Management Decision Making and the Cost/Benefit of Multiple 100% Inspections

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ABSTRACT

This paper develops a model of the cost and quality effectiveness of single and multiple 100% inspections and applies that model to management decision making in the foundry. Four specific cost cases are evaluated against a series of potential scenarios of visual inspection error and the number of inspections performed. Conclusions are drawn about the general advisability of multiple 100% inspections. The work illustrates the relative value of improving incoming product quality and improving the effectiveness of the visual inspection operation and finding that overall cost can be reduced equally by either action to a degree. The work also concludes that repetitive sorting of rejected product to find inadvertently rejected good product is counterproductive in both quality and cost.

INTRODUCTION

Reliance on attribute visual inspection is nearly universal in the casting industry and manufacturing in general to confirm the quality of parts prior to shipment. It has also been noted by many that visual inspection is not 100% effective and indeed is often far from the ideal. Juran estimated back in 1935 that 100% inspection was only 80% effective. By 1979 Sinclair summarized 25 different case studies in inspection effectiveness and demonstrated that not only was Juran essentially right-minded in his estimate, he was an optimist. It can be taken as a given that the human species is unlikely to develop into an error proofed condition any time soon.

Given the reliance on visual inspection to confirm the quality of products prior to shipment, management of a foundry is presented with a significant challenge: how can we overcome inspection error in manufacturing processes? This is especially difficult as managers must optimize cost without sacrificing outgoing quality—indeed, quality must not only be protected but, if possible, improved. Frequently, foundries and their customers, in an effort to deal with this challenge resort to inspection strategies that involve re-inspection of accepted product. Their hope is that additional inspection(s) will confirm the veracity of the good parts and uncover any missed nonconforming parts prior to examination. There is an underlying assumption about the general cost effectiveness of inspection, especially that subsequent inspections have equal effectiveness to the initial inspection on a cost and quality basis. It may well be asked whether such a strategy is truly cost effective and if a second inspection was beneficial, why not utilize a third to truly weed out every defective part?

In this paper a model of the remaining quality after a sequence of 100% inspections performed with known inspection error will be developed. This model will then be linked to four cost cases of specific applicability to the foundry industry. Scenarios will be evaluated using the model to establish common sense guidelines for making management decisions regarding multiple 100% inspections of castings.

BACKGROUND

The impact of inspection error on attribute inspection effectiveness has been studied by several researchers. This work can be fairly divided into two categories: those that have evaluated the impact of inspection error on attribute sampling programs and those that have focused on the problem of 100% inspection and subsequent 100% inspections.

Jaraiedi considered the effectiveness of consecutive 100% inspections where multiple characteristics were evaluated simultaneously and each characteristic had its own inspection error parameter. He and his team investigated the impact on the average outgoing quality level (AOQL) but did not consider cost optimization. Application of this work to the foundry is difficult for at least two reasons. First, the work necessarily complicates the fundamental attribute nature of the visual inspection of castings and divides it into several different characteristics. Second, the analysis is not greatly useful without knowledge not only of the magnitude of the inspection error, but of the specific inspection error associated with each critical characteristic to be checked. Burke et al utilized Jaraiedi’s work in a case study to demonstrate the real necessity of improving product quality rather than relying on long series of successive 100% inspections. Yet this point does not provide much help in direct application of the work to the foundry situation.

Maleyeff considered both cost and multiple 100% inspection systems with inspection error. He and his team simplified the application to a single attribute but considered only one level of inspection error, one level of incoming fraction defective to the inspection and only one cost scenario. This cost scenario, developed for the
biomedical industry, utilizes an exceptionally high average cost of sending a bad part to the customer as is common where product liability and similar considerations abound.

What is needed for the foundry manager has not yet appeared: a straightforward probability model for quality under inspection error that is combined with realistic variation in incoming fraction defective to the inspection and more normative foundry cost scenarios. This would truly be useful to the casting plant manager or quality manager.

**THE QUALITY MODEL: SINGLE INSPECTION**

There are two errors that can be made in the process of inspection by attributes. The inspector can accept a bad part and the frequency of this error will be referred to as the miss rate. This rate can be defined as the number of defective parts accepted divided by the total number of inspected, actually defective parts. Similarly, the inspector can reject a good part and the frequency of this error will be referred to as the false alarm rate. The false alarm rate can be defined as the number of acceptable parts rejected divided by the total number of actually good parts inspected. The model of inspection assumes that there is independence in the decision making, that is, the decision to accept or reject a part is not swayed by the decisions made on prior parts or knowledge of the lot quality ahead of time. These assumptions have been challenged but generally are accepted as part of the inspection task.

It is clear that the measurement of false alarm rate and miss rate requires clarity and an understanding of just what constitutes a good and bad part. For purposes of this analysis, it will also be assumed that sufficient references exist to absolutely define good from bad parts. This is fundamental to reasonable quality control and customer satisfaction.

It follows then that after a single round of inspection of a lot of size N with a fraction defective of p, that the number of acceptable parts in the lot is N(1-p)(1-f) and the number of unacceptable parts in the lot is Np. Where inspection error exists, the number of bad parts called good by the inspector is simply Npm, where m is the miss rate. The number of good parts accepted by the same inspector is N(1-p)(1-f) where f is the false alarm rate. In a similar manner, the number of good parts called bad will be N(1-p)f and the number of bad parts called by inspector correctly as bad will be Np(1-m). This information can be conveniently laid out in a tabular format as in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Inspector judges good</th>
<th>Inspector judges bad</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Actual Good</strong></td>
<td>N(1-p)(1-f)</td>
<td>N(1-p)f</td>
<td>N(1-p)</td>
</tr>
<tr>
<td><strong>Actual Bad</strong></td>
<td>Npm</td>
<td>Np(1-m)</td>
<td>Np</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>N(1-p)(1-f) + Npm</td>
<td>N(1-p)f + Np(1-m)</td>
<td>N</td>
</tr>
</tbody>
</table>

It may be helpful to illustrate the use of Table 1 with an example. Suppose a tub of 1000 castings is to be inspected and it is known that 10% of those castings are nonconforming. Suppose further that the inspector operates with a miss rate of 15%; m = 0.15 and a false alarm rate of 5%; f = 0.05. The results to be expected with this example are found in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Inspector judges good</th>
<th>Inspector judges bad</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Actual Good</strong></td>
<td>855</td>
<td>45</td>
<td>900</td>
</tr>
<tr>
<td><strong>Actual Bad</strong></td>
<td>15</td>
<td>85</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>870</td>
<td>130</td>
<td>1000</td>
</tr>
</tbody>
</table>

Interpreting these results, it can be seen that the percentage of parts actually conforming and sent on to the customer is 855/870 or 98.28%. The defect rate to the next operation has been improved from 10% bad to 1.724% bad. This equates to a 17,241 PPM.

It should be noted that in the example, the number of castings that were rejected at the inspection was 130, only 85 of which were actually bad. Depending on the next operation for these rejected castings, they may be melted or re-inspected or perhaps reworked in some manner. Regardless, a cost is associated with false internal rejects that may be substantial. This paper will consider the impact of further inspection with error on these parts in the later sections.

It should also be observed that the overall effectiveness of the inspection depends on both types of errors (miss rate and false alarm rate) and the relative percentage of bad product in the lot (since the errors are weighted by this amount). In the example, the overall effectiveness is simply the percentage of correct decisions, here 94%. This results from the 855 correct decisions about good parts and the 85 correct decisions about bad parts (total =
THE QUALITY MODEL: MULTIPLE INSPECTIONS

It is of considerable practical interest to consider the case where, in the interests of purging of nonconforming product that which is sent on from the inspection location, to subject those parts deemed acceptable by the inspector to another round of inspection. The hope here is to catch any parts that the inspector might have missed. In this regard, some general awareness is made of the potential for inspection error in miss rate. It is seldom acknowledged, at least in the author’s experience, that this practice also subjects the lot to another round of false alarm error, generating many more rejections than are actually present. The associated cost penalty for this oversight can be significant. Perversely, the presence of further rejections in subsequent inspections appears on the face of it to justify the practice, seeing all that the inspector “missed the first time around.” Actually, these further rejections may well be composed of truly good parts that have now been called bad by a well-meaning but error prone inspector. The size and significance of this penalty is very well worth investigating.

If one takes the quantity of parts judged good by the inspector from the initial inspection and puts these parts through a second inspection, the same impact on this new lot occurs through inspection error. While the lot has a reduced quantity of bad parts and a different fraction defective, the effect is the same; bad parts will be missed as a function of the miss rate and good parts will be inadvertently called bad as a function of the false alarm rate. Tables, such as Table 1, can be drawn up for the second and third such inspection and so on. These can be generalized where \( j \) = the number of inspection cycles \( (j = 1 \) on the first inspection, \( 2 \) on the second and so on). Table 3 provides the result.

<table>
<thead>
<tr>
<th></th>
<th>Inspector judges good</th>
<th>Inspector judges bad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Good</td>
<td>( N(1-p)(1-f)^j )</td>
<td>( N(1-p)(1-f)^{j+1}f )</td>
</tr>
<tr>
<td>Actual Bad</td>
<td>( Npm^j )</td>
<td>( Np(1-m)m^{j+1} )</td>
</tr>
</tbody>
</table>

Table 3. Multiple Inspection Results with Error

The expressions in Table 3 do not consider replacement of the parts rejected, so the total number of parts subject to a second inspection, for example, is simply that number “surviving” after the first inspection. Likewise, those that may be submitted to a third inspection are those that are called good through the second inspection.

The plots in Fig. 1 all begin with \( p = 0.10 \) which is 100,000 bad parts in one million, or 100,000 PPM. This can be conveniently written as 5 on a base 10 logarithmic scale. This also has the effect of straightening out the plots, which otherwise would be power curves asymptotic to the x-axis.

Figure 2 illustrates the impact of a varying false alarm rate on the quality. This impact is contributory only as higher false alarm rates reduce the number of good parts in the lot (by falsely rejecting them) and thus slows the rate at which a given quality level is achieved on the balance of parts remaining.

Examining just the results of Figs. 1 and 2, it might be concluding that there is strong support for the strategy of consecutive 100% inspections. To get the particular PPM quality level desired, one just needs to keep checking the lot over and over. The practical reality of this impression serves as a harsh wake up call. The actual quantity remaining after such a procedure is significantly reduced, so delivery issues become important. For example, assuming that each lot began the inspection process with 1000 pieces, after 4 inspections (and a roughly 1 PPM outgoing quality) with a very good inspector \( (m = .05, f = .05) \) only about 733 pieces remain (despite only 100 actually bad parts were in the lot to start). With an inspector at a false alarm rate of \( f = .1 \) and \( m = .05 \), only about 591 parts would remain—though near 1 PPM quality. Of course, delivery problems are only the tip of

MULTIPLE INSPECTIONS AND QUALITY LEVEL

Using Table 3 and the definitions established thus far, the impact of multiple inspection cycles on accepted parts can be investigated. Given that the inspection takes place with error of both miss rate and false alarm rate, the magnitude of these errors has an impact on the efficiency with which multiple inspections reduce the resulting level of defective parts. Figure 1 displays the resulting quality as a function of the number of successive 100% inspections through which the lot was processed. The figure illustrates the effect of varying the miss rate on the effectiveness of the inspection cycling. At higher miss rates, it takes more 100% inspection cycles to find all of the nonconforming items, but eventually each lot, initially at 10% nonconforming, can be brought to any desired quality level in this fashion.

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the iceberg. The cost of such repeated inspections must be appreciated.

**THE COST OF MULTIPLE INSPECTIONS AND THE ASSOCIATED QUALITY LEVEL**

The subject of quality cost and its various categories has been taken up by many. 11 The costs associated with inspection itself, a part of the classic appraisal costs category, have also been considered by this author and others. 12 This specific research pursues the total cost associated from the practice of multiple, successive 100% inspections in the pursuit of an improved outgoing quality level. Three quality costs will therefore be considered for the purposes of this paper.

**THE COST OF INSPECTION**

Managers making decisions on the basis of cost and quality must know the cost, on a per piece basis, for the completion of the inspection operation. Inspection is not free, even when combined with other operational steps, for example, in a cleaning room. Standard accounting practice might develop such a cost on a labor plus fringe basis, plus the allocated burden (overhead) of the operation of the inspection function. Typically supplies are minimal and may be ignored. In most foundries, the inspection function is largely visual in character and therefore relatively low cost on a per piece basis.

**THE COST OF INTERNAL REJECTS**

Parts rejected at the inspection station may have several different destinations, each with a somewhat different cost structure. Briefly, the typical paths are to scrap the part and recycle it into the melt, to rework the part by various means in an effort to save it or to subject it to a special inspection in order to make a decision to melt or repair it. A few shops may be able to regrade the casting and offer it at a reduced quality level to a secondary market. All of these options represent costs beyond those of simply having a good part pass inspection.

**Melt Option**

In some respects this may be the cheapest option from a cost perspective and it certainly entails the least risk of further processing and inspection error. On castings with a low value added cost in them beyond the inherent metal value, it may well be best to just scrap the part from a cost perspective. It should be remembered that “just scrapping the part” actually involves some subtle costs such as melt losses, documentation, alloy segregation, storage, etc.

**Rework or Repair Options**

Rework and repair options add a few layers of complexity and cost to the product. First, an additional quality boundary must be established and maintained that delineates what may be reworked/repairs from that which must be scrapped. This necessitates another inspection judgment, performed at the repair department (or perhaps by the inspector after the initial pile is reviewed) and may or may not receive the same planning and quality attention as the initial, mass production inspection. Given the factors that influence the effectiveness of visual inspection, it is unlikely this second inspection will have an equal effectiveness as the initial inspection. This has both cost and quality implications.

Second, the cost of the rework or repair must include the cost of processing the part through the standard mass production inspection for purposes of confirmation, documentation and labeling and other quality system considerations. This is a requirement within the ISO 9001 system of requirements.

Third, it is to be expected that the pile of product headed for the rework or repair bin is largely, but not entirely, actually bad. Added inspections with any appreciable miss rate will re-contaminate the value stream with parts now considered good but were in reality bad. This can, and depressingly often does, result in a series of repeated inspection-rework cycles that can introduce difficult to measure but very high costs. Unless tracking mechanisms are created to count the number of times a part has been repaired—and a company knows what number of cycles will exceed the available margin on the part—the ensuing confusion and ugly work in process volume can make scrapping the part at the first rejection very attractive as an option.

**Special Inspection Options**

Where it is suspected that a high false alarm rate is present in the inspection process, it may be worth the trouble to inspect the rejected parts to cull the parts that were “falsely accused.” This makes sense only when it can be reasonably be believed that the second inspection is more effective (less miss rate, less false alarm rate) than the initial inspection. “Going through the trash” of what has been rejected is not a particularly attractive prospect, unless you can recognize jewels others passed up. Using the same personnel to perform the second inspection clearly is not helpful. It should be recognized that those capable of a truly better inspection will cost more and will likely not have this work as a planned part of their day—forcing over time or other cost penalties.

As an illustration of this, consider the example in Table 2. If the parts the inspection operation considered unacceptable were inspected again by the same inspector, of the 45 good parts, he would accept 42.75 of them, but reject still 2.25 of them. Of the 85 bad parts, he would reject again 72.25 of them, but pass (owing to his miss rate) 12.75 of these. This adds 55.5 parts to the 870 parts called good from the initial inspection. The number of parts able to be shipped has thus increased from 870 to 925.5. Unfortunately, this group of 55.5 added parts is 22.97% actually bad and adding it to the prior good pile pollutes its 1.724% defective rate to almost 3% defective. The good intentions of those who desire to save as many
parts as possible will invariably pollute the product stream unless there is no appreciable miss rate error.\(^{13}\)

It can be proven in the general case that if a second inspection of equal effectiveness \((f\text{ and }m\text{ are equal})\) is conducted on parts judged unacceptable in an initial inspection and those parts considered now acceptable are added to the initial group of accepted parts, that quality will always be worse.

**Table 4. Re-Inspection Results of Initially Rejected Parts**

<table>
<thead>
<tr>
<th></th>
<th>Inspector judges good</th>
<th>Inspector judges bad</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Good</td>
<td>(N(1-p)f(1-f))</td>
<td>(N(1-p)f^2)</td>
<td>(N(1-p)f)</td>
</tr>
<tr>
<td>Actual Bad</td>
<td>(Np(1-m)m)</td>
<td>(Np(1-m)^2)</td>
<td>(Np(1-m))</td>
</tr>
<tr>
<td>Total</td>
<td>(N(1-p)f(1-f) + \frac{Np(1-m)m}{Np(1-m)})</td>
<td>(N(1-p)f^2 + \frac{Np(1-m)^2}{Np(1-m)})</td>
<td>(N(1-p)f + \frac{Np(1-m)}{Np(1-m)})</td>
</tr>
</tbody>
</table>

After one inspection, the percent defective in the group judged good by the inspector can be given as:

\[
\frac{Npm}{Npm + N(1-p)(1-f)} \quad \text{Equation 1}
\]

Where the numerator of the ratio is the actual bad judged good after the initial inspection and the denominator is the total quantity judged good after the initial inspection. This is in accord with the results in Table 1.

After an inspection of the rejected product from the first inspection, and assuming \(f\text{ and }m\) are the same for the second inspection, the portion now judged good from the re-inspected rejects from the first inspection can be given by Equation 2.

\[
\frac{Np(1-m)m + N(1-p)(1-f)}{Np(1-m)m + N(1-p)^2} \quad \text{Equation 1}
\]

The first term of Equation 2 is the actual nonconforming in the accepted group after re-inspection and the second term is the actual conforming quantity in the accepted group after re-inspection.

The new percent defective, assuming the newly accepted parts are added to those previously taken as acceptable can be represented by Equation 3.

\[
\frac{Np + Np(1 - m)m}{Np + N(1-p)(1-f) + Np(1-m)m + N(1-p)f(1-f)} \quad \text{Equation 3}
\]

This can be algebraically simplified to Equation 4.

\[
\frac{p(2m - m^2)}{p(2m - m^2) + (1-p)f(1-f^2)} \quad \text{Equation 4}
\]

The result of Equation 4 can be shown mathematically to be always greater (i.e. a worse outgoing rate of defective product) than the result of Equation 1 (the original outgoing defective rate from a single inspection). This is true because for all \(f < 1\), the quantity \((1-f^2)\) is greater than the quantity \((1-f)\) and the quantity \((2m-m^2)\) is greater than \(m\) where \(0 < m \leq 1\).

Repeated feasting on that which was rejected in good faith yields a diet richer and richer in nonconforming material, despite appearances to the contrary.

**THE COST OF EXTERNAL REJECTS**

An external reject is a bad casting sent on to the customer (typically, a machine shop or the customer’s machining department). It is assumed in this analysis that 1) the customer will find every actually bad part and 2) the customer will not reject actually good parts. These assumptions of course are shared by your customer. They believe they are perfect inspectors and that their criteria for acceptability are shared between you and them. How true these assumptions are however can be a matter of great debate. It does seem appropriate from a cost and quality perspective to assume bad parts will (at least) be found, rejected and returned to you at your cost plus the customer’s trouble. Depending on the industry and the specific customer, this may mean fees, third-party sorting costs, root cause and corrective action investigations (which are not free), meetings and at least, a replacement part for the ones returned, with shipping both ways paid by the supplier. In general, cost of quality literature places external returns costs at a high factor above internal rejection costs. It is typical for this cost to be 10 times higher, or more.\(^{14-16}\)

**THE COST MODEL**

This paper considers the three cost categories in four discrete cases designed to be applicable to the casting shop manager. While the actual cost figures are not necessarily parallel, the relative cost ratios between inspection cost, internal rejection and external rejection cost should be in ranges useful within a foundry context. The reader can, with a simple spreadsheet, incorporate the formulas in Table 3 and their own cost figures to develop their own cost analysis, if desired. The cost cases chosen for this work are described in Table 5.
Table 5. Description of Cost Cases

<table>
<thead>
<tr>
<th>Inspection Cost</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Reject Cost</td>
<td>$2.00</td>
<td>$0.50</td>
<td>$2.00</td>
<td>$2.00</td>
</tr>
<tr>
<td>External Reject Cost</td>
<td>$20.00</td>
<td>$20.00</td>
<td>$5.00</td>
<td>$50.00</td>
</tr>
</tbody>
</table>

COST MODEL AND CASE RESULTS

Consider the role of multiple inspections on a lot of 1000 parts where the incoming fraction defective is 10% (p = 0.10) and the inspection is typical of manufacturing visual inspection, at roughly 80% effectiveness, with the miss rate at 0.15 and the false alarm rate at 0.20. The results by case and number of inspections with total cost as the dependent variable are found in Fig. 3.

THE COST CASES VERSUS THE NUMBER OF INSPECTIONS

Figure 3 illustrates that quality costs are generally very high for those foundries that do not inspect their product at all. At zero inspections, cases 1, 2 and 4 reveal their high for those foundries that do not inspect their product. However, it should be noted that it was already observed that this misconception, especially that inspectors generally do not make many errors, or that if they do, they are infrequent lapses of attention leading to a few “missed parts,” is revealed by the Tables 7 – 10. It is not unusual to find inspection operations performing well below 80% overall effectiveness. This emphasizes the significance of the cost of this issue.

It should be noted that W. Edwards Deming, in his epic work, “Out of the Crisis,” proposed a test for whether 100% inspection or no inspection at all should be conducted to minimize total cost. This test involved the ratio of inspection cost and failure cost and comparing it to the expected fraction defective in incoming lots under statistical control. Unfortunately, this test did not factor in the effect of inspection error.17

Figure 3 illustrates that costs rise after the initial inspection in every case. Given the parameters of inspection efficiency used in Fig. 3, after a single inspection the outgoing quality has been reduced from 10% bad to about 2% (20408 PPM). If this is a suitable level of outgoing quality for your customer, added inspections will simply add cost.

It can be further observed from Fig. 3 that five inspections are necessary at this inspection effectiveness and incoming quality level to get to typical automotive OEM expectations of between 10 and 100 PPM. Obviously it would be quite painful to actually plan to perform five successive 100% checks into every passing product.

This model of inspection and the cost cases can be used to develop diagrams that cover the key aspects of the financial considerations. This work should be of great interest for those interested in achieving quality at the 100 PPM level or below.

TOTAL COST VERSUS INSPECTION EFFECTIVENESS AND INCOMING QUALITY

Figures 4 and 5 evaluate the relative benefit of inspection improvement and incoming quality level. Figure 4 incorporates N = 1000, with one inspection at cost case 1. Figure 5 shows the results of Fig. 4 but after two inspections.

Similar figures can be prepared for cost cases 2, 3 and 4. To enhance the ability to compare directly, Table 7 has been prepared, illustrating the data in Figs. 4 and 5. Tables 8, 9 and 10 illustrate the cost savings per 1000 pieces inspected, for cost cases 2, 3 and 4, respectively.

The overall shape of Figs. 4 and 5 is hardly surprising. Lower costs are associated with improved quality, whether it is in inspection improvement or in incoming quality. This trend is certainly true in all cost cases, however, the relative amount of savings varies.

What is perhaps surprising to some is that on a cost basis, as much can be saved in improving inspection effectiveness from 80% to 90% as can be achieved in what is perceived as a far more difficult task: reducing the internal defect rate from 20% to 10%.

It has been noted in earlier work18,19 that many misconceptions surround the relative effectiveness of visual inspection in manufacturing operations. The cost of these misconceptions, especially that inspectors generally do not make many errors, or that if they do, they are infrequent lapses of attention leading to a few “missed parts,” is revealed by the Tables 7 – 10. It is not unusual to find inspection operations performing well below 80% overall effectiveness. This emphasizes the significance of the cost of this issue.

To highlight directly the impact of inspection improvement on total cost of inspection, Fig. 6 was prepared, using the conditions N = 1000, p = 0.10 and cost case 1. Inspection effectiveness (in terms of miss rate and false alarm rate) was allowed to vary, indicating the total cost. A single point on the plot represents “perfect” inspection; zero misses or false alarms.

TOTAL COST WHEN RE-INSPECTING INITIALLY REJECTED PARTS

It is of interest to evaluate whether the total cost of quality is reduced if the producer inspects parts and subjects those, initially rejected to a second inspection; and adds the now judged good parts to those shipped and rejects only those that are rejected twice. The cost models described in Table 5 can be applied to the results of such a procedure, using the relationships established in Table 4. It should be noted that it was already observed that this
approach to operating inspection increases the number of defective parts shipped. However, this process does reduce the total number of parts called bad and thus the internal reject rate. The question becomes this: “Is the added cost of inspection and greater defectives reaching the customer less than that saved by having fewer internal rejects?

To answer that question, the case where \( N = 1000 \), \( m = 0.15 \) and \( f = .05 \) and \( p = 0.10 \) should be considered. It should be assumed that the second inspection is equivalent in effectiveness to the first inspection.

**Table 6. Description of Cost with One Inspection Compared to Inspection with Re-Inspection of Initially Rejected Parts**

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection Cost</td>
<td>$500.00</td>
<td>$500.00</td>
<td>$500.00</td>
<td>$500.00</td>
</tr>
<tr>
<td>Internal Defect Cost</td>
<td>$260.00</td>
<td>$65.00</td>
<td>$260.00</td>
<td>$260.00</td>
</tr>
<tr>
<td>External Defect Cost</td>
<td>$300.00</td>
<td>$300.00</td>
<td>$75.00</td>
<td>$750.00</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$1,060.00</td>
<td>$865.00</td>
<td>$835.00</td>
<td>$1,510.00</td>
</tr>
</tbody>
</table>

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<tr>
<th></th>
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<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection Cost</td>
<td>$565.00</td>
<td>$565.00</td>
<td>$565.00</td>
<td>$565.00</td>
</tr>
<tr>
<td>Internal Defect Cost</td>
<td>$149.00</td>
<td>$37.25</td>
<td>$149.00</td>
<td>$149.00</td>
</tr>
<tr>
<td>External Defect Cost</td>
<td>$555.00</td>
<td>$555.00</td>
<td>$138.75</td>
<td>$1,387.50</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$1,269.00</td>
<td>$1,157.25</td>
<td>$852.75</td>
<td>$2,101.50</td>
</tr>
</tbody>
</table>

In the scenario considered, the top half of Table 6 provides the costs associated with the initial, single inspection for the four cost cases. This cost picture can be compared to that with re-inspection of the rejected parts from the initial inspection. It can be clearly observed that in every case the cost of internal rejects is reduced, but the cost of the added inspection plus the cost of the added external defects overwhelms that savings. In short, the total cost for such a procedure is always greater. Re-inspecting rejects does not pay in cost or quality.

**SUMMARY**

A quality model was developed for single and multiple inspections where the lot size, incoming fraction defective and inspection error were known or could be estimated. The model is applicable to the case of successive inspections without replacement.

This quality model was applied to four cost cases that have relative costs of appraisal and failure pertinent to many foundry operations, at least those of moderate to high volume production.

While the lot size throughout the work was considered constant at 1000 pieces, this choice was driven purely to make the examples and illustrations have numerical values that were convenient.

**CONCLUSION**

One may fairly draw the following conclusions from the work that was presented.

1. Repeated inspections of accepted product, at any reasonable level of inspection effectiveness, will improve the outgoing quality level. The defect rate in outgoing product will fall as a power curve of \( j \), the number of inspections.

2. Repeated inspections of accepted product at poor inspection effectiveness are very cost inefficient and are especially sensitive to false alarm rates. The internal costs of false rejections and the associated penalties of dealing with rework, repair or re-inspection costs of this product, which develop under these inspection conditions, reap less incremental value than the improvement expected in overall outgoing quality.

3. Repeated inspections of rejected parts, in hopes of finding parts wrongfully rejected, cannot be recommended on a cost or a quality basis. Successive inspections of rejected parts are very sensitive to miss rate error and adding back product accepted under these circumstances will reduce the overall outgoing quality and increase costs accordingly.

4. Improving the quality of inspection itself by reducing the miss rate and/or reducing the false alarm rate is a valid and powerful means to reduce the ongoing cost of quality. In the cases considered in this work, an improvement in effectiveness of inspection (from 80 to 90%) of 12.5% was as valuable on a cost basis as a 50% reduction in the internal reject rate (from 20% to 10%).

Shining light on the counter-intuitive nature of the impact of successive inspections considering inspection error should provide value to foundry quality and plant managers. Drawing attention to the high earned return for investments made in inspection efficiency improvement should be especially of value for management decision making and cost reduction strategy development.

**REFERENCES**


Fig. 1. The relationship between quality and the number of inspections through which the lot is processed is shown above for four different miss rates and a constant false alarm rate.
Outgoing Quality with Inspection
Impact of changing FA rate

Fig. 2. The relationship between quality and the number of inspections through which the lot is processed is shown above for four different false alarm rates and a constant miss rate.
**The Cost of Quality**

![Graph showing the cost of quality with Log PPM on the x-axis and Total Cost on the y-axis. The graph includes data points for different cases labeled Case 1 to Case 4.](image)

*Fig. 3. The total cost of quality is shown for repeated inspections. It should be noted that the cost cases depicted are described in Table 5. The conditions of each inspection are: N=1000, p = 0.10, m = 0.15, f = 0.20.*

**Relative Cost Incoming Quality and Inspection improvement**

![Graph showing the relative cost with Percent defective incoming on the x-axis and Total Cost per Case 1, 1 inspection on the y-axis. The graph includes data points for 80% and 90% effectiveness.](image)

*Fig. 4. The total cost of quality is shown for one inspection under two levels of inspection effectiveness. The p value has been allowed to vary to show the relative effect of incoming quality on cost. The cost case is 1 per table 5.*
**Relative Cost: Incoming Quality and Inspection Improvement**

- **$2,760**
- **$2,190**
- **$1,677**
- **$2,010**
- **$1,670**
- **$1,364**
- **$500**
- **$1,000**
- **$1,500**
- **$2,000**
- **$2,500**
- **$3,000**

**Fig. 5.** The total cost of quality is shown for two inspections under two levels of inspection effectiveness. The p value has been allowed to vary to show the relative effect of incoming quality on cost. The cost case is 1 per table 5.

**Total Quality Cost with Inspection Error and 1 inspection**

**Cost Case 1, p = 0.10; MR at FA from 0.2 - 0.05**

- **$1,330**
- **$1,240**
- **$1,150**
- **$1,060**
- **$970**
- **$880**
- **$790**
- **$700**
- **$0**

**Fig. 6.** The total cost of quality is shown for one inspection under varying levels of inspection effectiveness. The p value has been fixed at p = 0.10. The cost case is 1 per Table 5. Similar plots (though at different y-intercepts) can be created from the other cost cases. The point at $700 is generated from perfect inspection, the lowest cost (and highest outgoing quality condition).
### Table 7. Description of Savings for Improvements in Inspection or Incoming Quality, Cost Case 1

Moving from incoming fraction defective of 20% (p = 0.2) to 10%

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 80% inspection effectiveness</td>
<td>$520</td>
<td>$570</td>
</tr>
<tr>
<td>At 90% inspection effectiveness</td>
<td>$360</td>
<td>$340</td>
</tr>
</tbody>
</table>

Moving from 80% effective inspection (MR = FA = 0.2) to 90% (MR = FA = 0.1)

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At p = 0.20</td>
<td>$520</td>
<td>$750</td>
</tr>
<tr>
<td>At p = 0.10</td>
<td>$360</td>
<td>$520</td>
</tr>
<tr>
<td>At p = 0.01</td>
<td>$216</td>
<td>$313</td>
</tr>
</tbody>
</table>

### Table 8. Description of Savings for Improvements in Inspection or Incoming Quality, Cost Case 2

Moving from incoming fraction defective of 20% (p = 0.2) to 10%

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 80% inspection effectiveness</td>
<td>$430</td>
<td>$480</td>
</tr>
<tr>
<td>At 90% inspection effectiveness</td>
<td>$240</td>
<td>$220</td>
</tr>
</tbody>
</table>

Moving from 80% effective inspection (MR = FA = 0.2) to 90% (MR = FA = 0.1)

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At p = 0.20</td>
<td>$430</td>
<td>$555</td>
</tr>
<tr>
<td>At p = 0.10</td>
<td>$240</td>
<td>$295</td>
</tr>
<tr>
<td>At p = 0.01</td>
<td>$69</td>
<td>$61</td>
</tr>
</tbody>
</table>

### Table 9. Description of Savings for Improvements in Inspection or Incoming Quality, Cost Case 3

Moving from incoming fraction defective of 20% (p = 0.2) to 10%

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 80% inspection effectiveness</td>
<td>$220</td>
<td>$210</td>
</tr>
<tr>
<td>At 90% inspection effectiveness</td>
<td>$210</td>
<td>$175</td>
</tr>
</tbody>
</table>

Moving from 80% effective inspection (MR = FA = 0.2) to 90% (MR = FA = 0.1)

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At p = 0.20</td>
<td>$220</td>
<td>$360</td>
</tr>
<tr>
<td>At p = 0.10</td>
<td>$210</td>
<td>$325</td>
</tr>
<tr>
<td>At p = 0.01</td>
<td>$201</td>
<td>$294</td>
</tr>
</tbody>
</table>
Table 10. Description of Savings for Improvements in Inspection or Incoming Quality, Cost Case 4

Moving from incoming fraction defective of 20% (p = 0.2) to 10%

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 80% inspection effectiveness</td>
<td>$1,120</td>
<td>$1,290</td>
</tr>
<tr>
<td>At 90% inspection effectiveness</td>
<td>$660</td>
<td>$670</td>
</tr>
</tbody>
</table>

Moving from 80% effective inspection (MR = FA = 0.2) to 90% (MR = FA = 0.1)

<table>
<thead>
<tr>
<th>Saves per 1000 parts inspected</th>
<th>Single Inspection</th>
<th>Twice Inspected</th>
</tr>
</thead>
<tbody>
<tr>
<td>At p = 0.20</td>
<td>$1,120</td>
<td>$1,530</td>
</tr>
<tr>
<td>At p = 0.10</td>
<td>$660</td>
<td>$910</td>
</tr>
<tr>
<td>At p = 0.01</td>
<td>$246</td>
<td>$352</td>
</tr>
</tbody>
</table>