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Technical Paper

Mutual effects of defective components in assemblies

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ABSTRACT

The focus of this study is a known and disturbing actual problem. The industry will soon celebrate a century of quality awareness and efforts. Still, according to field data, many new products exit the manufacturing systems defective. This study proposes mutual effects among assembly's components as an explanation to this phenomenon – many defective new products. While each item in a serial manufacturing process moves individually, items are joined to others in assemblies. There, a single defective component suffices to disqualify a whole assembled unit! Surprisingly, few studies have focused on the repercussions of defective items on production. Particularly, there appears to be no study that quantifies these mutual effects of components which arrive from different sources with different defect rates. Thus, this study is also a first attempt to analyze and quantify these mutual effects. Apparently, the mutual effects of their components amplify the defect rates of assemblies dramatically, to the extent that defects due to common or random causes become significant.

1. Introduction

This study was motivated by the reality portrayed in Table 1, where the industry averages (IA) of the number of defects per 100 cars detected within 90 days of purchase through the years 2004–2013 (JD Power & Associates, *Initial Quality Study* [1]), are shown. This work aims to reveal and explain the causes for this phenomenon.

May 16, 1924 is the date when Walter A. Shewhart first presented the statistical control chart [2]. It really is a wonder, then, that after 90 years of quality awareness and efforts, there are still so many defective products – each car, on average. It should be noted that both flaws found after 90 days or detected prior to delivery of the cars, are excluded in Table 1. Note also that these findings in the car industry do not imply that other industries are better – "All participating mask shops (in the 2013 photo-mask industry survey) reported shipping masks targeting the 22 nm node or smaller, and on average, yields were greater than 90% at all nodes down to 22 nm." [3]

Feigenbaum [4] 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., to deal with the consequences incurred after an item is detected as defective. However, extra production capacity is required even before items are actually damaged and for these matters the type of the defect does not matter, whether dimensional, form, surface quality, hardness of contact, or other defects, all consume additional capacity. Feigenbaum estimated that hidden plants amount "to 15 percent to as much as 40 percent of productive capacity". The present study also aims to develop means to quantify this figure and, more important, to evaluate and compare alternatives.

A preliminary remark concerning the focus of this study is in order here. To the best of the author's knowledge, the type of analysis presented in the sequel has never been done before. One possible explanation may be that the present study integrates different domains and thus represents a novel departure. While the mathematics may seem straightforward, our application is not trivial – as will soon be seen, a single attempt to make a similar application in a simple special case led to erroneous results. Another reason could be confusion with reliability theory – though the mathematics may seem similar, the focus is different. Reliability, e.g. [5] is concerned with products, while the present study considers manufacturing processes. Reliability analyses evaluate the probability that components and systems will remain functional while in use. This study, on the other hand, focuses on the yield of manufacturing processes – the proportion of conforming units that are produced. The practical implications of this distinction are discussed in the sequel, too. Regardless of analytical sophistication, this paper explains a known and disturbing problem, provides means to quantify it, and

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Table 1
Industry averages of the number of defects per 100 cars.

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
IA	119	118	109	125	118	108	109	107	102	113

Source: JD Power & Associates, *Initial Quality Study* [1].

underlines those attributes that distinguish it from other concerns. Furthermore, the analysis suggests ways of coping with the problem.

The paper is organized as follows. Assumptions and notation are provided next. Section 3 presents a brief review of known results on serial processes. This lays the foundations for the analysis of assembly operations in Section 4. The results are discussed in Section 5 and conclusions are drawn in Section 6.

2. Assumptions and notation

Let p_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 for each activity have already been selected. Since performed in different stations, it is reasonable to assume that the operations are (close to be) independent. Note, again, the difference between the defect rate and the failure rate of reliability theory – defect rate characterizes manufacturing/production operations, while failure rate (e.g., [6]) characterizes components, products or systems.

Shewhart, in his pioneering book [7], distinguished between assignable and other causes for poor quality. It should also be noted, that here, defects due to ***common***, or random causes, are considered, not quality deterioration due to *assignable* causes as in [8]. This makes independence between items a reasonable approximation, in addition to activity independence. Finally, in repetitive production, long term averages are proper performance measures to use, rather than first time quality as in [9].

In sum, four assumptions are made:

1. The stations for each activity have already been selected;
2. Activities/operations are independent;
3. The processing of items in a station are independent;
4. Long term averages are proper performance measures to use.

Notation:

c_i – unit processing cost of activity i;
C_n – total cost of n activities;
m_k – the assembly coefficient of the kth component type – the number of units of type k component in an assembly;
p_i – the average defect rate of operation/activity i;
p_A^a – the actual defect rate of an assembly;
Q_i – the number of units on which activity i is performed;
Y_i – the yield of – the number of conforming units manufactured by activity i.

3. Defect rates and input/output ratios

If activity i is performed on Q_i units, the mean number of acceptable units is only $(1-p_i)Q_i$. This is easily 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:

$$Q_n = Q_0\prod_{i=1}^{n}(1-p_i). \tag{1}$$

This expression was used to develop the following cost model [10]:

$$C_n = c_0x_0 + x_0\sum_{i=1}^{n}c_i\prod_{j=1}^{i-1}(1-dj), \tag{2}$$

where x is the quantity that enters the process (Q in Eq. (1)), d_j is station's j's defect rate (p in Eq. (1)) and c abbreviates 'cost'. This cost model leads to the conclusion that "the total costs (C_n) of production actually decrease... if we have quality problems and therefore a defect rate greater than zero" (Ibid)! Certainly, costs do not decrease in the presence of quality problems, on the contrary, costs increase. There are simply, a couple of errors in this cost model.

First, it assumes that each defective item is detected and removed as soon as it is damaged. This is not the standard case, as demonstrated in Fig. 1, which portrays a serial manufacturing process where each node represents an operation. Each defective item divides its manufacturing process into three segments. In the first segment the item conforms to specifications; this segment ends when the item is damaged. At this point the second segment starts and it ends when the defective item is detected; while the third segment extends from detection onward. Note that, unless the item is conforming, at least one segment is not empty. Typically, the detection of defective items occurs in later stages, often after delivery as Table 1 indicates. Thus, the second segment is not empty and costs are wasted on the processing of defective items.

The second and more severe error in the cost model (2) is in the application of Eq. (1). The cost model applies it forward. Hence, the number of conforming units – the yield, decreases as we move forward in the process. For example, in a moderate size process of 70 operations, with defect rate of 1% each, less than half (49.5%) of the units that enter the process will come out conforming! No one can allow this pattern to occur in practice. There are sales targets and/or orders to deliver; a manufacturer that let this happen loses sales in the better case, and is likely to find himself out of business in most cases due to the failure to timely deliver orders.

This discussion demonstrates the issue that rose in the preliminary remark in the introduction – not the mathematics but its application matters.

If inspections are performed, defective items that are detected can be removed, leading to savings in terms of costs incurred by and capacity required for future operations. A defective item can either be scrapped, used as is but offered at a lower price, reworked, or repaired. The last two cases involve costs and consume capacity in addition to regular capacity and costs, while in the first two cases capacity is wasted and income is lost, which is equivalent to cost increase. Again, the type of the defect does not matter, whether dimensional, form, surface quality, hardness of contact, or other defects, all require additional capacity and incur additional costs.

Production planners know how many end items are needed. From these figures, order quantities are calculated backward, as in

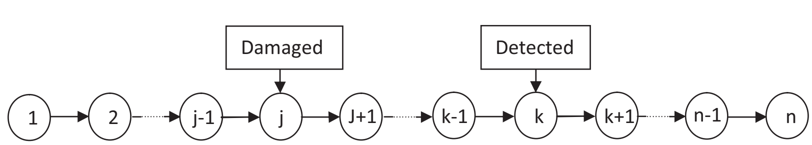

Fig. 1. A defective item divides the manufacturing process into three segments.