be rejected. As in self feedback, this may be accomplished through automation or by operator intervention. This type of feedback will be referred to as “downstream” feedback, or “buddy checks”.

The final type of feedback is depicted at the bottom of the diagram by loops labeled  $t_1$ ,  $t_2$ , and  $t_3$ . This type of feedback is the result of inspection at the end of a process (or part of a process). This inspection may be accomplished through performance testing, visual inspection, measurement, destructive testing, etc. Sampling or 100% inspection may be used (although 100% destructive testing probably is not a great inspection strategy). Information regarding the results of these inspections is fed back to the appropriate upstream operations. Since this type of feedback has inherent delays and often requires significant non-value added inspection, it is usually more desirable to use

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<sup>6</sup> If the defect was caused by something other than this operation, then this information should be used via “downstream” or “end-of-process” feedback to make improvements in upstream operations.

self and buddy checks. However, there are cases in which performance testing or final inspection are required to detect defects. In these cases, an effort should be made to minimize the delay of the feedback to upstream operations.

These three types of feedback can be used within very different types of processes, and are readily present in everyday life from the human control of muscles to a thermostat controlling room temperature to quality control of a manufacturing process. Whatever the process being controlled, feedback is used to provide information about the output of a process and the status of the process. This information may be used to verify intended operations (i.e. moving a hand or drilling a hole), to correct current problems (i.e. hand getting burned or a drill bit breaking), or to prevent future similar problems (i.e. placing a guard over the exposed heating element or monitoring drill torque). The method of obtaining this information to be fed back also varies, and is somewhat dependent on the type of process. Feedback to one's brain occurs within the nervous system, and requires little thought or planning. Feedback regarding the development of a product may result from customer surveys or sales information. Feedback within a manufacturing process may occur informally between machine operators, formally through periodic performance reports, or through any number of other methods. It is important to match the method of feedback to the needs of the system.

### **3.3 Rapid and Accurate Information**

Whether the type of feedback used is self, downstream, or end-of-process, the information must be relayed both rapidly and accurately. While it may seem obvious that the feedback needs to be accurate, it is an aspect which is often overlooked or taken for granted. Accurate quality feedback refers not only to correctly identifying a part as acceptable or defective, but also to classifying the defect, determining the proper operation for notification, and providing correct and relevant information for improvement of the operation. Accuracy may also include information regarding the trend of factors contributing to the defect and information about the timing of defect creation. These

aspects of the information can all be very important in determining the root cause of problems, and making changes which improve the process.

An equally important property of the feedback is the speed at which it is relayed. The time from processing to receiving feedback (also called lead time or delay time) has to be sufficiently small such that the status of the system has not significantly changed. This is especially important in a system which has dynamic properties. For example, if a particular machine has drifted slightly out of adjustment due any number of reasons (including temperature), then this information must be relayed rapidly enough so that the machine is in the same position so that adjustment corrects the problem. While a more desirable solution may be to eliminate the drift in the machine, this also requires the feedback of this information and may not always be possible (thus requiring this constant "control" type of feedback).

Rapid feedback is also very useful in root cause analysis and problem containment. Not only should the delay be short enough such that the system has not significantly changed, but also short enough so that information regarding the processing of the part still exists. Often times this information resides in individuals' memories. The most effective analysis and improvement will occur if the operator remembers the processing of the part or the status of the system at the time of the processing. It is much easier to determine the cause of a defect occurring 10 seconds ago vs. 10 hours vs. 10 days (or 2 parts vs. 5,000 parts vs. 50,000 parts ago). Additionally, in the case in which there is a recurring defect, the delay time is directly related to the number of additional defects. An example of this would be the use of an incorrect component due to model complexity (i.e. selecting the wrong brushcard or bearing). The lead time in detecting this defect and acting to correct the problem directly determines the total number of defects. A lengthy delay could cause several hours (or days) of lost production and have devastating effects on the supply chain.

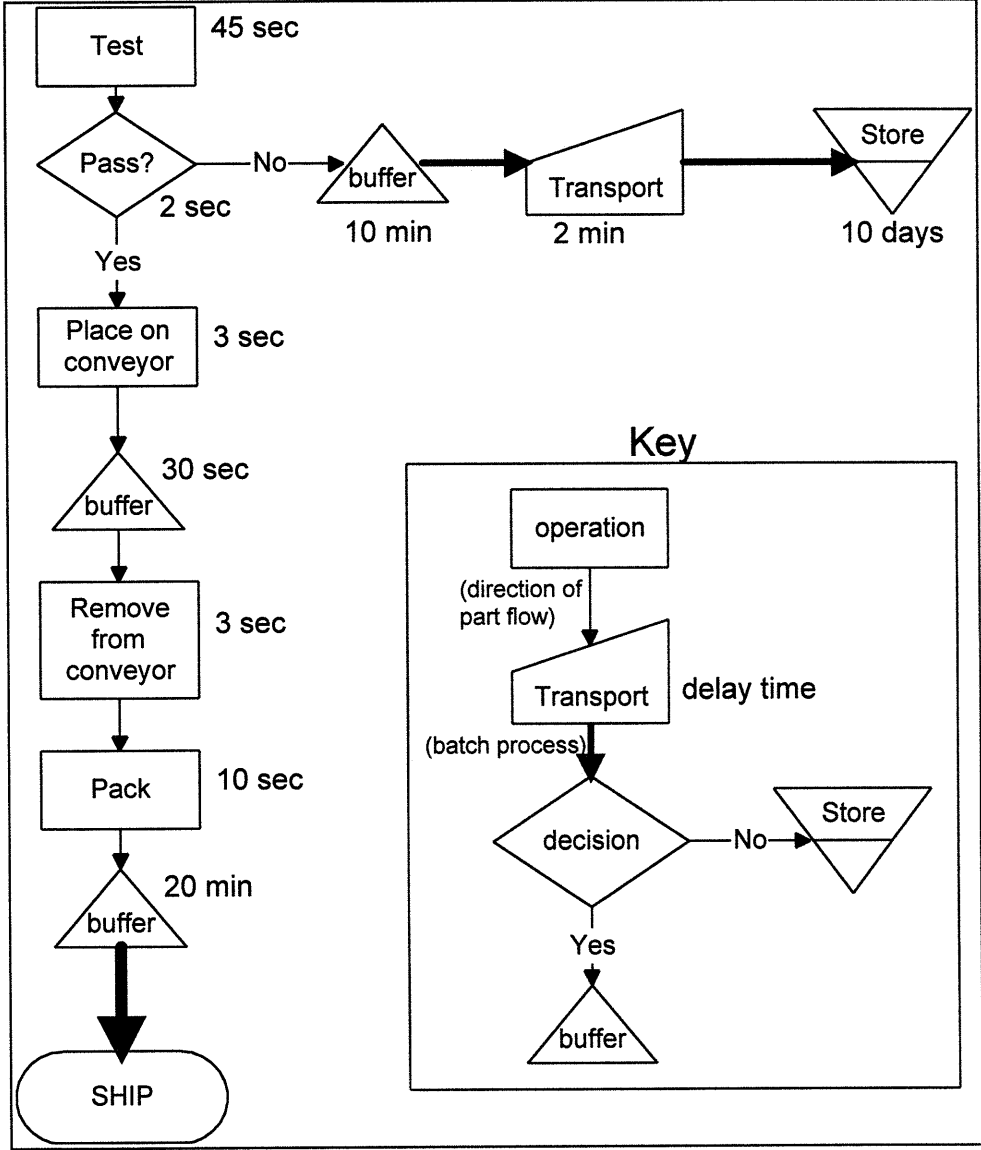
In general, rapid and accurate information is obtained by improving the process which creates and relays the information. This may include devising new types and methods of feedback (using more self and buddy checks), or improving existing operations or processes within the system (computerizing report generation or reorganizing the process). When using end-of-process feedback, the delay time can also be reduced by reducing the lead time of the part within the manufacturing process. Since one of the goals of lean manufacturing is to reduce lead time, lean tools and methodologies may be helpful in obtaining the rapid and accurate information needed for effective quality feedback.

### **3.4 Process Mapping**

The development and use of process maps can be very helpful in identifying opportunities for process (and operation) improvement. Additionally, a complicated or confusing process map may identify the *need* for process improvement. A process map is basically just what the name implies; it is a *map* of the *process* that is used to create a product. Process maps can be developed for various levels of abstraction from very high level operations (i.e. purchased parts enter the plant) to very detailed operations (i.e. the part is removed from the conveyor). One of the greatest challenges in developing a useful process map is selecting and consistently maintaining the appropriate level of abstraction.

While process maps in general show the operations required to complete a task, it can be very useful to include additional information. This may include the presence of large delays, points of inventory buildup, processing times, the presence of batch processing, etc. Additionally, special operations may be depicted with unique symbols for the purpose of highlighting or simply to improve readability of the map. These special operations may include decision points, transportation steps, or deviation from the normal flow. Unfortunately, universal standards do not exist for these symbols and keys are needed. While consistency in use and selection of symbols is generally desirable, the flexibility in selection may be beneficial in highlighting aspects of a particular process

(i.e. to show repetitive packing and unpacking of parts). An example of a manufacturing process map is shown in Figure 6.



**Figure 6 - Generic Manufacturing Process Map**

The process shown is a simple one in which parts are tested and either packed for shipment or stored for repair, depending on the result of the test. Rectangles are used to represent physical operations, which may or may not be value-added. The process begins at the top of the diagram with a normal operation labeled "Test". The average

processing time of 45 seconds is shown next to the rectangle representing this operation. A decision operation comes next and is represented by the diamond shape labeled "Pass?". Parts which did not pass the test are placed in an inventory buffer represented by the triangle. The average time spent in this buffer is shown to be 10 minutes. Parts are transported out of this buffer in batches, and are stored for an average of 10 days. This transport operation requires an average time of 2 minutes. Parts which pass the test operation are placed on a conveyor to be automatically transported to the packing area. Parts remain on the conveyor for an average of 30 seconds before they are removed and packed for shipment. Packed parts wait an average of 20 minutes before they are shipped in batches out of the area.

Development of process maps like the one shown above require (and contribute to) a good understanding of the process itself. Since process maps often span across several peoples' areas of expertise, it is unusual that a single person know in detail every step in the process. Therefore, the development of a process map usually requires the input of several individuals. A team oriented approach may not only expedite the development process, but may have additional benefits when improvement activities begin. The map itself is developed by following the product through the process and documenting what the product sees. If possible, it may be very useful to physically follow the parts as they flow through the actual process. As the part flows through the process, all operations and delays are represented (from the product's perspective) with the appropriate symbol. While it is quite probable that team members will identify opportunities for improvement during the process map development stage, these ideas should not yet be discussed as this may distract from and prolong the development process. These ideas should be retained for future reference, but the focus should remain on documenting the current process.

A completed process map is not only useful for identifying improvement opportunities, but it is also quite useful as a communication tool. Team members will have a common frame of reference (on a piece of paper) that can be used to communicate ideas or concerns. Since a common reference is provided, confusion about terminology or

practices is greatly reduced. However, the big payoff comes when the map is used to identify opportunities for improvement.

### **3.5 Waste & Delay Reduction**

In general, processes are improved by reducing the overall waste and delay associated with the process. Waste is defined as any operation or part of an operation which does not contribute to the goal of the process. Readily apparent examples of waste include the movement of material (unless that is the goal) and repetitive handling of the same part. The delay in a process refers to the total time a part spends in the process, or the lead time. In the case of quality feedback, the delay of the process generating defect information must be minimized. Large inventory buffers and batch processing greatly increase total process delay times. The reduction of waste and delays has the effect of streamlining the process and accomplishing the goal more efficiently.

Waste and delays can be identified through the use (and development) of process maps. The purpose or goal of the process which has been mapped must first be determined and clearly stated. Any operation shown in the process map which does not contribute to the goal is waste. Proposed changes which eliminate specific wasteful operations (and therefore change the process) are generally more powerful than changes which improve specific operations. The general approach is to identify the operations which are most wasteful, and brainstorm process changes which eliminate these wasteful operations. Incorporation of feasible changes in the process map should result in a simplified and more efficient process map. This map (or the original) is then used to evaluate the effect of additional ideas for improvement.

Large delays are often the result of inventory buffers and batch processing. Since unnecessary operations contribute greatly to process delays, the delay reduction process should follow waste reduction. The next step should be to identify remaining operations (or buffers) with the greatest delays. Significant reduction in lead times could easily be achieved through the elimination of buffers and the incorporation of single

piece flow. However, other system performance metrics such as throughput must be considered. Reduction of inventory levels or batch sizes below a certain level may have devastating effects on the system's performance. While there are generally large opportunities for delay reduction in this area, additional analysis or changes may be necessary. For example, the reduction of inventory levels may require a preventive maintenance program to increase the reliability of the equipment, so that system performance is not affected. The reduction in batch size may require a significant improvement in changeover times. These factors must be considered before implementing changes, or failure is quite possible.

Once the process of waste and delay identification and proposed reduction is complete, several viable options may exist. Selection of the appropriate course of action should include not only the development of new process maps and analysis of their respective benefits, but also an analysis of the time and cost required for implementation. It is also quite possible that the changes be implemented in stages, so that significant benefits can be quickly realized.

## **4. Implementation and Results**

This chapter discusses the implementation of the approach described in Chapter 3 to a component's manufacturing and assembly process described in Chapter 2. Defect information is fed to upstream operations from the Retest/Repair/Scrap area. A process map of this area is developed, and the process is streamlined through the reduction of waste and delays. The physical and operational changes made are presented, along with the resulting process map. Numerical and cultural results complete the chapter.

### **4.1 Feedback Used**

The type of feedback used in the implementation of this approach is mainly that of end-of-process or final inspection feedback. Defects are detected and the relevant information is generated in the Retest/Repair/Scrap Process. The goal of the feedback is to effectively and quickly communicate the existence of defects to upstream operations. Additionally, this information is to be available to engineers working on specific projects or recurring defect causes. The information can be very useful to them in determining current problems, providing direction of efforts, and to evaluate past changes. Communication to upstream processes takes place face-to-face between relevant operators, with the future possibility of more sophisticated channels (such as through machine controller interfaces). Communication to engineers or managers involved in specific projects continues to take place via daily and weekly reports (engineers can also check the tally sheet at any point in time for current information). The primary change in these reports is the content, which includes much more timely and accurate information due to the delay reduction. Everyone involved has access to information regarding the current status of the system.

Although the type of feedback chosen generally has the greatest inherent delays, there are several reasons for its selection. The first is that the process is completely decoupled from the assembly and manufacturing process. There is essentially an infinite buffer between the automated product testing and the Retest/Repair/Scrap

Process, and changes can be made in the area with no fear of disrupting the throughput-sensitive assembly operations. This is quite important in that it greatly reduces the risk associated with the changes, and allows for relatively rapid implementation. Scheduling changes to be implemented in the assembly process may take months.

Secondly, the product design and assembly operations make it very difficult to detect defects before the motor is completed. Many of the defects occur during assembly, and are internal to the motor. An example of this is the scoring of a bearing during the assembly. Inspection of the bearing requires disassembly of the motor, which destroys the value of assembly. Measurement of the insertion force required may provide an in-process self check of the bearing's condition (scoring the bearing should require greater forces), but has not been successful in past trials. The defect shows itself through excessive noise and vibration when power is applied. However, this detection method requires that the motor be fully assembled and tested.

The third reason for using the final inspection type of feedback is that all defective parts flow through this area. The significance of this is that effective feedback from this area should reduce defects of all kinds, not just those currently known or targeted.

Establishment of self and buddy checks generally require tests to be developed to screen for specific defects. A different test is required to detect each known defect. This would not only miss unknown defects, but would also consume significant time and resources during development. Feedback from the end of the process requires establishing only one type of feedback, and is flexible enough to identify future types of defects. In some ways, it is more able to learn and react to dynamic situations.

The final reason for choosing this type of feedback is the simple fact that it already exists, but in an inefficient form. Improvement of the existing process is not as radical of a change as redesigning the whole system. This reduces the overall risk to those involved, and can be accomplished in a shorter time period. Additionally, having a

familiar and common starting point reduces difficulties in communication of ideas. Change in an existing process also makes it easier to leverage off of these changes, and spread the results and learnings into other areas.

## 4.2 Process Map

The process map shown in Figure 7 traces the flow of a product from the automated performance testing (labeled “dyno test” in top left corner) through retesting, noise and vibration testing, repair, and scrap to shipment out of the area (bottom left corner).

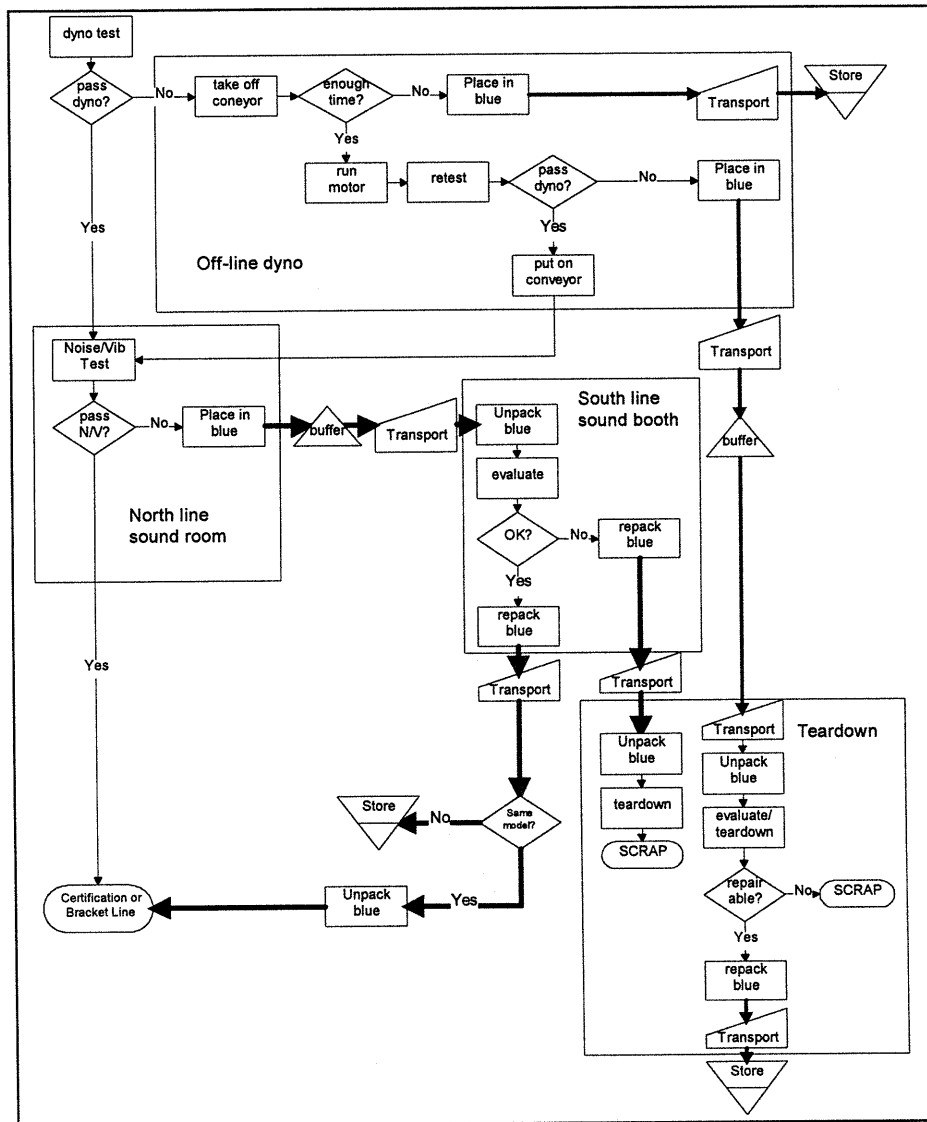


Figure 7 - Retest/Repair/Scrap Process Map

This is the process in which performance and noise/vibration rejects are discovered, defects are detected, and defect causes are determined. This section of the overall process was selected for detailed analysis because it contributes to more than 98% of the time from occurrence of assembly defect to detection.

There are several important attributes of the process map shown in Figure 7. The first is the level of complexity. There are 41 steps in the process, with intertwined loops and several decision points. The second is the existence of “Store” operations, or dead-ends within the process. Parts which proceed down these paths remain there indefinitely, as there is no clearly defined or consistent process in place. Parts generally pile up at these locations until an individual takes special action to clear them out. The third important attribute of the process map is the existence of several buffers. This is a location in which parts accumulate, but do not leave the normal flow of the process. The fourth is the existence of batch processing, denoted with thick arrows between operations. The batch processing surrounds transportation operations, and is used to reduce operator time spent moving parts between locations. The final important attribute of the map is the existence of the four boxed sections. These sections represent four different physical areas of the plant. However, the relative size and proximity of the areas is not shown to scale. The “Off-line dyno” area and the “North line sound room” are separated by only a wall. The “teardown” area is located approximately 40 feet from the “North line sound room”, and the “South line sound booth” is approximately 300 feet from the other three areas. While this is not accurately portrayed in the process map, it is an important aspect of the process.

### **4.3 Waste & Delay Reduction**

The process map is used to identify and reduce or eliminate waste and delays in the process, thereby improving the process. The reduction or elimination of waste will not only make the process more efficient, but it will also improve the flow of parts through the process. This reduces lead time, and has the potential to make the system

performance less sporadic. The reduction or elimination of delays reduces the lead time through the process, and allows for more timely feedback.

In order to identify and reduce waste, one must define waste in the context at hand. It could easily be argued that the entire process shown in Figure 7 is non-value added. That is, nothing within the process adds any customer perceived value (other than screening out defective parts). This is not to say that everything in the process is waste. While it may not add customer perceived value, the process does serve an internal purpose. That purpose is to determine which parts are acceptable (testing), to recover some of the value of those that are not (repair), and to determine the cause of the defect in those that are not acceptable (defect detection and classification). Any use of resources that does not contribute to these objectives is waste.

A noticeable and rather large waste found in the process is the physical transport of parts from one area to another. The largest of these is the transport of large batches of parts to and from the "South line sound booth", as it is located some 300 feet from the other operations. Since 7 of the 41 operations are significant transport steps, reorganization of the physical layout may result in significant waste reduction. This may also allow for a reduction in batch size, reducing the delay time. Another apparent waste is the packing and unpacking of parts before and after each transport step. Perhaps the reorganization of the area may also allow a method of transport that does not require the packing and unpacking of parts.

Substantial delays exist in the process as a result of the dead ends, buffers, and batch processing. The "Storage" steps (dead ends in the process) not only introduce significant delays in the process, but also decrease the accuracy of the information obtained. When there is a net inflow into these areas (which there normally is), the reported scrap and defect rates are lower than the actual rates. When these parts are specially processed days, weeks, or months later, the reported scrap rate is inaccurately high. This results in large spikes whenever inventory is cleared out. Scheduling

problems are also incurred, as there can be a significant amount of uncounted inventory. This inventory has not yet reached the count point (final packing or scrap), but also is not available for processing into new motors. The model mix, status, and amount of this inventory is not tracked, and special processing is required for each part. Additionally, since there is such a large delay in processing these parts, and they are not processed in a first-in-first-out (FIFO) manner, the defect and scrap information is of little practical use for improvement or even quality tracking purposes.

Buffers in the process also create delays. These buffers exist mainly for the purpose of accumulating a sufficiently large batch of parts to be transported to other areas. This process is slightly different than most in that the goal is not to maximize throughput, but is simply to quickly and accurately process whatever parts are rejected from the assembly line. The ultimate goal is to reduce the number of defects (through quality improvement), and therefore significantly *reduce* the throughput through this area. While the buffers do serve to decouple the operations within this process, the most effective operation of the system would have no buffers so that delays were minimized. Again, the reorganization of the physical layout may significantly reduce the batch sizes (and therefore buffer sizes) required.

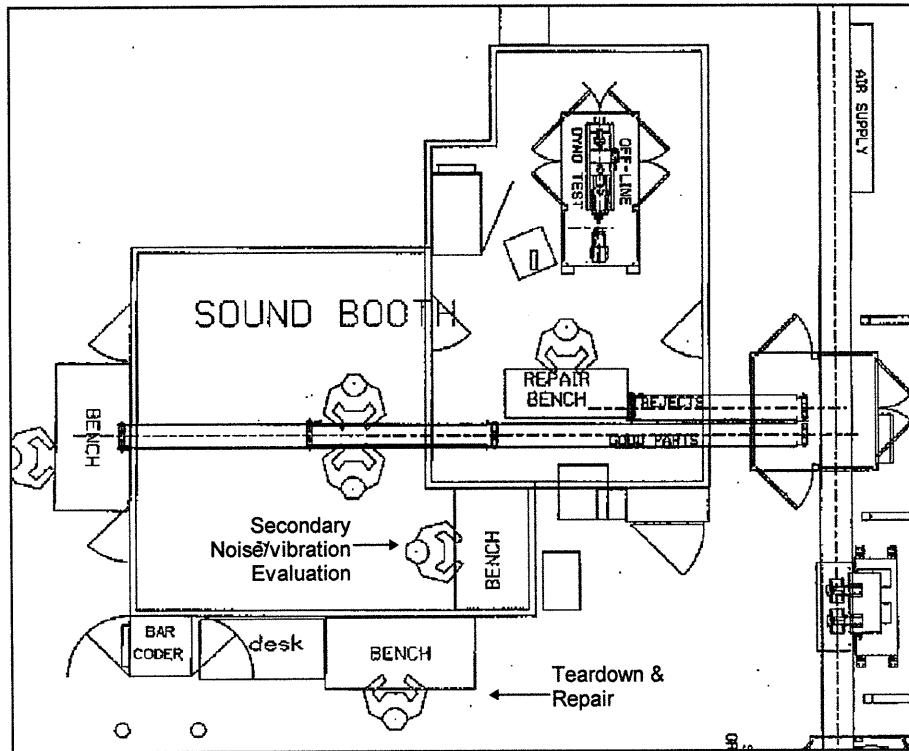
#### **4.4 Changes Made**

Both physical and operational changes were made to reduce waste and delays in the process, so that rapid and accurate quality feedback to upstream operations could be accomplished. Two physical changes were made involving the relocation of operations. Operational changes were made in the methods of part transport, batch processing, and part storage.

Since there were large wastes identified in the transport of parts between areas, and the potential for other improvements was identified, a reorganization of the areas within the process was examined. Ideally, the required operations within the process would all be conducted in a single area. However, the noise/vibration test and secondary evaluation

must be conducted in a quiet environment, separate from some of the other operations which can generate considerable noise. The next best solution is to group compatible operations, and place these groups as close as possible to each other. The groupings should be physically close so that transport steps are minimized, and there should be an effective means of communication between these groups.

The solution implemented was chosen from several options as being the most cost effective. This solution managed to maintain simplicity and ease of implementation, without greatly sacrificing effectiveness. The reorganization involved moving the essential operations performed in both the "South line sound booth" and the "Teardown area". The secondary noise/vibration evaluation was moved to a corner of the "North line sound booth" and the surrounding wasteful operations were eliminated. This move required clearing out the area to be used, acquiring a small table for a work area, and providing a power supply to operate the motors. The "Teardown area" was relocated to an area adjacent to the "North line sound room" and "Off-line dyno", and required only the clearing of the area, movement of the workbench, and connection to the plant air supply. The presence of a window in the sound booth provided an effective means of communication between the areas. These physical layout changes are shown in Figure 8.



**Figure 8 - Physical Layout Changes**

These physical changes succeeded in eliminating several of the wasteful operations in the process, and allow some operational changes to be implemented. However, the transport of parts to the “Teardown area” is still required. Since the distance has been greatly reduced, the time required has also been reduced and there is less waste. In fact, these transport operations are small enough to allow single-piece flow between the operations, which greatly reduces the delay times associated with batch processing. Additionally, intermediate buffers have been eliminated, freeing up floor space and further reducing lead time.

The final operational change made was to eliminate the dead-ends or storage points in the process. One of these was eliminated by radically reducing the delay caused by the secondary noise/vibration evaluation. In the past, parts had been stored because model changeover usually occurred before the batch was processed and returned for packing. With the new process, parts are processed almost immediately, eliminating the

possibility of a model changeover problem. The remaining two “Storage” operations were eliminated through a combination of eliminating the changeover problem, freeing up operator time, and providing an outlet for these parts to re-enter the process. The resulting process map for the area is shown in Figure 9.

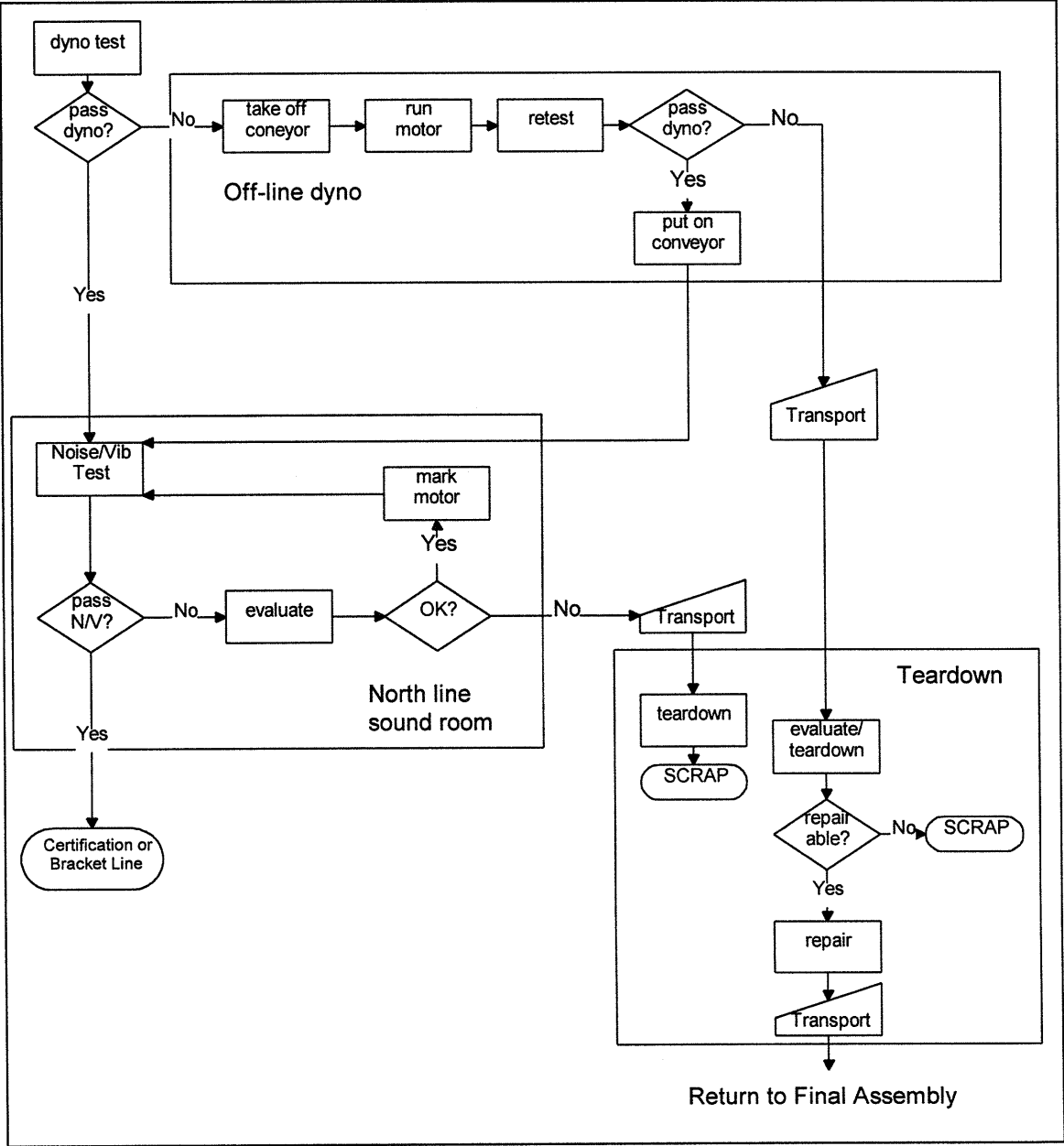


Figure 9 - Improved Process Map

Several differences can be seen when comparing the new process map shown in Figure 9 to the old process map shown in Figure 7. The process is less complex, and 41 steps have been reduced to 22. Buffers and dead ends have been eliminated. The four areas have been reduced to three. Single-piece flow and FIFO have been achieved throughout the process.

## **4.5 Results**

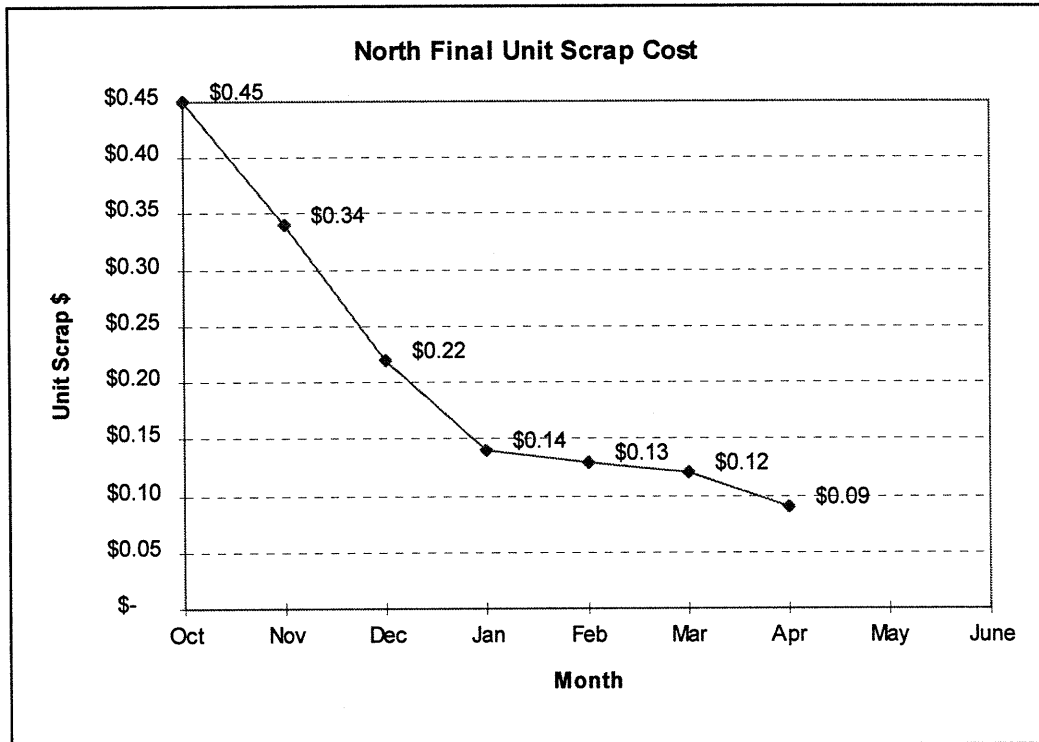
Results of the implementation of this approach should be examined from three perspectives. The first is the measurable effect of process improvements in the Retest/Repair/Scrap Process. The second is a more qualitative look at the cultural results of the changes. The final perspective is that of the effect of these tools on the end goal of quality improvement.

The changes described above significantly affected performance measures of the Retest/Repair/Scrap Process. Lead time through the process has been drastically reduced (by at least 95%), resulting in a decrease in average time from occurrence to detection of approximately 90%. Inventory in the area was reduced by 95% in four weeks (the remaining 5% of inventory consisted of very infrequent model runs, and would be purged at the next model run). The space used by the operations and inventory was immediately reduced by approximately 50%. The elimination of waste has resulted in a noticeable decrease in the effort required to perform the necessary operations.

The qualitative aspects of the changes include those of the operator's job satisfaction and the work team's attitude. Because of the elimination of the overwhelming inventory awaiting processing and the elimination of wasteful operations, the operator's observed stress level has significantly decreased. The operator also has a greater job scope which includes performing repairs, operating two assembly machines, and most importantly, the root cause analysis of problems as they are discovered. The operator welcomed these changes, and seemed to feel as though he had a greater impact on the

overall system. The operator noted that the most significant change from his perspective was the change in the workteam's attitude toward him. In the past, he had felt like he was not part of the workteam. In fact, there were discussions in team meetings that he should not be included in the headcount of the team, as he really is not part of the operation of the team. However, after the changes were made, the operator had time to get more involved in problem solving with the team. This resulted in a more cooperative relationship, rather than that of policing for defects. The operator had more contact with the daily operations of the workteam, and became more integrated into the team. This is something that was important to the operator and his job satisfaction. Contact with upstream operators was not limited to those in the final assembly workteam. The operator increased contact with sub-assembly personnel, and was able to follow up on a problem originating in die casting. This is significant in that die casting is located in a completely separate manufacturing area of the plant, and has a relationship much like that of an outside supplier to the assembly operation.

The final examination of results is the effect of this approach on quality improvement. The use of feedback loops to drive quality improvement should have the effect of continually reducing the defects and scrap produced by the system. The elimination of delays and waste in the feedback mechanism should provide information that is both timely and accurate enough to provide direction for this improvement. However, since this method relies on information that is gathered at the end of a series of operations, complete elimination of defects and scrap is not expected. There is some threshold level of quality that would require the use of "self" or "buddy" checks to surpass. The actual results of the implementation are shown in Figure 10.



**Figure 10 - Results of Implementation**

The graph shows the unit scrap cost (cost of scrap divided by output volume), by month. Although accurate monthly information for the time period before October does not exist, the average unit scrap cost was approximately \$0.50. Implementation of the changes described was completed in mid-November. As can be see in Figure 10, a continual decrease in the unit scrap cost has been achieved. A decrease of 50% was observed in only 4 weeks, and an 80% decrease has been accomplished to date.

## **5. Conclusions and recommendations**

This chapter presents conclusions drawn from the methodology, implementation, and results presented in the previous chapters. The combination of feedback and lean manufacturing tools can be very effective in improving quality. General recommendations are made to Acme Motor Company, and specific recommendations are made for further improvement of the system studied.

### **5.1 Conclusions**

Several conclusions can be drawn from the approach, implementation, and results presented. The first is that the combination of feedback loops and lean manufacturing tools can be quite effective in driving quality improvement. Secondly, quality improvement can be accomplished without large capital expenditures. Rapid and accurate feedback is essential to making effective improvements. Process mapping can be very useful in identifying waste and delays in a process, even if the process itself is non-value added from a customer's perspective. Finally, change can be a very good thing.

The example implementation has shown that using lean manufacturing tools within a non-value added process to provide feedback to the manufacturing process can be quite effective in improving quality levels. The informational feedback loops are essential to making these improvements, and process mapping is a useful tool in improving the process by which this information is obtained. Used separately, these tools can have significant benefits. However, in the system examined, using quality feedback without streamlining the process would have little benefit. Additionally, streamlining the process without using the information to make improvements would only have the benefits of reduced inventory, lead time, floor space, and operator effort. Quality levels would not be affected without cooperative efforts to make improvements.

Significant quality improvement can be accomplished without large capital expenditures. The approach described does not require large (or even any) monetary investments. The changes made in the system studied required only the physical relocation of some operations and some operational changes. A few man-hours (and some persistence) is all that was required to accomplish these changes. Further improvement may require some investment in the area of material handling, and other solutions may require capital expenditures. However, this is not a property of the approach, as has been demonstrated in the example implementation.

The ability to make any effective improvement requires timely and accurate information. This information is first required to determine that an improvement is needed. Additional information is required to determine a course of action. This information must be accurate, otherwise the solution may exacerbate the problem. Finally, the information must be obtained in a timely enough manner such that the status of the system has not radically changed, otherwise the solution may not be effective.

Process mapping can be very useful in understanding the operation of a system, as well as identifying opportunities for improvement. By identifying the goal or objective of a process, and having the operations documented in detail, high potential areas can be more easily identified. Eliminating operations that do not contribute to the objective of the process results in waste reduction and process simplification. When used to provide feedback to upstream operations, process simplification can also reduce the delays and increase the accuracy of information that is fed-back.

Finally, change can have positive effects for all involved. Not only did the changes improve the system's performance dramatically, but there was also a positive effect on the culture. The operator most affected by the changes was part of the change process, and has derived a significant increase in job satisfaction. The operator has become more integrated with the workteam, and has a greater job scope including making

tangible improvements. These changes were welcomed, and seem to have had a positive effect on his overall well-being.

## **5.2 Recommendations**

The two types of recommendations that can be made are general recommendations to Acme Motor Company and more specific recommendations for the manufacturing system studied at the Dansville plant. The general recommendations to Acme involve the use of feedback and lean manufacturing to improve the quality and performance of various processes. Recommendations to the Dansville plant not only include spreading the use of this methodology, but also include recommendations for further improvement of the system studied.

In general, Acme Motor Company should attempt to use this approach (or variations of this approach) in similar manufacturing systems, in general manufacturing systems, and within any general type of process in which the quality of the output is important. The approach should be directly transferable to similar manufacturing systems, and may require slight customization for dissimilar systems. The general approach of providing feedback about the quality of output and streamlining the process which generates this feedback should be effective across a broad range of manufacturing and non-manufacturing processes.

The Dansville plant should also spread the use of this approach, leveraging off of the changes already made. Simply transferring the approach and the lessons learned to similar manufacturing areas should provide similar results. This could most effectively be done in areas that are near the line studied, where participants would be able to observe the benefits of the approach.

Several things should be done to both maintain the benefits derived and to further improve performance. The first is to develop detailed process maps for the rest of the

manufacturing process, and identify opportunities for improvement in these areas. Specific areas of opportunity may include housing processing (from casting to final assembly), armature material handling, and the changeover of the final assembly line. An increase in the amount of feedback to satellite processes (from both the end of their respective processes and from the final assembly line) could result in defect reduction similar to that in final assembly. The development and use of additional in-process checks could further increase the rate and quality of feedback in the assembly process. This could take the form of the development of self or buddy checks (which have very short delays) or communication of data already collected. Examples would be the measurement of insertion force to detect scored bearings, or the use and communication of reject data from the dynamometers, respectively. The monitoring of performance reject data (perhaps through SPC) could provide a great deal of information about the trend of critical upstream processes. This information is already automatically collected, and is obtained after very short delays in the process.

The improved Retest/Repair/Scrap Process still includes some waste and delays, particularly in the transport of material between operations. Further improvement in the process may address this by providing more efficient means of part transport (i.e. conveyors or further refinement of the physical layout). Finally, to insure that the derived benefits are maintained, attention should be paid to the Retest/Repair/Scrap Process. In particular, this process (and the operators within) should be treated as essential to the manufacturing system. These operators should not be pulled to perform other operations, as the buildup of inventories and delays will result. Additionally, these operations serve as a check against recurring defects (such as incorrect component usage), and serve to minimize the effect of such an error.

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