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DEFECTIVE ITEMS, INSPECTION ERRORS AND YIELD

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Abstract. *Quality is a principle subject in industrial engineering (IE). There exists no perfect process and some extent of failures, including the production of defective items is unavoidable. A defective item for the purposes of this presentation is an item that cannot be used as it is, as planned. A detective item is either scraped, sold for lower price, reworked or repaired and in any case involves loss of money. Rather unnoticed is the fact that costs of poor quality are accumulated prior to the production of any defective item. A common method to improve quality is to inspect the items and remove those that found defective. Inspections, however, are also imperfect and prone to errors, which have devastating effects. Despite their significance, these effects are rather unnoticed, too. In this study, long term repercussions of both the existence of defective item and of inspection error are examined.*
Key words: *Defect rates, Inspection errors, Quality costs.*

1. INTRODUCTION

Feigenbaum [1] (page 47) minted the term "*hidden plant*", and defined it as "the proportion of plant capacity that exists to rework unsatisfactory parts, to replace product recalled from the field, or to retest and re-inspect rejected units;" i.e., consequences that are incurred after an item is detected as defective. However, capacity is used before the item was even damaged. Moreover, when inspections are used, conforming units are falsely rejected due to inspection errors. The production capacity consumed to produce these falsely rejected units is also wasted! Feigenbaum estimated that *hidden plant*s amount "to 15 percent to as much as 40 percent of productive capacity". Here, means to quantify this figure and more important to evaluate and compare alternatives are provided.

2. DEFECT RATES AND I/O RATIOS

Let d_i denote the average defect rate of operation/activity i. (The defect rate depends on both the activity and the station chosen to perform it but let's assume the stations are already selected for each activity.) Note that defects due to ***common***, or chance, or random causes are considered here, not quality deterioration due to *assignable* causes as in [4]. Assume also that:

1.activities/operations are independent;

2. the processing of different items in a station are independent, too.

Then, if activity i is performed on Q units, the mean number of acceptable units is only (1- d_i)Q. Averages are proper measures since long term performance is considered. The calculation can easily be extended to serial processes. If Q_0 units enter the first activity in a serial process of n operations, the mean number of acceptable units at the end is

$$Q_n = Q_0 \prod_{i=1}^{n} (1 - d_i) \qquad (1)$$

Freiesleben [3] used this term to develop a cost model, which led him to the conclusion that "the total costs of production actually decrease if we have quality problems and therefore a defect rate greater than zero"! Even worse, "Although at first this might sound surprising, the decreasing total costs of production for poorer quality levels are to be expected"!!

Certainly, no cost decrease due to poor quality. Cost increase because larger quantities should be processed to compensate for the poor quality, but IE/operations management perspective is required to see it. Figure 1 portrays a serial production process chart; e.g., [2], where each node represents an operation.

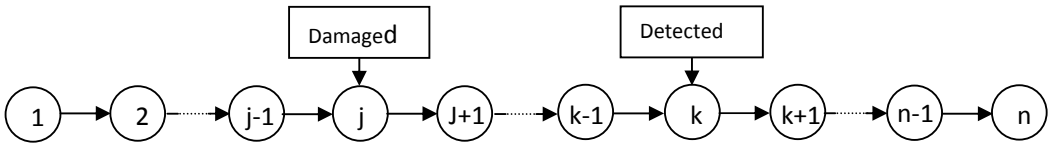

Figure 1. A defect item divides the production process into three segments

d \ n	10	20	30	40	50	60	70	80	90	100
0.001	1.010	1.020	1.030	1.041	1.051	1.062	1.073	1.083	1.094	1.105
0.005	1.051	1.105	1.162	1.222	1.285	1.351	1.420	1.493	1.570	1.651
0.01	1.106	1.223	1.352	1.495	1.653	1.828	2.021	2.235	2.471	2.732
0.02	1.224	1.498	1.833	2.244	2.746	3.361	4.113	5.034	6.161	7.540
0.03	1.356	1.839	2.494	3.382	4.586	6.219	8.433	11.436	15.508	21.029
0.05	1.670	2.790	4.659	7.781	12.996	21.706	36.253	60.550	101.129	168.904

Table 1. Q^{in}/Q^{out} ratios

Each defective item divides its production process into three segments. In the first segment the item is conforming. This segment ends when the item is damaged. The second segment starts right after the end of the first, and ends when the defective item is detected, and the third segment is after detection. Both last segments cannot exist – be empty, but the first segment contains at least one activity: $j \geq 1, j \leq k \leq n$. If inspections are made, defective items that are detected can be removed and thereby save the costs associated with, and the capacity required for future operations. A defective item can either be scrapped, used as it is for lower price, reworked or repaired. The last two cases involve costs and require capacity, additional to the regular production capacity and costs, while in the first two cases capacity is wasted and income is lost, which is equivalent to cost increase. Moreover, inspection and corrective actions can affect only the last two segments and the corresponding cost. Only process improvement can affect the first segment and its corresponding cost.

Further, there are sales targets and/or orders to deliver. "One of the customer's highest priorities is timely delivery of usable material." [9] The operations management community developed material requirements planning (MRP); e.g., [8], to meet this challenge. "MRP ... represented a huge step forward in the planning process. For the first time, based on the schedule of what was going to be produced ... the compute could calculate the total need" [9]. That is, production planners know how many end items are needed. From these figures, order quantities are calculated backward. The principal argument of this paper is that similar approach should be taken when quality is considered. Whenever defective units are not used as intended, more units should be produce to replace these units. A reworked unit is just as an additional one with, perhaps, additional preparation activities, and repair requires additional repair capacity. Thus, (1) should be re-written as in (2), where d_i is the fraction of defective units that are not repaired:

$$Q_j^{in} = Q^{out} \Big/ \prod_{i=j}^{n} (1 - d_i), \qquad (2)$$

This calculation accounts for all items that will be damaged, and not repaired, in operation j and subsequent operations up to the last activity, n. Furthermore, this is the minimal quantity – larger quantity maybe processed in activity j if defective items from preceding operations have not been removed earlier. Suppose $j = n$-19; i.e. there are 20 operations to go, including j, and all share the same defect rate of 1%. Then, $Q^{in} = Q^{out}/0.99^{20} = 1{,}226\ Q^{out}$. Namely, 1226 units will be processed, knowing that only 1,000 of them will be useful!

Additional illustrations of this impact are presented in Table 1, were common defect rates, d is shared by n operations. Notice the stepped line in the table – the numbers to its right are larger than 2, implying that (often, much) more than half the processed items will eventually be defective!! Again, no inspection can change these figures, only process improvement can reduce the quantities Q_j^{in}.

Paradoxically, attempts to fix the situation may worsen it! A defective item can be detected either in a coincidental manner; e.g., incompatibility during assembly, or by inspections. Inspections, however, are, too, imperfect and involve errors; e.g., [9]. It turns out that inspection errors can reduce the yield of the process, often even more than the defect rates.

3. EFFECTS OF INSPECTION ERRORS

There are two major types of inspection errors: Type I - disqualifying conforming units and Type II - missing nonconforming items and let them slip through to proceeding operations. These nonconforming items were referred to in noting that the numbers of Eq. (1) are minimal. Here, Type I

error - disqualifying conforming units, is of more concern. Further, when inspections are considered, inspections are often used for process monitoring; e.g., [12], while here, inspections are used for cleaning - detection and removal of defective units. As noted, defective units cannot be used as intended. Hence, more units must be produced to replace them. This conclusion is, now, extended to include items that are falsely disqualified, too. Enlarged production facility and infrastructure to make extra production capacity is required to compensate not only for defective items but also for good items that are falsely rejected!

How bad is it? Suppose the type I error probability is α, then $\alpha \cdot (1- d)$ of them are falsely disqualified. To illustrate, let d = 1% and α = 5%. Then, of 1,000 units, 10 are defective and another 49.5 units, about 5 times more, are falsely rejected, on average! No wonder, thus, that Type I errors are termed the producer's risk; e.g., [7]. Further, there is another similarity between false rejections and defective items - both accumulate along the production processes. Schorn [10] considered a processes which consist of a single casting operation in the foundry industry. More often however, many more operations are involved. In wafer fabrication in the semiconductor industry, for example, "each process flow contains 300-700 process steps" and "many inspection steps are added to the process flow" [6]. Consider for instance, a process of 70 operations, with a defect rate of 1%, each. The yield of this process is about 50%. This implies that if 1,000 units are required, 2,021 units should enter the process. Note by passing the magnitude of nonconformance! Further, consider the contribution to costs of this part of Feigenbaum's *hidden plant*. If seven inspections are added, say after each ten operation, with α = 5%, each, then the good intention results in a yield decrease to 34.55%! Consequently, the number of units that should enter the process, to yield 1,000 units, grows from 2,021 to 2,894, knowing in advance that 1,021 units will turn defective and another 894 will be falsely rejected, on average, leaving the 34.55% yield. Of the 2,894 units that enters the process, about 277 are defective after 10 operations - upon arrival to the first inspection. Another 131 units are falsely rejected in this inspection. This pattern continues until the last inspection which falsely rejects 52.6 units before passing the required 1,000 units.

Besides, false rejections are of conforming units. Hence, their number grows larger as quality improves: $\alpha \cdot (1- d)$ grows larger as d decrease. Luckily, the increase is rather small when the defect rate approaches zero. It grows only to 49.75 when d = ½%. But the question remains: does the detection of up to 10 defective units worth the rejection of almost 50 conforming units? This indicates the need for strong inspection tools - less error prone. However, often the two error types stand in conflict. That is, when the probability of one decrease the probability of the other increase.

A note before closing regards another difference between both error types. Falsely rejected items are removed while missed defective items continue to flow in the process. In the example, 14 defective units, on average, slip through the first inspection, letting 2,500 units to continue to the eleventh operation. Some 6 defective units to slip through the last inspection, in addition to the 1,000 required units.

4. CONCLUSIONS

While six defective units is much less than 1,021, this reduction is achieved at a huge price - 894 units are falsely rejected. If, the defect rates are reduced, instead, the yield grows. To illustrate, if all the defect rates are reduced to ½%, the yield grows to 70.4%. Feed of only 1,420, rather than 2,021, units will yield 1,000 conforming units, and with inspections the required feed is of only 2,034 units.

As indicated in the introduction, cost are accumulated up to the rejection point by each rejected item, either defective or false reject. These are part of the internal reject costs, which, thus, seem to be much higher than in e.g., [10]. Moreover, rejected units cannot used as intended. Hence, more units must be produced to compensate for them. These extra units require to enlarge the production facility and infrastructure to add production capacity. This requires both larger capital expenditure - for construction, equipment, etc., and higher operation cost, beyond the direct capacity increase, to support the larger infrastructure - energy, material handling, etc.

These repercussions of inspection errors advocates alternative approaches to improve quality. Such emerging alternative takes advantage of advances in sensing technology and uses sensors to apply a diagnosis oriented strategy, which focuses on the creation of a near-zero level of defective production [5].

In this note, a serial process was used for demonstrations. Studying the ramifications of inspection errors in non-serial processes, are subject for future works.

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