To be or not to be (before reflow): That is the question (in AOI)

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Abstract
Rarely do PCB manufacturers have the resources for purchasing an inspection machine for every stage of the manufacturing process. Typically, therefore, they have to decide whether to deploy AOI prior to the reflow oven ("in-process") or after it ("end of line"). An argument can be made for both cases. On the one hand, a high-performing post-reflow AOI machine has the capability of inspecting all fault types (solder related faults and component level faults) at the end of the line. At this point all boards can be manually fixed and some coarse level, time-delayed information can be fed back to the in-process side. On the other hand, one pays the price for finding faults at such a late stage in the process. By the time the fault has been found, multiple boards have been built - all possibly with the same faults. Thus, the in-process side of the house would suggest that AOI be moved back into the process to find faults as the boards are actually being built. Faults can be fixed immediately and process information can be fed back in a timely manner to stop faults from occurring and to prevent further faults. The theoretical economic argument is strong that earlier detection leads to reduced re-work and scrap which increases the profit margin. The in-process argument suggests that if the paste is correctly applied and the parts are correctly placed, then any solder related defects will be small if not non-existent at the end of the line. The end of line camp counters that some defects will be created by the oven and, thus, will be missed by in-process inspection. This debate of whether to deploy pre-reflow vs. post-reflow can only be settled by real empirical data. In this paper we present the results of a study at a manufacturing site in the US which contrasts using post-place inspection to find and correct defects and also to perform process control vs. using a post-reflow inspection system to find defects at the end of the line. We will quantify and contrast the benefits and drawbacks of each type of inspection alone and will also discuss any synergies between the two inspection strategies.

Automated Inspection

The argument over whether or not automated inspection is necessary in the electronics assembly line has yielded to technology advancement. High density circuit layouts, shrinking component geometries, the cost of rework and retest combined with ever thinner profit margins changes the question to, ”Where should I deploy automated inspection?”.

There are several places in an electronics assembly line where automated inspection technologies can be deployed. Automated inspection at key process points can give important real-time and historical objective and quantitative feedback of process indicators, manufacturing and material defects and process capability. All agree that the closer to the defect generation it is detected, the cheaper the repair. The cost, in fact grows by a factor of 10. If a defective print costs a penny, then post placement rework is a dime and post reflow repair is a dollar. Test failures can cost as much as the material cost of the product and all the labor! Field failures are the most expensive in terms of real costs and reputation.

In spite of this, manufacturers often deploy automated inspection at a single point in the process. Management knows only that inspection equipment is a cost. Inspection equipment does not add value, since it is not required to produce the product. This may seem short sighted, but it is a valid thought. If all of the manpower, methods, materials, and machines did their job properly than the product should be perfect. Unfortunately, we live in the real world. The best most manufacturers hope for is that they can get a dramatic improvement in quality by deploying a single inspection technology in a single place. Deciding where requires a thorough analysis of the process current defect pareto and extrapolating the effect of inspection technology in the line.

Since, return on investment calculations are not based upon intellectual conjecture it is important to look at the real defect data from the line in question.

Post-Paste Inspection

While the topic of this paper is really around post-place vs. post-reflow, a word about post-paste is required. It has been conjectured that 80% of defects can be traced back to paste print errors. And while this may or may not be true, it is true that paste inspection alone will not prevent most defects.

Until recently, inspection of pasted boards has mostly been performed by manual visual methods or on a periodic sample basis. This has been sufficient for most SMT manufacturing processes. Solder printing is almost always performed automatically, using stainless steel stencils in direct contact with the PCB. Paste is rolled into the stencil apertures using steel blades at 05. to 2.0 inches per second. So paste print quality and paste height is well controlled.

Random defects occur when paste is not released from the stencil. This is most often due to improper aperture design or apertures becoming blocked by dry paste. Random deposit issues can also occur when paste is not replenished often enough or dispensed across the entire board area. Defects also occur as a result of setup errors, support errors and as a result of temperature and humidity fluctuations.

Inline automated 2-D inspection is offered as an option on most high end solder print systems. And although it has a negative impact on cycle time it is generally sufficient to detect systematic errors. However, it is not fast enough to inspect every paste brick on every board. So the value of the inspection is limited and is usually applied to well known potentially defective print apertures.

Stand-alone and inline 2-D and 3-D inspection systems are also available. These systems can inspect the entire print without affecting cycle time. They are especially useful for high reliability products, high volume production environments and for stencils with very small apertures. They are also useful also for high volume production lines where defects can add up quickly.

But in all cases, paste print inspection is a Go/No Go process. Defective solder prints are washed from boards and the boards can be reprinted. The cost of rework is fairly low and the impact of poor solder paste prints on the future operations is avoidable. Solder paste print inspection is a predictor of future process errors including low solder or excess solder, no solder, tombstoned components and even missing parts. However, we believe it is not a substitution for post placement or post reflow inspection.

Post-Place vs. Post-Reflow Inspection: Where do the majority of the defects come from?

If we eliminate the paste deposition process as the major contributor to defects, we must now look at the placement process and the reflow process. Certainly it is well known that defects do occur. As previously described, these defects are often caught by one form of test or human inspection at the end of the line and in most cases repaired. However, as vendors of AOI equipment, we are often asked to describe what the optimal test strategy is for our customers. Customers from the in-process side of the house insist that an in-process test and measurement strategy provides optimal benefits. Customers from the test side of the house prefer an end of line test. The real answer needs to come from data which supports where the majority of the defects are occurring. In this paper we measured the defects both at post-place and post-reflow at a number of customer sites. We will report the Pareto of defects and discuss a set of experiments we did to see what were the strengths and weaknesses of each type of inspection.

Customer Defect Profiles

We looked at three types of customers. For each type of customer we inspected the boards using the Landrex Optima optical inspection systems. Figures 1-3 show defect paretos for these customers.

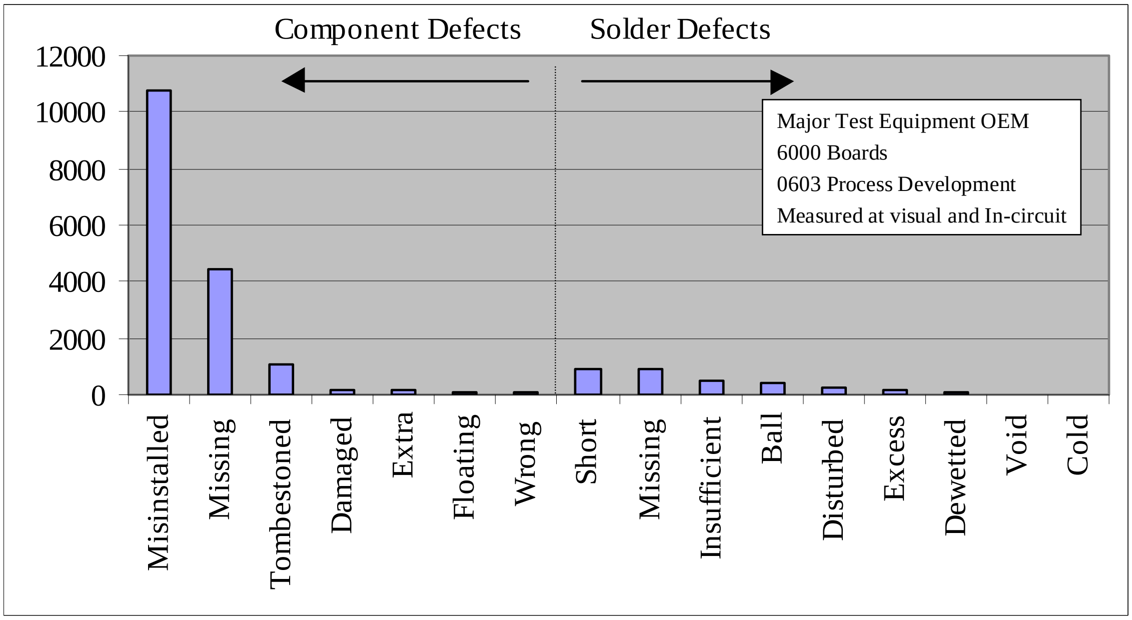


Figure 1: Defect spectrum from a high mix/low volume OEM

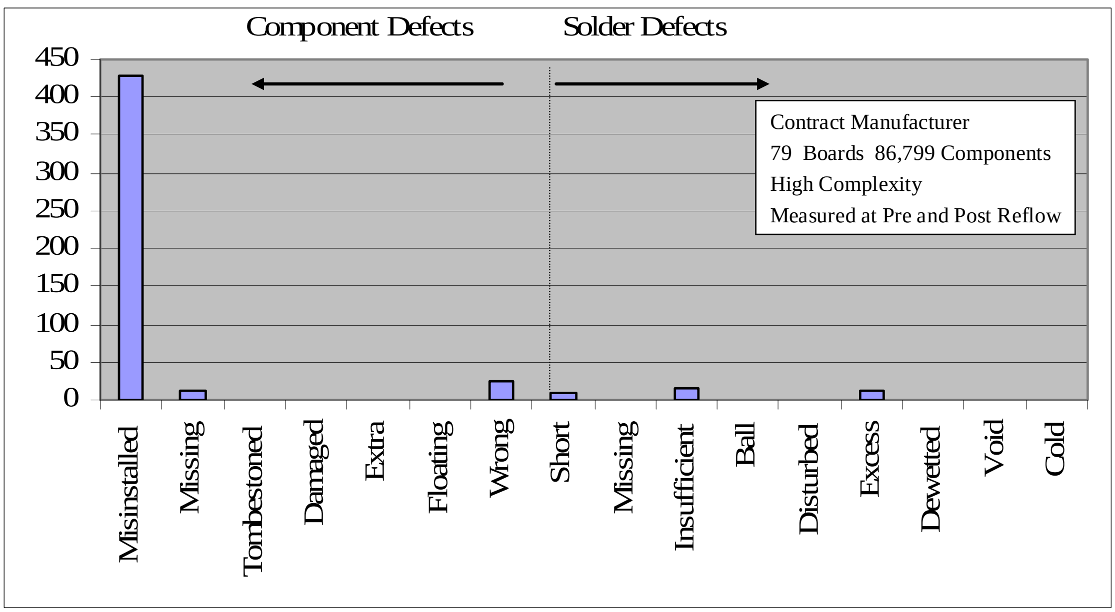


Figure 2: Defect spectrum from a low volume/high mix EMS

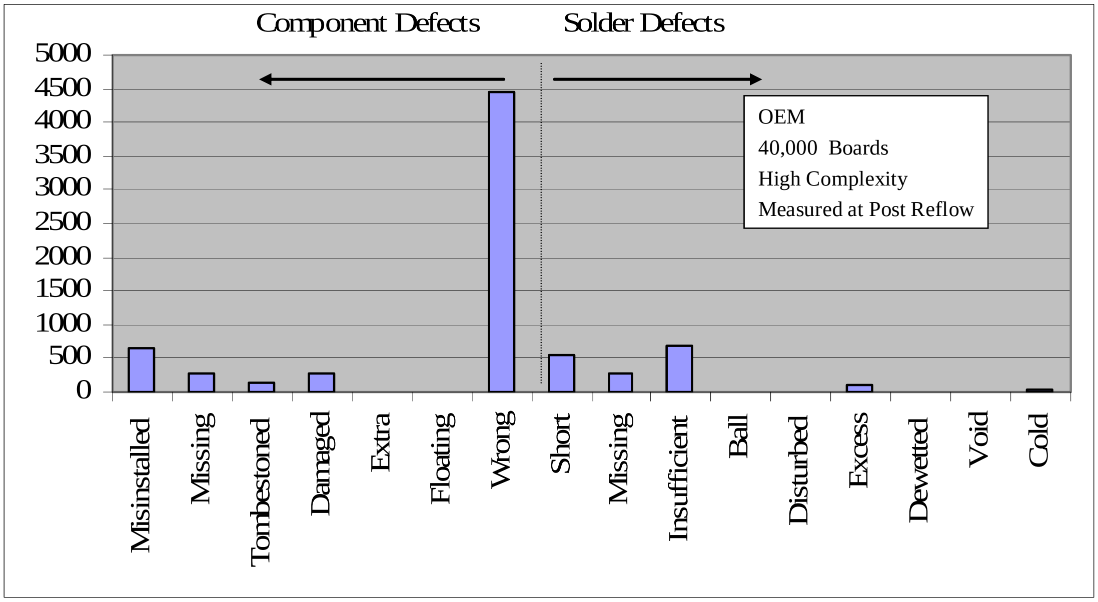


Figure 3: Defect spectrum from a high volume/low mix OEM

The data for each of these customers and aggregated across them shows that *the majority of defects were related to component placement issues* than post-reflow issues. Over all the customers, component placement issues were approximately 90% of the total number of defects. While we understand that this data represents is a sample of customers and further sampling of their boards, it is striking (and surprising) to see that post-place defects dominated the spectrum.

An Experiment: What happens if we fix the defects at post-place and then inspect and post reflow?
From a cursory look at this data, it would suggest that manufacturers are better off detecting the majority of the defects, which occur at post-place, and fixing them earlier in the process. If this truly is where the problem lies, it suggests that the best use of AOI technology is post-place AOI. However, even if our assertion is correct, many manufacturers are concerned that if they only inspect at post-place that they will miss the "post-reflow" defects.

Naturally, in the absence of data one way or another, this seems like a very valid concern. Thus, we proposed an experiment where we would

1. Inspect boards at post place,
2. Find and fix the post-place defects
3. Then inspect the boards at post reflow.

We did this study at a customer site with high volume/high complexity boards. We found that there were 3 categories of defects that we found at the end of the process. These were solder bridges, excess solder, and insufficient solder and represented 0.00544% or about one-half of 1% of the total defect spectrum.

Solder defects found at the end of the line have non-random route causes that could be understood and rectified elsewhere
At the face of it, the result from the previous experiment seems obvious. Even without doing the experiment, we expected we would find solder defects at the end of the line once all the placement defects had been fixed. However, we wanted to know if we would find "random" solder defects that couldn't be anticipated or if we would find defects that had a root cause somewhere else in the process. To our surprise, we found all the solder defects were in the latter category.

On this particular assembly 0402 resistor networks were responsible for majority of the solder insufficient and solder excess. The root cause was found to be solder pad to pin width ratio. The incorrect solder pad to pin ration

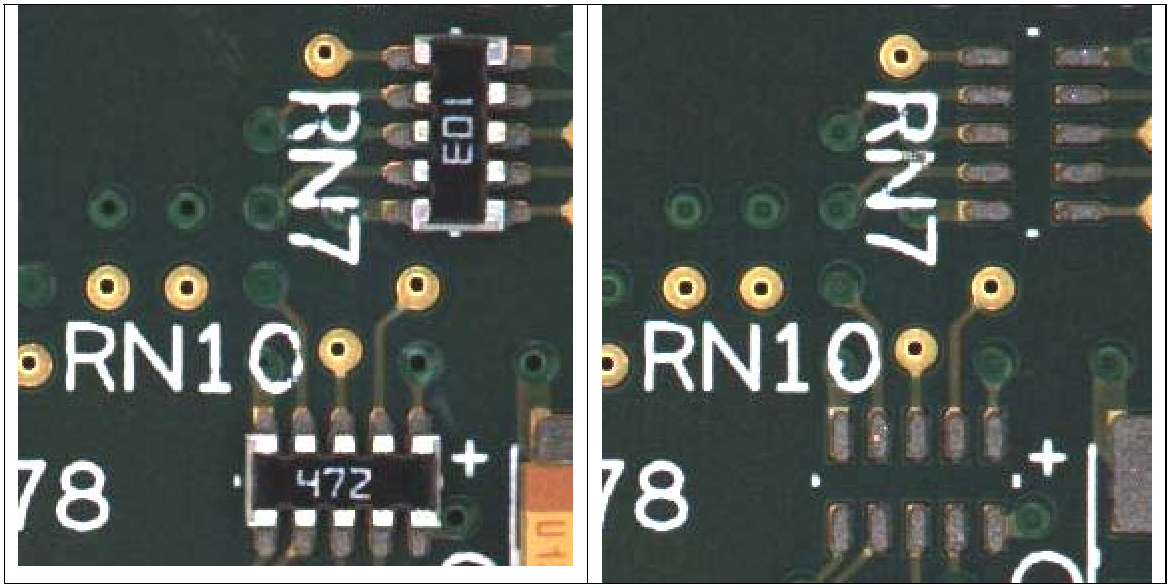


Figure 4: The majority of the insufficient/excess solder defects were due to design errors. For RN7 and RN10, imaged at post-place (left) and also post-paste (right), the corner endcaps are larger than the inner endcaps. However, the pad dimensions for all the leads are the same. This resulted in insufficient solder at the corner endcaps and excess in the center endcaps. It is interesting that paste inspection would not have caught this design defect (see right image). However, some more sophisticated processing at post-place could have discovered this design error.

Most of the solder bridges were found on the IC shown in figure 5. We found that the root cause of the bridges were due to excess pressure on the part during placement. This could be corrected at the placement system by changing the placement pressure or the component height.

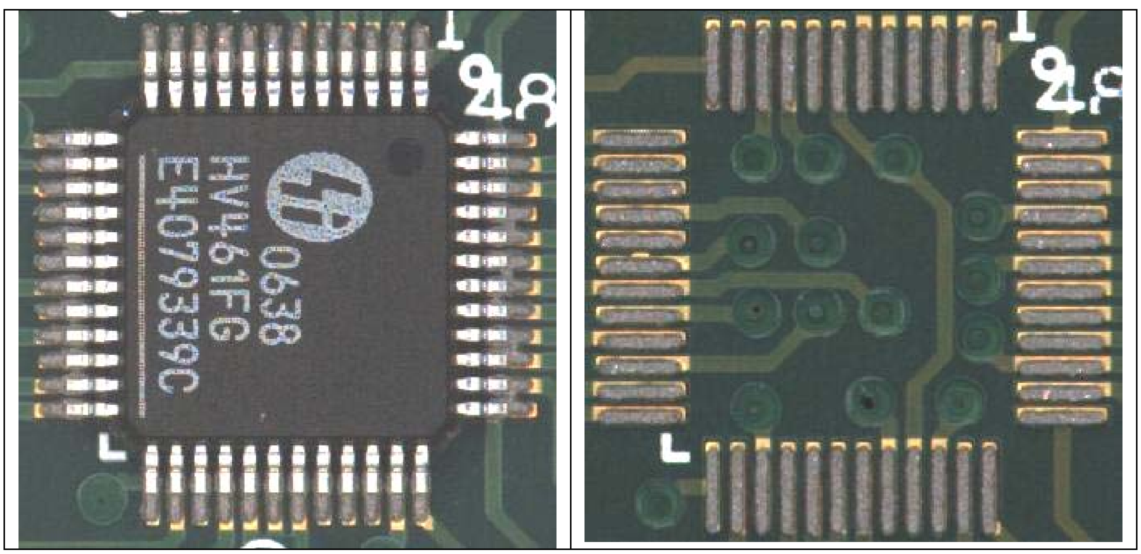


Figure 5: Image of at post-place (left) and post-paste (right). In all cases, the paste deposition for this part was "correct" (e.g. without bridges). However, the part consistently failed for solder bridges after the oven. Looking at the post-place image, it is easy to see that the paste is being "squashed" by the pick and place process and, therefore, causing the bridges to occur. This bridging defect could also be caught at post-place rather than post -reflow.

The summary of our experiments were that

- The majority of defects were caused by the placement setup or placement process.
- A small amount of defects were due to design errors.
- No defects actually occurred because of the reflow oven.
- Inspection at post-paste did not help to identify the reflow defects.

- All of the defects (or potential defects) could have been identified at post-place.

Admittedly, this was one controlled study done at one customer site and more studies need to be done. However, the results surprised us and we came to the tentative conclusion that the most effective spot for inspection is post-place.

What about the theory that the oven cures placement defects by drawing the parts back into place?

This theory has been around for a long time. If one believes this theory, it suggests that post-place inspection is like Chicken Little exclaiming that the "sky is falling" when in reality things aren't that bad when the board exits the oven. However, we have seen at multiple customer sites that the oven can mask or disguise some real problems that should be addressed. Figure 6 and 7 illustrate some of the hidden problems that can't be diagnosed at post-reflow.

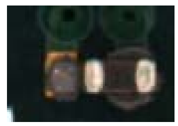


Figure 6: What will the post reflow defect category of this part be? This part (as imaged at post-place) is actually grossly misplaced. However, it's diagnosis at post-reflow will likely to be tombstoned or missing.

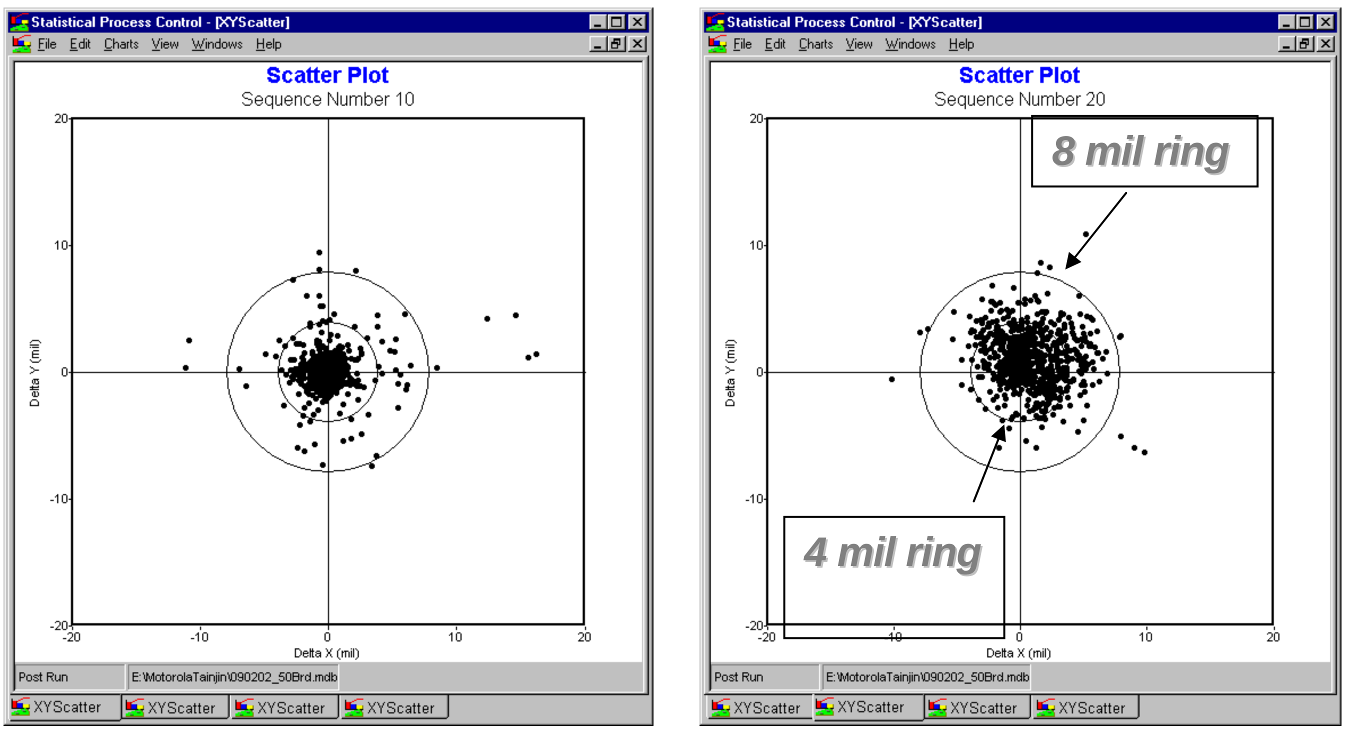


Figure 7: The scatter plot shows the measured position of the parts (delta x, delta y) with respect to where they should have been placed (0, 0). The left plot and right plot are of the same type of board generated from two different lines. The lines happened to be configured with all the same type of equipment. The plot on the left shows 3x more gross defects than the plot on the right. However, the plot on the right shows that the line that generated this board is likely to go out of control generating many more gross defects.

The resulting message is that although we might find gross defects at the end of the line, we might be missing the forest for the trees which can result in more defects in time.

We should add that the addition of lead-free solder has changed the landscape somewhat. Our customers report that lead free solder paste does not do as good a job of pulling the parts back to center. Thus, they have reported more placement errors found at the post-reflow stage.

For some products, one can only inspect at post-place (and not post-reflow). How well does the end product come out?

Let's examine results from a major multinational EMS using post placement AOI only in a high volume line. In this factory, shields are placed prior to reflow, so post reflow inspect is not an option. Without any AOI company was faced with low first pass yields and high field return.

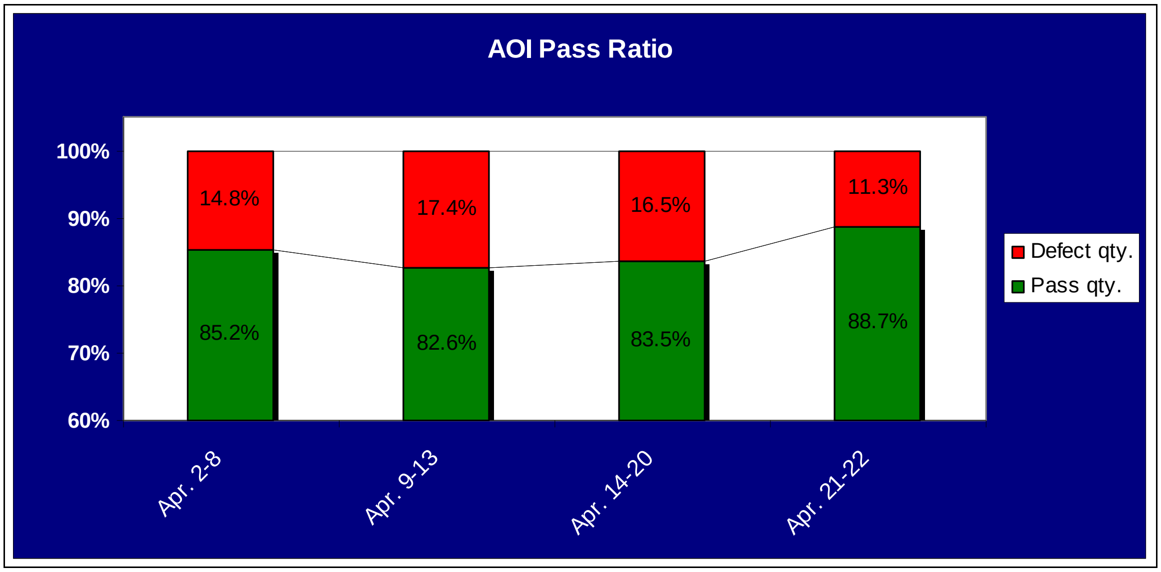


Figure 8: Without any AOI, this figure shows an analysis of yield over time indicating an average yield of 85%. In other words, 15% of boards have defects.

The customer added the optima 7200 post-place inspection system into their line. They fixed the defects that were found and attempted to do some elementary root cause analysis based on the data. They were skeptical that only post-place inspection could increase their end of line yield, so they performed a long-term study where they measured the defects prior to the introduction the machine and the defects after the machine. Addition of post-place inspection reduced their total number of defects by an order of magnitude and greatly increased their end of line yield. In this case, post-reflow inspection combined with functional inspection at the end of the line was sufficient to meet their inspection needs.

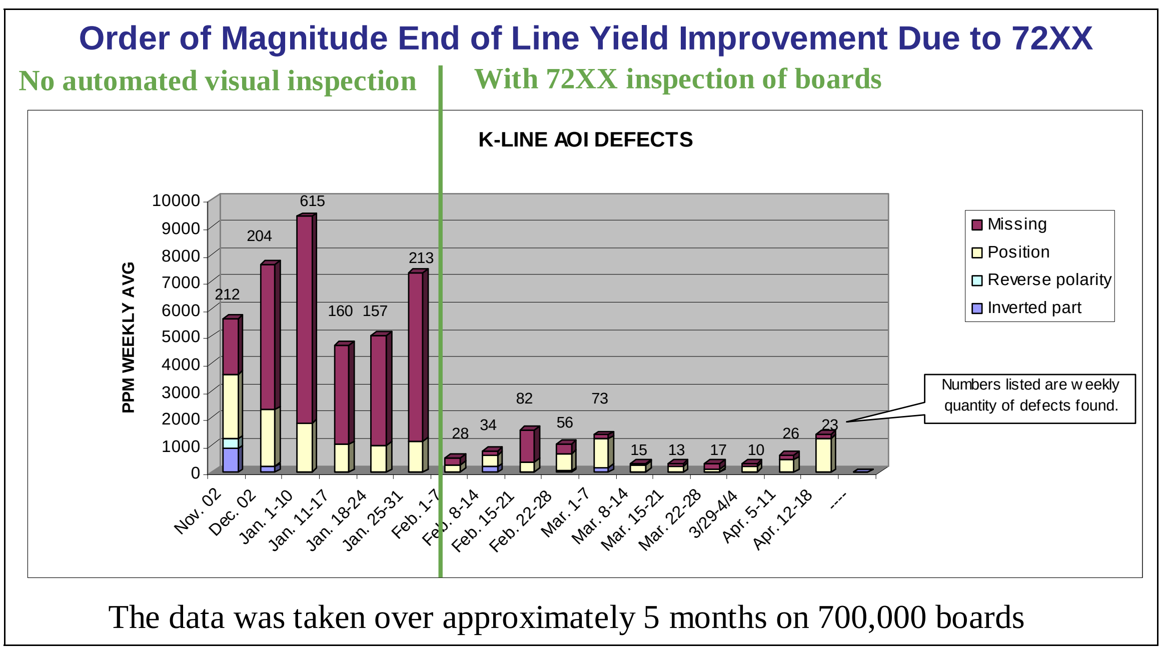


Figure 9: Long term study of defects found before and after the introduction of post-place AOI. This customer could only use post-place AOI because shields were put on prior to reflow. The result of using only post-place inspection alone was dramatic defects decreased by an order of magnitude.

In addition to simply finding and fixing defects, further analysis of the data showed that a single placement equipment was responsible for 71% of the defects. Thus, by analyzing the data, they were able to quickly go in and fix the "fat rabbit"

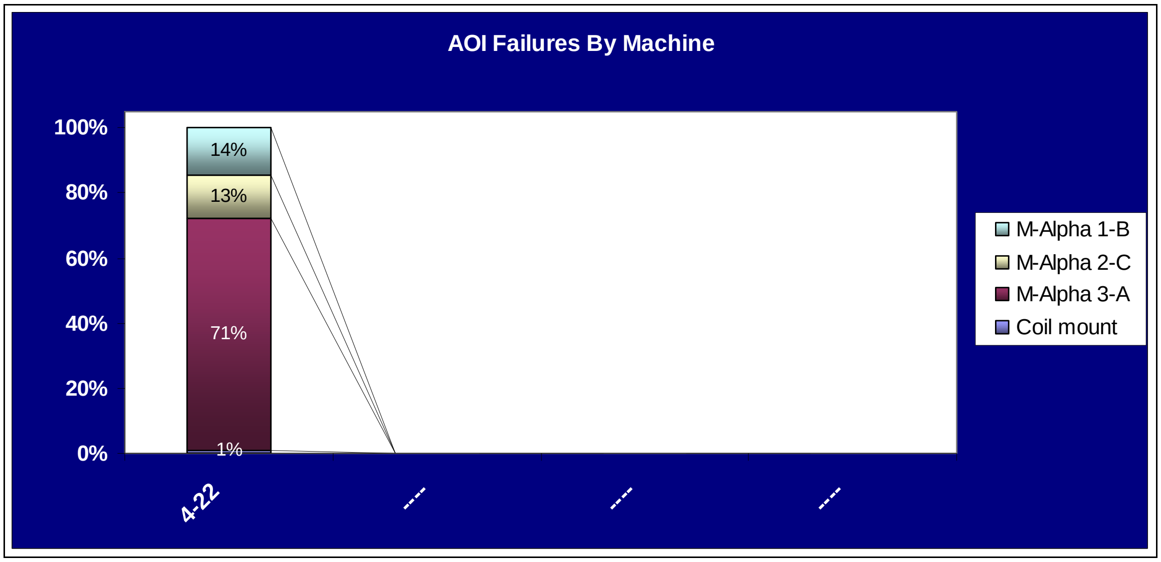


Figure 10: Analysis of one week's worth of data from the post-place inspection system shows that the third-placement machine is causing the majority of the defects. Information such as this makes the role of a process engineer much more effective. Without post place AOI the production line is in "fire fighting" mode; Trying to correct defects that have already occurred without the knowledge of how they occurred.

Implementation of post placement AOI at this factory had an immediate and long term positive result. They found that they were able to create quality product without any post-reflow inspection.

Post-Place inspection vs. Post-Reflow inspection: Let's talk dollars and cents
Implicitly, everyone knows that earlier detection results in less rework and less bad boards being built. Although we can make the theoretical economic argument, the argument has more impact if we look at real data.

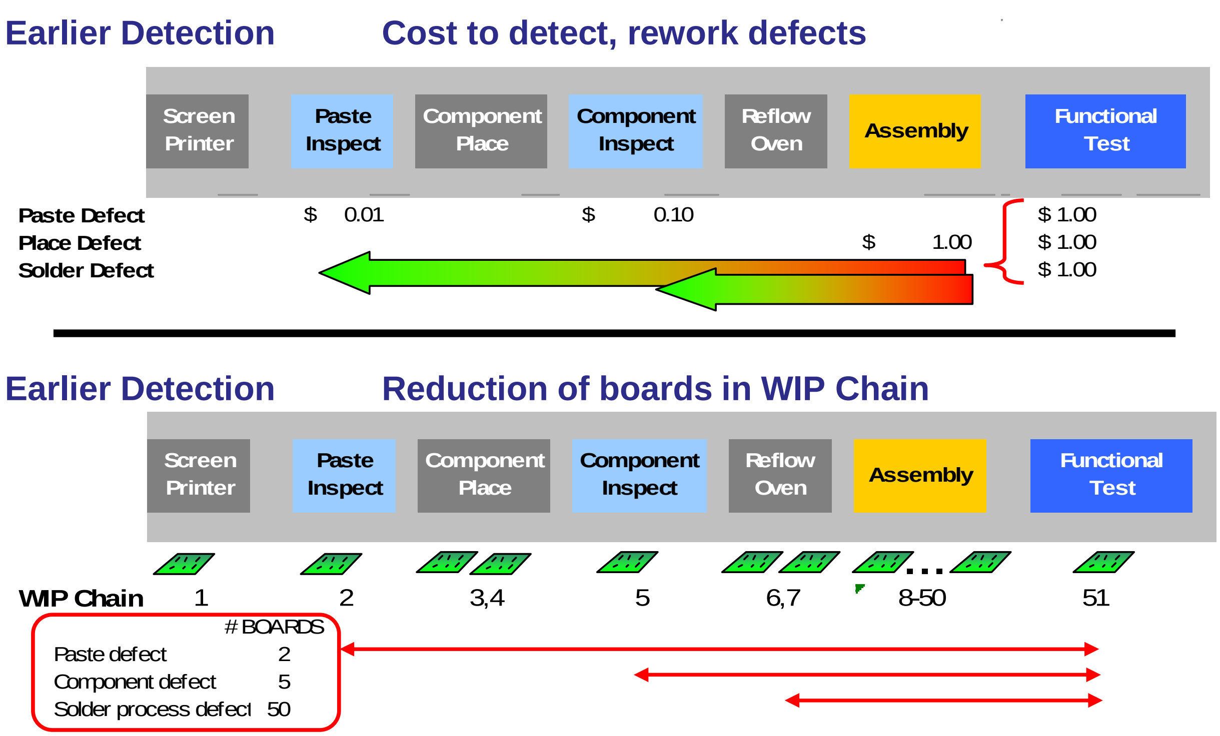


Figure 11: A theoretical depiction of how earlier analysis reduces costs and number of bad boards built.

A major test equipment manufacturer collected defect data over time to determine where best to employ AOI. Their defect data, illustrated in Figure 1, shows that 90% of the defects totaling 15000 defects were placement related. If the repair costs present above are useful estimates then the cost of repair at post place in this case would be $1500 dollars. At post reflow perhaps as high as $15,000 dollars and in test an astounding $150,000 dollars.

Post-Place inspection will add even more to the economic bottom line if it provides measurement data

The advantages of AOI prior to reflow are not limited to lower repair costs. The most significant benefit is being able to determine root cause of variable defects and correct them. Preventing defects from occurring altogether.

Let's fully analyze the variable data from a Low Volume/ High Complexity contract manufacturer, the most numerous still existing in the US. A 79 board run was inspected representing a total of 86,799 components.

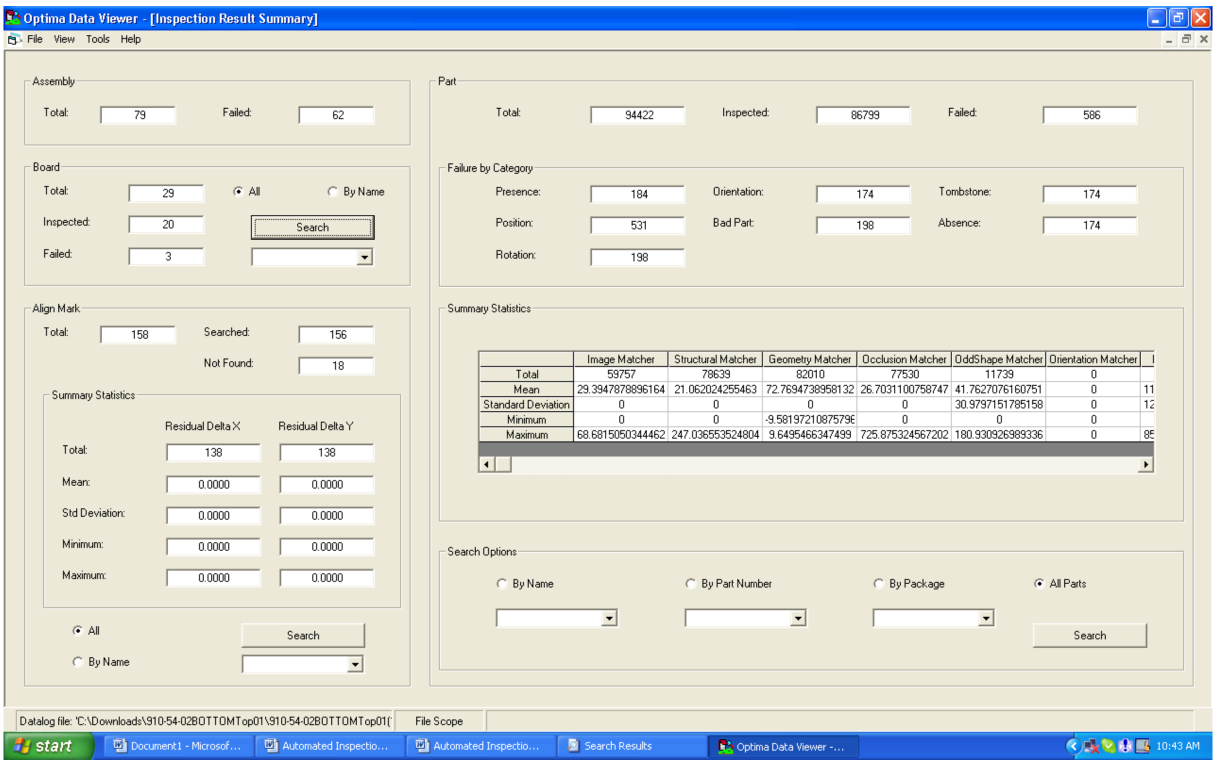


Figure 12: The Defect Pareto

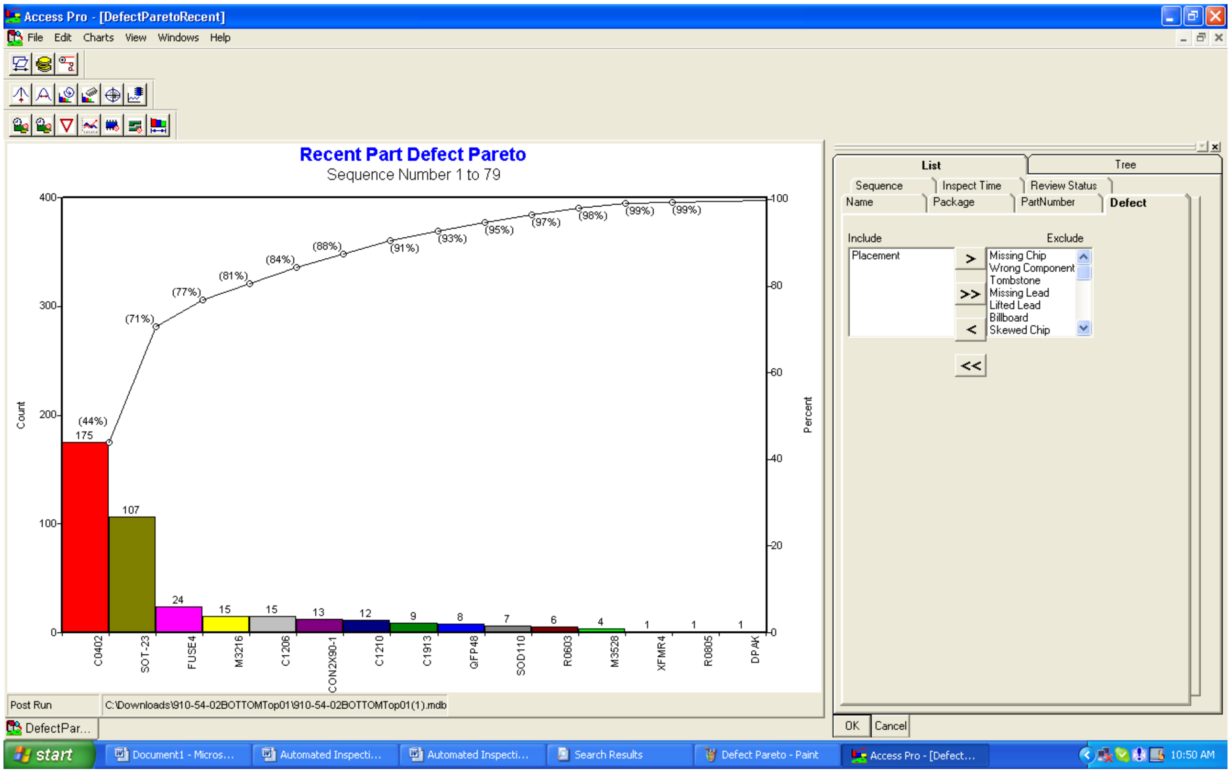


Figure 13: Drill down by package type.

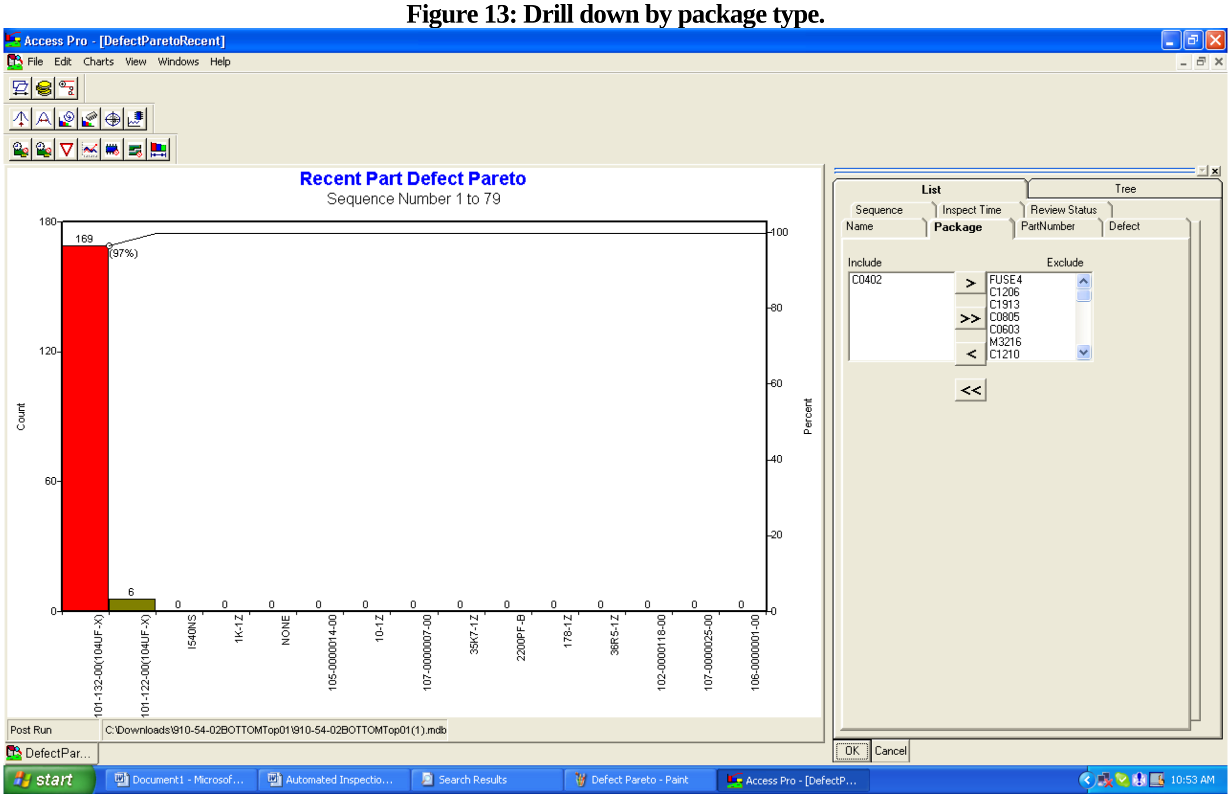


Figure 14: Drill down by part number

Figure 12 shows that 87% of the defects are placement errors. Figure13 shows that 72 percent of the placement errors are made up of two package types. Almost half of the defects (44%) were 0402 Chip Capacitors. Figure 14 shows that 97% of the CC0402’s were of a single part number.

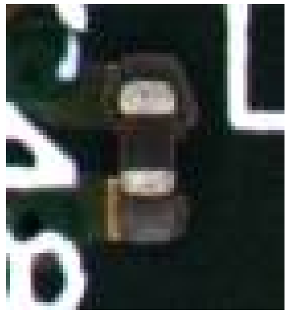


Figure 15: Defect image of one of the CC0402s.

Figure 15 shows a defect image of one of the CC0402s. Clearly the part is being misplaced. The question is why? Now that we know which part number is the problem, we can use our measurement data from our post-place analysis to take a more detailed look at the data.

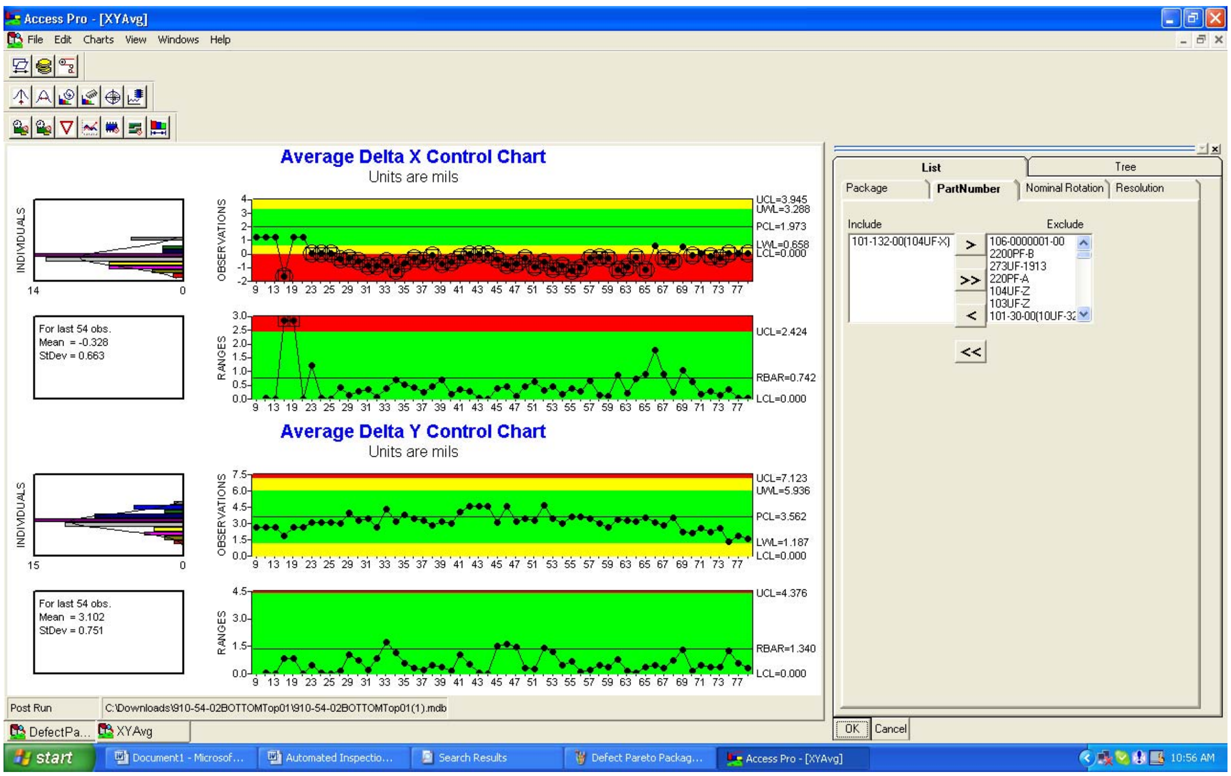


Figure 15: X-Bar R chart for the problematic part number.

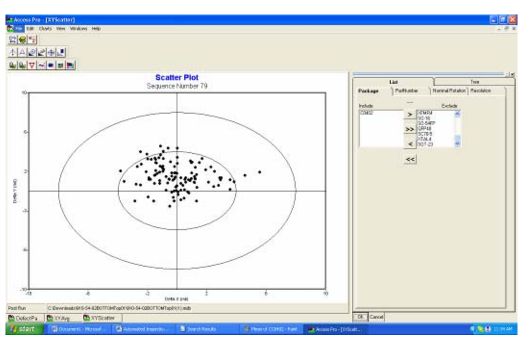


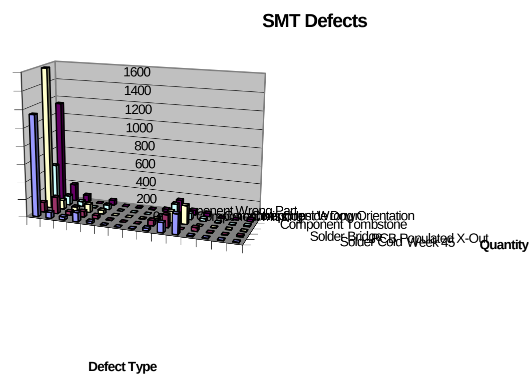
Figure 16: Scatter plot of the problematic part number

By filtering the X-Bar R chart for this part number, we see that the mean placement offset is -0.328 mils in X and 3.102 mils in Y. It is important to note, however that the standard deviation in X is larger than the mean offset. This indicates a large variation in placement position. A scatter plot of CCO402 indicates that the placement offsets are widely distributed. The total analysis indicates a vision file tolerance error or worn nozzle, which can easily be corrected.

What is my cost if I only inspect at Post-Reflow?
It is also true that post placement inspection is not sufficient to detect all defects. Since some defects occur during the reflow process. Low and Excess solder are impossible to detect prior to reflow. And even at post paste inspection, if the paste bricks are of the correct height and volume and properly centered on the pads, they may still result in solder insufficients and solder excess after reflow if the Pin to Pad ratio is not correct. Most process engineers recognize insufficient and excess solder are process indicators and should be detected, but not be repaired. Adding heat to a solder joint is likely to create conditions related to latent failures. Tombstone components, billboard components and lifted leads as well as solder bridges do need to be detected and repaired.

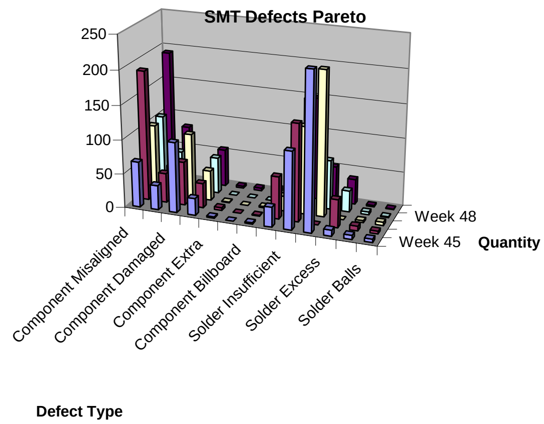
As a single point of inspection, it is clearly capable of screening defects from further processing. This can reduce the burden on test, but increases the cost of repair compared to post place inspection. WIP is higher and since many factories will “rack and stack” reflowed boards for later inspection; placement machine setup errors can go undetected through the entire batch. Random sampling reduces the chance for this. But the best method is an inline defect review station with software that displays the defective board and images. Inline inspection requires that barcodes be attached to the boards so that defective board can be re-routed to rework areas or that boards be processed as they exit the oven and reviewed immediately.

Let us examine a typical defect Pareto from a well known high volume/high variety DC/DC Power Converter OEM. This factory employs only Post Reflow AOI.



	Compone nt Wrong Part	Compone nt Misaligne	Compone nt Missing	Compone nt Damaged	Compone nt Upside Down	Compone nt Extra	Compone nt Wrong Orientatio	Compone nt Billboard	Compone nt Tombston	Solder Insufficien t	Solder Bridge	Solder Excess	Solder Cold	Solder Balls	PCB Populated X-Out
Week 45	1144	67	36	103	25	2	0	2	29	113	228	9	6	5	5
Week 46	111	190	43	64	36	4	0	1	62	142	0	41	7	4	14
Week 47	1593	101	43	95	44	1	0	2	22	128	211	0	3	5	6
Week 48	450	105	55	0	53	0	0	0	0	158	72	31	4	1	11
Week 49	1137	192	83	0	55	3	4	7	26	150	52	37	2	1	27

In this example, the distribution of defects appears bipolar. This is because component defects are separated from solder defects. What jumps out clearly is that Wrong Parts are 10x higher than any other defect. If we can eliminate wrong parts our process looks very different. In fact, wrong parts are a very expensive defect. The wrong components must scrapped after removal and the inventory levels are affected for what ever product those parts were intended.



	Component Misaligne	Component Missing	Component Damaged	Component Upside Down	Component Extra	Component Wrong Orientatio	Component Billboard	Component Tombsto	Solder Insufficient	Solder Bridge	Solder Excess	Solder Cold	Solder Balls
Week 45	67	36	103	25	2	0	2	29	113	228	9	6	5
Week 46	190	43	64	36	4	0	1	62	142	0	41	7	4
Week 47	101	43	95	44	1	0	2	22	128	211	0	3	5
Week 48	105	55	0	53	0	0	0	0	158	72	31	4	1
Week 49	192	83	0	55	3	4	7	26	150	52	37	2	1

Misaligned components are now seen as the lead cause of defects, followed by missing components and upside down components. Unfortunately variable data is not available post reflow. The Process Engineer must try to determine the root cause without the benefit of drill down SPC.

Our theorem is that the earlier we detect a defect the lower the cost of repair. If this is true then inspection prior to reflow is the best place to detect these defects. In fact, in the previous example if these defects were detected prior to reflow, most of these defects could have been prevented. In a high speed production line most defects occur as a result of set-up errors, reel changes, undetected eco's and pick and place machine errors. In low volume high variety production lines the entire production run can be complete before a single board is inspected.

Summary: A Distributed AOI Strategy

If a single point of inspection is desired, post reflow inspection is usually chosen. It is capable of detecting defects and thus is a defect-screening tool. It will prevent placement defects from escaping into test; however, it is not capable of preventing defects, detecting process trends or providing timely quantified feedback. The cost of repair is much higher post reflow.

Post placement AOI provides the data to measure and improve the process and is proven to reduce the number of non-solder defects post reflow and has the potential to prevent reoccurrence of errors thus raising first pass yields. Post placement inspection has a proven capability to prevent defects from occurring. It is also the only place where variable data has any real meaning. A well designed post placement AOI system provides benefits that cannot be gained by any other inspection system. Post place inspection has many obvious advantages. It can quickly reduce set-up errors. It provides meaningful and timely feedback to the process. It reduces defects in WIP and eliminates the need for most rework. For manufacturers with shields Post Placement AOI is a requirement. For manufacturers with end of line AOI, adding post placement AOI will dramatically improve first pass yields and reduce rework by a factor of ten. For those without AOI, post placement AOI will reduce the inspection task at the end of the line.

The two inspection types, however, can work in tandem. Our analysis shows that by using Post-Place inspection as the "work-horse" to find and prevent placement and solder related defects, we can then use Post-Reflow as a safety net to catch the few remaining defects and also to monitor the effect of the oven on the process.