FINANCIAL CALCULATIONS FOR PROCESS CONTROL BY NON-DESTRUCTIVE 100% INSPECTION

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Abstract: In-line process control with sensors and instrumentation is financially similar to Verification-In-Process in NDT. One inspects 100% of production between process steps to assure that production meets specifications. Financial methods exist to prove that 100% inspection should be carried out. The added cost of testing is compared with the resources saved by eliminating the nonconforming material. The three methods to be presented are (1) the Deming Inspection Criterion for short-term projects, (2) the Internal Rate of Return method for long-term projects with investment and depreciation, and (3) the Productivity & Profit method which shows the decrease in profit when nonconforming material produces major detrimental costs.

Introduction: (1): The subject of this paper is how to make financial calculations which prove that 100% inspection should be used or should not be used. Making such financial calculations is of interest to the field of process control in manufacturing because it gives a quantitative justification for expending resource (money) on one or another approach to process control. Management requires justification for expenditures. Various competing factions within manufacturing vie for the pot of money allocated or available in a zero-sum game. Engineers, statisticians, scientists, and NDT professionals compete for funds to use on their own ways to produce a better product. If it could be proved financially that NDT should be used in certain cases on a 100% basis on all of production, then the decision of management would be straight-forward and product reaching the customer would be guaranteed to be good.

The major competition for 100% inspection by high-technology methods (including but not limited to NDT) is Statistical Process Control (SPC). This is a methodology dating from the 1930s (Shewhart, 1931) and codified in the 1950s (Western Electric, 1956). SPC experienced a revival in the 1980s under the dynamic leadership of W. E. Deming, one of its early advocates (Deming, 1982). SPC can keep a process under control only to the extent that it can indicate when a process has probably gone out of control. Then repairs or readjustments can be initiated. The process may have started to go out of control much earlier. Only by going back into historical data which may be hours, shifts, or days long can the engineer determine when the process began to go out of control and began to produce nonconforming material. SPC in its entirety is probabilistic. While this is its strength, it is also its weakness.

At the inception of SPC, there was no such thing as NDT. However, as NDT and other hi-tech metrology developed over time and became automated, the automated test methods interfaced with other electronics and computers became capable of performing all SPC functions hundreds of times faster than standard SPC. In addition, automated test methods can mark and discard all nonconforming parts. Only good material goes “out the back door.” Testing every part instead of five per hour (a typical SPC rate), NDT and its companion metrology methods can improve quality as-shipped while making feedback to repair the process much more timely.

Without rigorous financial justification for 100% NDT, the NDT expert would be in the same situation as the SPC professional preaching dogmatically that his/her method is best. In recent years a body of work has emerged which uses financial calculations to prove that 100% hi-tech inspection should be used under certain circumstances (Hoadley, 1986; Papadakis, 1985, 1996, 1997a, 1997b; Papadakis et al, 1988). The financial calculations are perfectly objective, for they prove just as definitively that 100% inspection is not necessary under a different set of financial circumstances. The engineers themselves or corporate controllers or treasurers can easily carry out the financial calculations. Software is available for at least one major method.

This paper will present three financial calculations (Papadakis, 1995, 1997b) applicable to testing the hypothesis that 100% hi-tech inspection should be carried out. One is a break-even calculation where costs are compared and little investment is required. The second is a return-on-investment calculation where and investment in equipment must be amortized over years. The third is a profit-and-loss calculation which shows the detrimental cash flow due to nonconforming parts if not detected. Use of these three methods will be shown in actual cases. The reader will see immediately how the methods could be specified to his/her problems.

Results: (2.1) Background: Manufacturing is the arena in which NDT and SPC meet most creatively. The creative synergy between NDT and SPC arises from the realization that manufacturing processes should be kept under control by statistical methods (SPC) before the calculation of the financial justification for ongoing 100% nondestructive testing.

Note that this formulation states that there are times when 100% hi-tech inspection (including NDT) should be carried on in manufacturing, perhaps for years, on the basis of finance alone. There are other requirements such as safety, government regulations, and contractual obligations which may require 100% NDT long-term. Other reasons such as changes in manufacturing parameters or sorting material made during process-out-of-control conditions require temporary NDT utilization. However, the thrust of this article is on the long-term use of 100% NDT justified by financial calculations.

With a process kept under control by SPC, and with the level of process capability achieved by engineering, it is still possible that a cost-benefit analysis will reveal that 100% NDT should be used to eliminate the outliers from the output. It has long been said that one cannot test quality into a product. This is true; you can only test disquality **out**. It is also said that testing is only an expense and cannot make a profit. This is **not** true. Two calculations below will show the profitability of testing. Testing eliminates the disquality of the nonconforming material; with the disquality eliminated, the associated disvalue (Hoadley, 1986) of each nonconforming part is eliminated. Because the disvalue of a nonconforming part is generally huge compared with the value of a good part, the eliminated disvalue can be much larger than the cost of the testing plus the cost of the junked part. The bottom line is that the "bottom line" is larger. The testing has made a profit.

It is quite possible that "continuous improvement" as advocated by quality professionals will make the 100% NDT unnecessary after a period of time. The cost-benefit ratio can be recalculated at any time. The NDT test must pay for itself during the estimated period before the improvement is achieved. The cost of generating the improvement must also be taken into account.

The Theory section below will describe the three financial calculations for proving the necessity of using 100% nondestructive testing.

(2.2) Theory: (2.2.1):*General:* Each of the three financial methods is applied to a single process in a factory. The process has an input and an output and is intended to add value to the input. The financial calculation is intended to prove whether or not 100% NDT should be utilized on the output of this process before the next step. In ISO-9000-2000 parlance, we are financially justifying Verification-In-Process (VIP).

Each method utilizes the concepts of k_1, the cost to test one part, and k_2, the detrimental cost if one part proceeds further into the production process or into a finished product. These costs may be treated cumulatively if it is more convenient, e.g., over a period of a year. Components which could contribute to k_1 are listed in Table 1.

Table 1. Partial List of Inspection Costs k_1

- Capital Equipment
  - Initial cost*
  - Depreciation – also considers residual value*
  - Actual cycle life
  - Planned production volumes

Cost of capital
Operating Costs
    Labor
    Rent, utilities, maintenance
    Piece cost (outside vendor quote as an alternative)
*Minor equipment expensed over one year is listed under operating costs

Depending upon the type of business and the other quality assurance measures in place, some or all of the costs listed in Table 2 could contribute to k_2. The NDT expert seeking to apply the financial methods below will have to be resourceful to find valid numbers for all of the various costs in k_1 and k_2. Help should be forthcoming from other experts such as the Controller of the factory where the process resides.

Table 2. Partial List of Detrimental Costs k_2

The added cost of processing the nonconforming part further
The cost of sorting lots later to find a nonconforming item
The cost of repairing batches of assemblies later
The cost of lost production later if lots of parts or batches of assemblies must be quarantined pending sorting and repair
Warranty costs
Costs of recalls
Law suits ($k_2 \rightarrow \infty$ for safety items)
Customer Loyalty impinging upon future sales

(2.2.2): *Specific Methods:* (2.2.2.1): Deming Inspection Criterion: The Deming Inspection Criterion is a break-even method for determining when to do 100% inspection. It is particularly applicable when there is no cost of capital to be depreciated for more than one year. The formula is

$$DIC = (k_2/k_1)\ \mathbf{x}\ p \qquad (1)$$

where k_1 and k_2 have been defined above and where p is the proportion defective. The value of p is empirically determined while the process is adjusted properly and under control. The decision criteria on testing 100% are

$$\begin{aligned} &DIC \geq 1 \text{ Test } 100\% \\ &DIC < 1 \text{ Do not test} \end{aligned} \qquad (2)$$

Space is divided into two zones, Test and No Test, by the hyperbola $(k_2/k_1)p = 1$.

(2.2.2.2): Internal Rate of Return: The Internal Rate of Return (IRR) method is used when an investment in NDT equipment is to be amortized over several years while the process continues to be used (Papadakis et al, 1988). If investing in the NDT equipment is profitable, then 100% inspection is recommended.

With the IRR method, two situations are compared:

- One would be
    Do not test
    Absorb the detrimental costs
- The alternate would be
    Test
    Invest in the new equipment
    Save the detrimental costs
    Pay the testing costs

The calculation for the NDT case is completely analogous to the IRR calculation for deciding to buy any new piece of equipment for the factory. One asks, “Will the new thing make money?” And how much? The new equipment must earn a rate of return higher than the “hurdle rate,” namely the rate of return for which the company is willing to invest money in capital equipment at the time the project is proposed. That figure, known to the factory controller and the company treasurer, is the criterion for saying "yes" to testing. The decision criteria on testing 100% are

$$\begin{array}{ll} \text{IRR} \geq \text{Hurdle Rate} & \text{Test 100\%} \\ \text{IRR} < \text{Hurdle Rate} & \text{Do not test} \end{array} \qquad (3)$$

The data for the IRR calculation must be written down as cash flow over several years. The investment is negative cash flow at time zero. The detrimental cost saved by detecting the nonconforming material is the positive revenue year-by-year. Costs of testing are negative cash flow. Taxes saved by writing off the depreciation on the investment are positive cash flow. For example, the cost saved could be warranty cost. The equipment may have some residual value at the time it is no longer needed.

All elements of the cash flow are summed for each year and used as data in the IRR calculation. Any factory controller will have a canned program to do the calculation. The output will be the rate of return on the investment and the time to pay off the investment.

(2.2.2.3): Productivity and Profit: The Productivity and Profit (P & P) method can show that disquality leads to disvalue which can be large enough to make substantial inroads into company profit. When the magnitude of the profit decrement exceeds to cost of testing including the equipment cost and amortization, then 100% inspection is recommended.

Consider that each process delivers economic profit to a company by operating at a sufficiently high productivity. Productivity is simply Value Out divided by Value In. Productivity must be greater than 1.0 for the process to produce any value-added to make its operation worthwhile. All the inputs and outputs of a process must be reduced to monetary amounts in this formulation. Consider that the process runs for a period of time and that the value elements are cumulative for that period of time. Basically there are three value elements, A, B, and C. Input Value C is the entire cost of running that process. Output Value A is the value expected to be received from sales of good output. Output Disvalue B is the detrimental cost which will accrue from nonconforming material going further into production and/or into the field as in k_2. Quantitatively, Value A is the number of parts N produced times the transfer price T. This transfer price sometimes is an internal fiction of the company and sometimes is quite real, arising from a competitive make-or-buy decision. The principle to realize is that the negative contribution to B from a nonconforming part can be much greater than the positive contribution T from a good part.

In terms of monetary values, the Productivity P is written in this theory

$$P = (A - B)/C \qquad (4)$$

In order to make a profit, the Productivity must be greater than 1.0. Economic Profit E is

$$E = P - 1.0 \qquad (5)$$

The dollars (or other currency) realized are just

$$D = E \mathbf{x} C \qquad (6)$$

For all the processes in the plant, the gain is the sum

$$\mathbf{\Sigma} D = D1 + D2 + D3 + \ldots\ldots \qquad (7)$$

The key to increasing D is to make Disvalue B approach zero. To do this, the number of nonconforming parts going further into the system must be decreased. As P is initially calculated with the process under control statistically, the way to decrease the number of nonconforming parts shipped is to apply NDT to 100% of production. The limit on the decrease in B will be the Probability of Detection of the NDT equipment. In general, A will be decreased slightly because the newly discovered nonconforming parts will not be shipped, B will be decreased greatly as each faulty part has a huge Disvalue, and C will increase slightly to cover the cost of testing.

Discussion: (3): The discussion consists of examples of the three methods.

(3.1) Deming Inspection Criterion: In one example (Papadakis, 1985), warranty replacement of a subsystem ruined by a faulty part cost \$1000. The guesstimate of the imponderable cost of customer loyalty was \$1000. Thus, k_2 = \$2000. The cost k_1 to test the part back in the factory was \$0.20 making (k_2/k_1) = 10,000. Since p was known to be greater than

1/5000, the value of DIC became greater than 2.0. !00% inspection by NDT was indicated and undertaken.

Other cases are given in the same reference and elsewhere.

(3.2): Internal Rate of Return: In an example (Papadakis, 1995, 1997b) on turbine engines used in aircraft, turbine discs were tested by Ultrasonic Testing for cracks in the manufacturing plant. Over a period of six years starting in 1983, a total of 35 defective parts were found with internal cracks. Both production volumes and the rate of defect production varied with the total production over six years being 27,335. Another step in production (shot-peening) assured that the defects would not have propagated to the surface and caused failures until the 7th, 8th, or 9th year in service. Thus, testing in Year 1 would not have had a measurable effect on the cost B until Year 7. Nevertheless, 100% testing was carried on "Just In Case" to be safe because of historical knowledge of earlier failures. (The IRR calculation was done *ex post facto*.) The data on previous failures indicated that the detrimental cost per failure would be $7,000,000 for the loss of an airplane or $500,000 for the loss of an engine and a nacelle in 1982 economics. The investment in equipment was $400,000 and the average testing cost per part was $17. With a reasonable hypothesis on the rate at which defectives would have created accidents after Year 6 if undetected at the factory, the cash flow was calculated for each type of loss, namely the plane and the subsystem. **The resulting IRR was at 106% for the loss of a plane due to each defective disc and at 47% for the loss of an engine and a nacelle.** As the hurdle rate in 1982 had been 12%, the purchase of the ultrasonic automated equipment was justified. Empirically, the result was that no loss was suffered by using all the parts declared to be good by the ultrasonic test; all the defectives had been found by the testing.

Other examples are available in the literature.

(3.3): Productivity and Profit: The same example used in (3.2) was used to calculate profit with the Productivity and Profit method (Papadakis, 1995, 1997b). The reader is referred to these publications for details too lengthy for this paper. The P & P calculations were carried on (*ex post facto*, also) with the same reasonable hypothesis about the rate at which defectives would have created accidents if undetected. An additional hypothesis was that the event of a failure would have triggered a recall campaign of a set of "related" parts so that less than the total number of defectives would have caused failures but so that the cost of the recall would have to be added to the cost of the failure event as a disvalue in B. An airplane lost was still $7 million but the recall added $8 million, making B = $15 million per failure. For a subassembly the value of B would be $8.5 million. P & P calculations were carried on for different numbers of planes or subassemblies destroyed. Results are in Table 3.

Table 3. Computations of Productivity and Economic Position

Test	Planes destroyed	Subassemblies destroyed	Recall campaigns	P	E	D (1996 U.S.D.)
No	0	0	0	2.521	1.521	82,466,000
No	35	0	0	(1.998)	(2.998)	(162,507,000)
No	0	35	0	2.198	1.198	64,938,000
No	0	1	1	2.365	1.365	73,990,000
No	1	0	1	2.245	1.245	67,486,000
No	2	0	2	1.968	0.868	52,471,000
No	3	0	3	1.691	0.691	37,456,000
No	4	0	4	1.415	0.415	22,945,000
No	5	0	5	1.138	0.138	7,480,000
No	6	0	6	0.861	(0.139)	(7,535,000)
Yes	0	0	0	2.498	1.498	81,843,000

Examining the lines in Table 3 showing the progression from 1 to 6 planes destroyed, one can see that the results show drastic decreases in profits ending in a major loss of $7.5 million compared with an expected profit of $82.5 million in line 1. Doing the ultrasonic testing including investing in the ultrasonic equipment lowers this profit to $81.8 million, a total of $700,000 which is small compared with any catastrophe. Considering the "bottom line," 100% Inspection by NDT can make a substantial profit. Use of NDT on 100% of production is justified by the P & P calculations in this case and in many other cases.

Other examples are available in the literature.

Conclusions: (4): The Deming Inspection Criterion, the Internal Rate of Return method, and the Productivity and Profit calculations can prove that 100% inspection by NDT will be advantageous and profitable in production environments.

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