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**Abstract:** Traditionally, quality control on an assembly line has been conducted by quality inspectors at the end of the assembly line. Defective or incomplete parts identified during the production cycle are typically transferred to a separate repair shop where such parts are reworked, retested, re-inspected or replaced. In contrast, today's repetitive manufacturing companies have begun to delegate the power and responsibility of quality inspection and control to assembly workers on the line. This so-called online (line-stop) repair policy has been receiving increased attention from many manufacturing companies. Through a series of computational experiments, this paper examines the effectiveness of the online repair policy, which empowers workers to assure quality on the assembly line. Under varied assembly line configurations, quality failure costs of the two repair policies are estimated and compared to verify the superiority of the online repair policy. The computational results indicate that the online repair policy can be far more effective in assuring quality and saving costs than the traditional offline repair policy.

**Keywords:** assembly line repair policy; quality assurance; cost of quality.

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## 1 Introduction

In the past decade, many manufacturing companies have begun to focus their attention on quality improvement initiatives, such as Total Quality Management (TQM), Continuous Quality Improvement (CQI) and Six Sigma, in an effort to overcome the pressure of mounting costs, fierce competition and customer dissatisfaction arising from poor quality. Noteworthy in such a quality movement has been the debate on assembly workers' significant roles in assuring quality in daily assembly operations. One of the key issues in this debate has been whether or not quality can be assured more effectively by delegating the responsibility and the power of quality control and inspection from quality specialists to the hands of assembly workers who are heavily involved with assembly operations (see, *e.g.*, Thirugnanam *et al.*, 2007). Work incompletion or defects occur owing to human and nonhuman factors. Typically, an abnormality may arise when:

- parts from the previous process are wrongly assembled, or found defective
- work instructions and guidelines cannot be followed
- a major delay or incompletion is caused by a shortage of part components, defective raw materials and poorly maintained machine/equipment
- a major delay or incompletion is caused by human factors such as fatigue, distraction, low skill levels and poor job attitudes and behaviours.

In a traditional assembly line, the primary responsibility of quality assurance is in the hands of quality specialists and final inspectors. Such a line typically adopts an offline repair policy in which incomplete or nonconforming parts, which are removed from the assembly line by workers or tagged 'defective' by inspectors, are often sent to a separate repair shop or other field rework facilities where such parts are reworked, retested, re-inspected, or replaced (Carter and Silverman, 1984). A correction or completion can be done either in a separate repair shop or by running the assembly line overtime after regular work is over. Feigenbaum (1991) refers to this separate repair shop as a 'hidden plant', which typically accounts for 15% to 40% of production capacity. Such a traditional offline repair policy also stresses full capacity utilisation (manpower and machine/equipment) and tries to avoid line disruptions as much as possible by keeping the assembly line moving at all costs.

Even though the offline repair policy has the benefit of not causing any major line disruptions or loss of production rate, its advantages can be negated by a potentially long repair time (*e.g.*, disassembly, repair, re-inspection, retesting and reassembly) and high operational cost (extra machines and equipment, workers, floor space, *etc.*). Robinson *et al.* (1990) suggested that a 'rule of 10' (off-the-line repair costs are ten times higher than online repair costs) should discourage the plant from using an offline repair policy and instead encourage the plant to use an online repair strategy. Perhaps the main drawback of the offline repair policy may be that assembly workers are not actively involved with quality assurance activities (Buzacott, 1999). When workers discover defective or incomplete units, they may not be able to pay immediate attention to the causes of the quality problems, owing to the very nature of the continuously moving assembly line. Under the offline repair policy, most problems are overlooked and go unnoticed during regular shop operations until after defective or incomplete units are discovered and transferred to a separate repair shop. This often results in higher costs associated with scraps, increased idle time and disturbances (Bock *et al.*, 2006). Also, the presence of a separate repair shop and end-of-the-line inspectors may weaken workers' awareness of quality problems.

In contrast, a contemporary perspective in today's quality assurance stems from workers at the source stations. Recognising that workers are the best source of improvement, many companies have brought workers into the thought process of daily operations by empowering them and making them cognisant and skilful through intensive training and education (Foster, 2006). In this approach, every workstation is considered a critical quality inspection and control point, and therefore each worker has to ensure that a defective or incomplete part never slips through its source station without being identified and fixed. This type of philosophy, called 'quality at the source', which is a basis of the online repair policy (also called the line-stop repair policy), is a valuable way of controlling and assuring quality at each worker's workstation and reducing appraisal costs at the final inspection. Quality at the source is one of the dominant principles of today's quality philosophies. It promotes the idea of 'right from the start' rather than 'detect and correct' (Mergen and Stevenson, 2002).

Under the online repair policy, the power and the primary responsibility for controlling and inspecting quality are delegated to workers on the assembly line instead of quality inspectors at the end of the assembly line. When abnormalities occur during the production process, each worker has the authority and the responsibility to stop the assembly line so as to prevent defects and carry out immediate, on-the-spot corrections. When a line is stopped, not only is each problem fixed, but every error or problem is also systematically traced to its cause, and a correction is made so that the same errors or problems cannot occur again. When the online repair policy was first initiated by *Taiichi Ohno* at Toyota assembly plants, the company reported that the production lines were stopped frequently and the workers became easily discouraged; however, as workers gained experience in identifying and tracing problems to their ultimate cause, the number of errors began to drop dramatically. Womack *et al*. (1990) reported that Toyota plants, where every worker was authorised to stop the line, rarely stopped its line and consequently increased its productivity. At Canon, such a management principle is called TSS. TSS stands for the Japanese words '*tomete*' – stop; '*sugu*' – right away; and '*shochi o toru*' – take measures to correct it (Japanese Management Association, 1987). While stopping the assembly line is discouraged in a traditional production system that relies heavily on conveyors, TSS gives workers the authority to stop the line. TSS is part of a quality control programme designed to prevent problems at their sources rather than trying to detect them after they have occurred.

The major benefit of the online repair policy is that it heightens workers' awareness of human mistakes or machine malfunctions that can cause defects and, subsequently, deteriorate quality. Another important benefit of the online repair policy is the development of teamwork between workers and management. Workers and management can foster a favourable environment for teamwork when they work together to achieve the same goals for the company (Feigenbaum, 1956; Womack *et al*., 1990; Goyal and Deshmukh, 1992; Shenawy *et al.*, 2007; Feigenbaum, 2009). While the online repair policy has a greater potential to bring many managerial benefits and better quality assurance than the offline repair policy, many companies have been reluctant to adopt the policy due to scepticism involved in the online repair strategy. Management and workers have been uncertain as to whether these potential benefits can be translated into substantial cost savings, and if there exists an appropriate systematic mechanism that can properly measure the true cost of stopping the assembly line against the cost of repairing defects at the separate workstations. The difficulty of nurturing an organisational culture in which the online repair policy can fully flourish may also have contributed to this reluctance (Caudron, 1995; Joiner, 2007). The purpose of this paper is to provide a corroborative result that can help management better realise and measure the potential benefits of the online repair policy. In doing so, this paper examines the impact of two different repair policies on quality assurance on an assembly line. Two quality failure cost models that can measure the effectiveness of the two policies on assembly lines will be developed and the performance of these policies under different assembly line configurations will also be measured. Given the lack of such measures that allow the firm to assess the true benefits of quality assurance, the proposed quality failure cost model can provide the firm with a viable quality performance indicator (Franceschini *et al.*, 2006).

## *1.1 Literature review*

Even though the benefits of the online repair policy have been well documented in recent studies on the automobile manufacturing industry, little research has been conducted as to how these benefits can be measured in terms of cost savings, especially with respect to quality failure costs (Feigenbaum, 1991). Although few previous studies have directly compared the two repair policies, the following research examined similar problems. In the most closely related paper, Robinson *et al.* (1990) compared the performances of three approaches (line-stop (online repair) policy, repair-shop (offline repair) policy, and asynchronous line-stop policy) based on production performance measures, such as work-in-process, average utilisation of workers in the repair shop, average number of items waiting for offline repair and defective rate. They observed that the line-stop policy performed better on shorter assembly lines and the probability of producing a defect decreased owing to an increased awareness of quality.

Lau and Shtub (1987) examined the effectiveness of a 'hybrid' line (*i.e.*, a paced line that can be stopped or slowed down for incompletion). They considered the factor of product quality via an incompletion cost component, but did not estimate quality failure costs explicitly. Buzacott (1990) proposed that if high quality and high labour productivity are to be pursued in typical manual assembly lines, assembly workers must be able to stop the line to avoid any defects that may be due to insufficient time to complete the task. Even though he recognised the importance of a line-stop policy for continuous quality improvements, he did not develop cost measures for evaluating the effectiveness of the line-stop policy. Leung and Lai (1996) compared the effects of online and offline repairing strategies on productivity in automatic assembly systems. Through simulated experiments, they concluded that the two different repairing strategies did not show any significant differences in their impacts on productivity unless a high defective percentage in assemblies was encountered.

Considering the uncertain and random nature of quality failures, Shin and Min (1995) examined the cost-effectiveness of a line-stop policy under the condition of stochastic task times using an expected cost model similar to the one proposed by Silverman and Carter (1986). More recently, Shin and Min (2001) first considered the cost of quality as part of performance measures and discovered that the line-stop policy outperformed the offline repair policy with respect to savings in total quality failure costs. However, they did not take into account the impact of varying worker skills on the efficiency of repair and the subsequent quality failures.

As this literature review reveals, few of the prior studies on the online repair policy consider quality failure costs as a key performance measure, even though quality costs are becoming an area of increasing concern. Crosby (1980) found that the average Cost of Quality (COQ) for the US companies ranged from 15% to 20% of every sales dollar. This usually includes the cost of reworking, scrapping, repeating service, inspection, tests, warranties and other quality-related expenses. Recognising the importance of COQ, especially quality failure costs, our current study surpasses previous works by proposing a quality failure cost framework within which we examine the cost-effectiveness of the online repair policy over the offline repair policy. The primary research question of the study is concerned with whether assuring quality at the source on the basis of the online repair policy will provide sizable savings over a traditional policy, which relies heavily upon an end-of-line inspection and an offline repair, and how efficiently those savings can be measured. In an effort to answer this question, this paper introduces a framework that measures the quality failure costs of the two different repair policies. In addition, to overcome the shortcoming of previous studies, which neglected the impact of varying worker skills on quality failures, this paper examines the effectiveness of the online repair policy under different assembly line configurations involving varying worker skills. To elaborate, this paper assesses the effects of the assembly line length, the different arrangements of assembly workers according to their skill levels, and the unit quality failure cost (internal and external) on cost savings through a series of computational experiments under different scenarios.

## 2 The framework of total quality failure costs

As defined by Crosby (1980), the cost of quality can be classified into the cost of 'good' quality (cost of conformance) and the cost of 'poor' quality (cost of nonconformance). Since the cost of poor quality is usually much higher than the cost of good quality owing to penalties associated with product defects, it is important for the firm to estimate it and then to develop built-in quality strategy (*e.g.*, Six Sigma philosophy) that enables the firm to prevent future quality failures. The next subsections will introduce and derive mathematical models that are designed to calculate the cost of poor quality.

### *2.1 Background of the proposed models*

The quality failure costs can be categorised into internal failure and external failure costs. Internal failure costs are associated with correcting a defect before the customer receives the item. These costs include the costs related to scrap, rework, lost labour hours and machine capacity, failure analysis, re-inspection and retesting, downgrading, longer lead times and higher inventory. External failure costs are associated with defects that are found after a finished product is shipped to the customer. These include costs of handling customer complaints, customer returns and product recalls, warranty repairs and replacement, and legal liability and lawsuits.

Quality failure costs are genuine losses that can be avoided if the quality is perfect. On the other hand, prevention and appraisal costs are incurred to reduce failure costs. For simplicity, our proposed models focus exclusively on quality failure costs. The rationale is that a higher percentage of the COQ (between 70% and 90%) is usually associated with failure costs (Juran, 1989). For example, Taruntaev (1993) observed that the cost of maintaining and repairing engine assembly equipment was sometimes equal to the original purchase cost of the equipment if an equipment failure occurred. Juran and Gryna (1988) assert that failure cost elements provide a major opportunity for cost savings and for removal of the causes of defects.

Prevention costs are not included in our cost models because of the unstructured nature of prevention efforts, such as quality planning activities, training and education of workers, and supplier training programmes. Another reason for the exclusion of prevention costs from our models is that prevention costs may be proportional to company-specific quality standards. In other words, such costs may change as manufacturing firms raise their quality standards and set their own tolerance limits for the range of acceptable products. Harrington (1987) also argued that prevention costs should be considered a cost-avoidance investment rather than a cost. Appraisal costs are also excluded because of the difficulty involved in comparing two repair policies. For example, the offline repair policy relies heavily on quality inspectors' final inspections, whereas the line-stop policy mainly relies on workers' on-the-spot inspections.

### *2.2 Notations and assumptions*

The two quality failure cost models that will be introduced in the following sections are based on the notations denoted below. These models are based on manual assembly lines manned by only one assembly worker per station.

Q = number of total production in units (target production units)

$y_i$ = total number of units transferred from station $i$ to station $i + 1$ (*e.g.*, $y_0$ = Q)

$m$ = number of workstations (workers) on an assembly line. All workers are connected in series, and can indicate $m$ possible opportunities for error in each production cycle.

$p_i$ = reliability of the $i$-th workstation (worker). (*i.e.*, $(1–p_i)$ indicates the probability that a defect occurs at the $i$-th workstation, and is assumed to be statistically independent and identical for each of the $m$ opportunities for error)

$q_i$ = reliability of the appraisal (inspection) process at the $i$-th station (*i.e.*, the probability of detecting a defect that has occurred at the $i$-th workstation)

$r_i$ = reliability of the repair job at the $i$-th station (*i.e.*, the probability that an identified defect will be correctly repaired at the $i$-th station). $r_i$ is considered only in a situation where a worker is responsible for correcting his/her own mistakes (*i.e.*, online repair policy).

$C_s$ = internal failure cost per unit

IFC = Expected Total Internal Failure Cost

$C_e$ = external failure cost per unit

EFC = Expected Total External Failure Cost

TFC = Expected Total Failure Cost (*i.e.*, TFC = IFC + EFC).

## 3 Measuring the impact of quality failures under the offline repair policy

To compare and contrast the efficiency and effectiveness of the traditional offline repair policy with the proposed online repair policy, we need to assess the impact of the offline repair policy on the cost of poor quality (*i.e.*, total quality failure cost). In doing so, mathematical equations are developed to determine the total quality failure cost under the offline repair policy. The following subsections delineate the detailed procedure for deriving such mathematical equations.

### *3.1 Controlling quality at the end-of-line and at the repair shop: the offline repair policy*

Under this policy, quality is primarily controlled by final inspectors and offline repair shop workers. When an assembly worker detects a defective or incomplete part during the predetermined cycle time, he/she is required to remove the defective or incomplete part immediately from the assembly line, and start working on the next part. Each incomplete or defective part is tagged ‘incomplete’ or ‘defective’, and is transferred to a separate repair shop. Workers at an offline repair shop will examine each defective or incomplete part and decide whether it should be scrapped or reworked and sold at a discounted price. If a defective part is detected at the final inspection station, it is tagged defective by inspectors and sent to the repair shop. Not all defective parts transferred to an offline repair shop can be saved. Some defective parts may be reworked successfully at additional costs, while some will never be corrected. Maintaining an offline repair shop, however, necessitates the retention of extra workers, floor space, machines and equipment, thereby incurring extra costs and resulting in a loss of productivity.

The number of good parts produced by station (worker) $i$ depends on the reliability of station $i$, $p_i$. Typically, $p_i$ is determined on the basis of a worker's skill level, experience and the amount of prevention efforts a company makes for its workers and quality system. Efforts such as education and training, quality planning and reporting, quality data acquisition and analysis, improvement of product and process design and control can work favourably for the improvement of $p_i$. At each workstation, bad or incomplete parts are identified and removed from the line and transferred to a repair shop. The number of parts being transferred to station $(i + 1)$ depends on the reliability of station $i$ and its reliability of inspection, $q_i$.

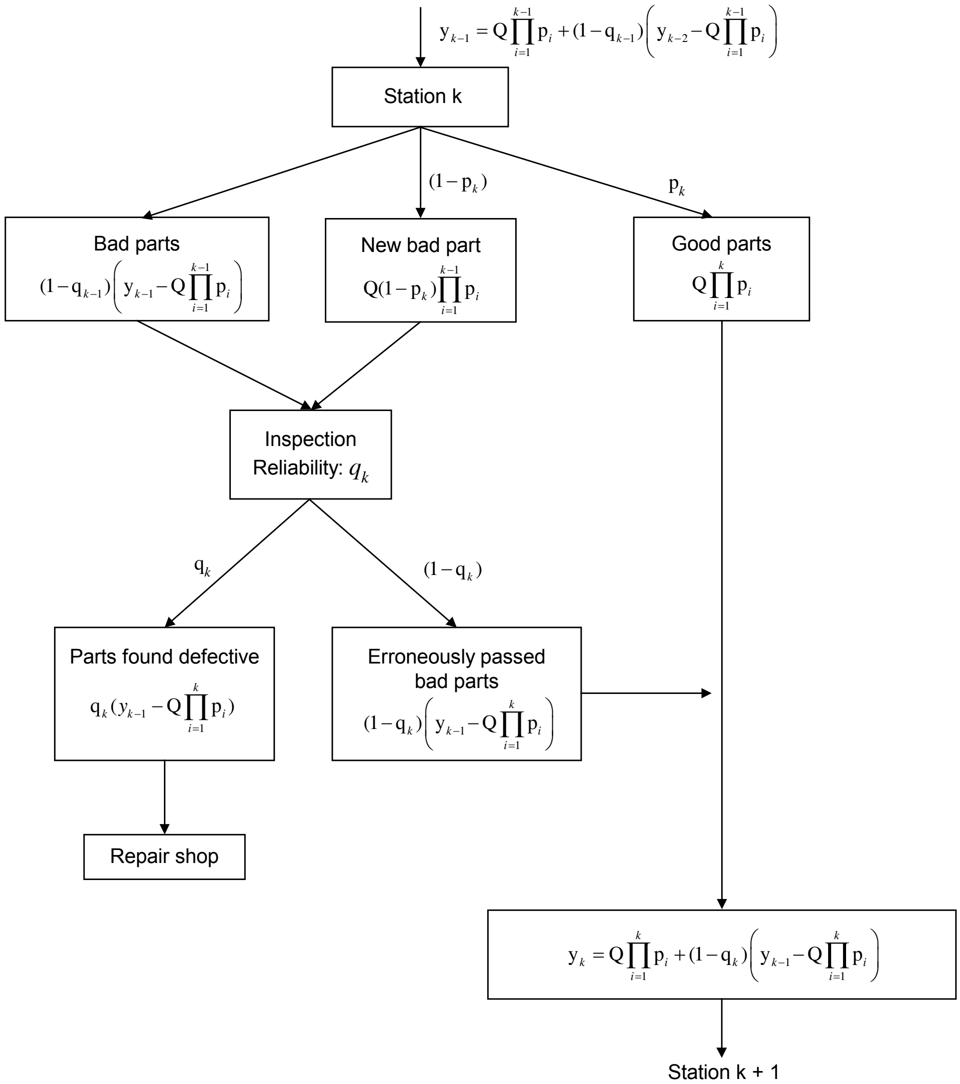
A quality inspection may be done by assembly workers, final inspectors and repair shop workers. Workers' own inspections may not be as rigorous as the ones done by quality inspectors because the offline repair policy mandates that workers should perform assigned tasks and inspect their work simultaneously during a predetermined, very tight cycle time before parts are transferred to a succeeding station. Also, because the primary objective of the offline repair policy is to minimise cycle time and maximise the production rate as much as possible, workers and management believe that workers are not primarily responsible for on-the-spot inspection and correction. It is generally accepted that inspection should be carried out at the end of the line by quality inspectors and correction should be done by the repair shop workers. Therefore, the reliability of inspection by workers may suffer and, consequently, a portion of bad parts may be erroneously passed to the next workstation. It is not unreasonable to assume that the reliability of inspection (*i.e.*, $q_i$) under this policy is inferior to the one under the online repair policy that is discussed in the following section. A schematic of the offline repair policy framework is summarised in Figure 1. As explained earlier, the offline repair policy can avoid line disruptions that may arise from frequent line stoppages, and resultant assembly line idle times. In general, capacity (manpower and machine/equipment) utilisation may be higher than that of the online repair policy.

### *3.2 Quality failure costs model for the offline repair policy*

Note that the proportion of good parts over the total production will be $\prod_{i=1}^{m} p_i$. As mentioned earlier, bad parts may be delivered to customers mistakenly because of workers' imperfect or insufficient inspection time, thereby incurring external failure costs. The Expected Total External Failure Costs (EFC) can be obtained by multiplying unit external failure cost, $C_e$, by the number of bad parts delivered to customers because of imperfect inspection. That is:

$$\mathrm{EFC} = C_e \cdot \left\{ (1 - q_m) \left( y_{m-1} - Q \prod_{i=1}^{m} p_i \right) \right\}. \tag{1}$$

**Figure 1** A schematic of the offline repair policy at station $k$




At each workstation, a worker can identify defective parts with a probability of $q_i$. If tagged defective, these defective or incomplete parts will be transferred to a separate repair shop and will incur internal failure costs. The Expected Total Internal Failure Costs (IFC) is calculated by multiplying unit internal failure cost, $C_s$, by the total number of parts found to be defective at the end of the line. That is:

$$\text{IFC} = C_s \cdot \left[ (1-p_1)\, q_1\, Q + \sum_{h=2}^{m} \left\{ q_h \left( y_{h-1} - Q\prod_{i=1}^{h} p_i \right) \right\} \right]. \tag{2}$$

Hence, the Expected Total Failure Cost (TFC) is obtained by summing IFC and EFC:

$$\mathrm{TFC} = \mathrm{C}_s \cdot \left[ (1-\mathrm{p}_1)\,\mathrm{q}_1\,\mathrm{Q} + \sum_{h=2}^{m} \left\{ \mathrm{q}_h \left( \mathrm{y}_{h-1} - \mathrm{Q} \prod_{i=1}^{h} \mathrm{p}_i \right) \right\} \right] + \mathrm{C}_e \cdot \left\{ (1-\mathrm{q}_m) \left( \mathrm{y}_{m-1} - \mathrm{Q} \prod_{i=1}^{m} \mathrm{p}_i \right) \right\}. \quad (3)$$

The parts found to be defective and/or incomplete at the end of the line are typically transferred to a separate repair shop, and are reworked, retested and re-inspected. This model does not specifically include rework costs associated with such activities. It is assumed that the unit internal failure cost, $C_s$, implicitly represents part of the cost of operating a repair shop. The amount of repair time required to correct each defective (or incomplete) item will be problem specific, and dependent on the nature of repair, thereby making such cost calculations very difficult. For example, if a correction requires a total disassembly of the part rather than a simple attachment on the end item, the impact on the cost of repair could be considerably significant. The percentage of defective units that can be successfully reworked will also play an important role when determining the total number of reworked units that can be shipped to customers.

## 4 Measuring the impact of quality failures under the online repair policy

To examine whether the proposed online repair policy outperforms the traditional offline repair policy in terms of cost-saving opportunities, we develop mathematical equations that can assess the true impact of the online repair policy on the cost of poor quality (*i.e.*, total quality failure cost). The following subsections delineate the detailed procedure for deriving such mathematical equations.

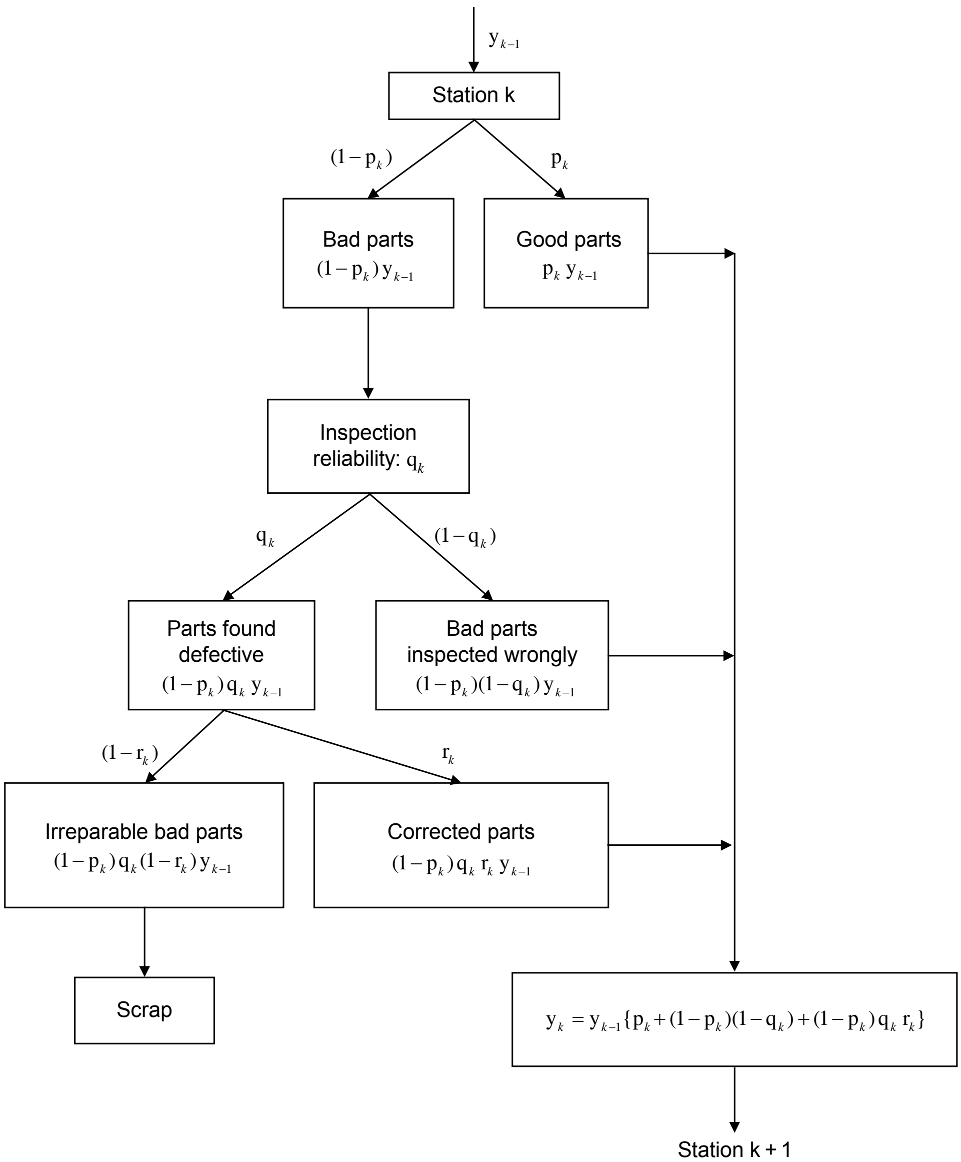
### *4.1 Assuring quality at the source: the online repair policy*

Under the online repair policy (a line-stop repair policy), workers are empowered to have the authority and the responsibility to stop the line when abnormalities occur. With the exception of extreme circumstances (*e.g.*, safety hazards, emergencies), workers are strongly encouraged to stop the line whenever work cannot be done according to work standards or production requirements. Management and workers should make every effort to anticipate or bring problems to the surface beforehand so that line stoppages can be avoided. If a problem still persists, the worker stops the line and switches on the abnormality indicator (*e.g.*, *Andon*, *Poka Yoke* devices, buzzer, line-stop buttons). Once a line is stopped, a ‘help team’, which consists of maintenance crews, supervisors, engineers, utility workers and/or available workers from adjacent workstations, is summoned to the spot immediately. Personnel that may be affected by the problem should also come to the station for on-the-spot confirmation as soon as a line stop is signalled. As problems are identified and solved promptly, resultant feedback will speed up workers’ learning processes, thereby contributing to continuous productivity and quality improvement.

### *4.2 Quality failure cost model for the online repair policy*

Under this policy, the primary responsibility of inspecting and controlling quality lies in the hands of workers who perform the assigned tasks, not quality inspectors. At each workstation, a worker is required to assure quality by inspecting and correcting his/her own work after performing the assigned tasks, and is fully responsible for the quality of the performed tasks. Since the online repair policy inherently requires workers to have reliable inspection capabilities and to work within a time commitment for inspection and repair, the probability of passing defective parts to the next station would be minimal and negligible. Increased spending on prevention efforts such as education and training, product and process design, and inspection technology would work favourably in enhancing the reliability of the workers' skill level for inspecting and repairing defective parts. Figure 2 shows a schematic of the online repair policy.

**Figure 2** A schematic of the online repair policy at station *k*



The number of good parts to be produced at the end of the line will be a function of $p_i$, $q_i$ and $r_i$. Bad parts are also produced with the probability of $(1–p_i)$ at each workstation but inspected rigorously with the probability of $q_i$ and repaired with the probability of $r_i$. Corrected parts are included in the computation of good parts. When workers cannot perform assigned tasks as specified, bad parts may be produced with the probability of $(1–p_i)$ at each workstation. These bad parts are identified by the worker's inspection. If bad parts are repairable and fixed correctly, rectified parts will be transferred to the next workstations. If bad parts are irreparable because they are severely damaged, or workers do not have the proper skills to fix them, or parts are corrected improperly, they are scrapped from the line, thereby incurring internal failure costs. Thus the Expected Total Internal Failure Cost (IFC) is computed by multiplying $C_s$ by the number of bad parts found to be defective at the end of the line:

$$\mathrm{IFC} = \mathrm{C}_s \cdot \left\{ \sum_{k=1}^{m} (1-\mathrm{p}_k)\,\mathrm{q}_k\,(1-\mathrm{r}_k)\,\mathrm{y}_{k-1} \right\}. \tag{4}$$

There may be a chance that a certain portion of bad parts will still be transferred to succeeding stations because of workers' unreliable inspection techniques (skills), inappropriate inspection methods, outdated inspection technology, or maladjusted and misaligned testing equipment. Human factors such as lack of motivation, fatigue and distraction could also contribute to poor inspections. However, it is not unreasonable to assume that the probability of defective parts passing a series of rigorous inspections (especially in a long assembly line) at every workstation is very small and negligible. Thus, the proportion of these parts has not been considered in the proposed models. The expected number of bad parts to be delivered to customers because of imperfect inspection (BPC), which results in external failure costs, can be obtained as follows:

$$\mathrm{BPC} = \mathrm{Q} \cdot \prod_{k=1}^{m} (1-\mathrm{p}_k)(1-\mathrm{q}_k). \tag{5}$$

The Expected Total External Failure Costs (EFC) can then be obtained by multiplying BPC by $C_e$:

$$\mathrm{EFC} = C_e \cdot \left\{ \mathrm{Q} \prod_{k=1}^{m} (1-\mathrm{p}_k)(1-\mathrm{q}_k) \right\}. \tag{6}$$

Thus, the Expected Total Failure Costs (TFC) of the online repair policy is given as:

$$\mathrm{TFC} = \mathrm{C}_s \cdot \left\{ \sum_{k=1}^{m} (1-\mathrm{p}_k)\,\mathrm{q}_k\,(1-\mathrm{r}_k)\,\mathrm{y}_{k-1} \right\} + \mathrm{C}_e \cdot \left\{ \mathrm{Q} \prod_{k=1}^{m} (1-\mathrm{p}_k)(1-\mathrm{q}_k) \right\}. \tag{7}$$

## 5 Computational experiments

To verify the efficiency and effectiveness of the proposed online repair policy relative to the traditional offline repair policy, we conducted a series of computational experiments comparing the cost saving potentials of the online repair policy to those of the offline repair policy under various scenarios involving different worker skills for solving Equations (1) through (7) specified in Sections 3 and 4. The following subsections provided the detailed results of the computational experiments.

### *5.1 Experimental scenarios*

The purpose of this experiment is to investigate the impact of two different repair policies on quality assurance in terms of total quality failure costs. We measure the performance of the online repair policy by considering three key line configuration parameters: the length of an assembly line in terms of the number of assembly workstations, the arrangement of assembly workers on an assembly line with respect to their skill levels, and the effect of unit failure costs ($C_s$ and $C_e$). More specifically, this study makes an attempt to find answers for the following questions:

- Q1: *What will be the effect of longer assembly lines on quality failure costs under two different repair policies?* The longer assembly lines tend to have more tasks to be performed and consist of more workers (workstations), thus entailing more room for errors and variations. We investigate the effectiveness of two repair policies by examining whether the length of an assembly line has any impact on the performance under different line configurations.
- Q2: *Will the different arrangements of workers, with respect to their skill levels, have any effect on quality failure costs under two different repair policies?* Typically, in the absence of the need for special skill matching, workers are placed on workstations randomly without much emphasis on their skill levels, except at the final inspection station under the offline repair policy. Under the online repair policy, the responsibility and the power of quality assurance are delegated to workers on the line. We investigate the effectiveness of two repair policies under four different arrangements.

  Arrangement 1 Arrange workers in *random* order without recognising the different skill levels of the workers.

  Arrangement 2 Arrange workers in *ascending* order. A worker with the lowest skill (least experienced) will be placed on the first workstation, and a worker with the highest skill (most experienced) will be placed on the last workstation.

  Arrangement 3 Arrange workers in *descending* order. A worker with the highest skill will be placed on the first workstation, and a worker with the lowest skill will be placed on the last workstation.

  Arrangement 4 Assume that worker capabilities (skill levels, experiences, *etc.*) are equal.
- Q3: *What will be the impact of unit failure costs (i.e., unit internal failure cost, $C_s$ and unit external failure cost, $C_e$) on the performance of the two different repair policies, when there is a significant difference between $C_s$ and $C_e$?* We examine the impact of $C_s$ and $C_e$ on the performance of the two different repair policies by recognising a possible difference between $C_s$ and $C_e$.

With this in mind, we have designed the experiment so that the results can reasonably reflect the goals of the experiment. Two computer programs have been written in MS Excel 2000 with Visual Basic. Each computer program calculates the IFC, EFC and TFC of each repair policy based on the proposed failure cost models. The cost savings (or loss) are then computed to observe the effectiveness of the online repair policy over the offline repair policy. The framework of the computational experiment is as follows:

- The length of an assembly line (the number of workstations, *m*): ten different cases ($m$ = 10, 20, 30, 40, 50, 60, 70, 80, 90, 100). These values of $m$ reflect small to fairly large assembly lines.
- Different skill levels of workers: The values of $p_i$, $q_i$ and $r_i$ are randomly generated within the range of 0.8 and 1.00. For example, in the case of Arrangement 2 with m = 10, ten different values of $p_i$, $q_i$ and $r_i$ are randomly generated and arranged in ascending order. The lowest values of $p_i$, $q_i$ and $r_i$ are assigned to the novice (*e.g.*, a worker who may have just finished basic training and has been assigned to assembly operations), and the highest values of $p_i$, $q_i$ and $r_i$ are assigned to the most experienced (skilled) worker. While there is a possibility that a skilled worker's inspection reliability ($q_i$) could be worse than that of a less-skilled worker, for the simplicity of the experiment we have assumed that skilled workers would have higher values of $p_i$, $q_i$ and $r_i$ than less-skilled workers.
- Three different scenarios of unit failure costs per problem: $C_s > C_e$, $C_s = C_e$, $C_s < C_e$ (assumed to be the same for both policies). As discussed before, $C_s$ represents a unit internal failure cost and $C_e$ represents a unit external failure cost. In this experiment, we have considered three different cases. The first case ($C_s > C_e$) reflects a traditional quality costing system in which internal failure costs are assumed to be larger than external failure costs, and the definition of quality is based on 'conformance to specifications'. Feigenbaum (1991) suggests that internal failure costs are approximately four times as much as external failure costs, and this ratio has been used in the experiment. In the second case ($C_s = C_e$), we assume that there is no noticeable difference between the two unit failure costs. The third case ($C_s < C_e$) reflects today's emerging perspective that recognises the importance of customer satisfaction and the impact on potential and current customers when defective items are delivered to customers. These issues are discussed in further detail in the later sections.

A total of 3200 test problems were randomly generated. For each test problem, IFC, EFC and TFC were computed for both repair policies, and the average savings of the online repair policy over the traditional offline repair policy were estimated. The savings were calculated as follows: Let $TFC_{OFF}$ = Expected Total Failure Cost resultant from the offline repair policy and $TFC_{ON}$ = Expected Total Failure Cost resultant from the online repair policy. Then, the savings (or loss in terms of negative savings) of the online repair policy over the offline repair policy were computed as follows:

$$\text{Savings }(\%) = \frac{(\text{TFC}_{OFF} - \text{TFC}_{ON})}{\text{TFC}_{OFF}} \times 100.$$

### *5.2 The results of the computational experiment*

Both Tables 1 and 2, along with Figures 3 and 4, summarise the experimental results showing that the online repair policy outperformed the offline repair policy substantially in all possible comparisons. In regard to *Q1*, both tables and figures clearly indicate that the average savings of the online repair policy decrease gradually as an assembly line becomes longer, regardless of the different arrangement of workers and unit failure costs. In general, an inverse relationship between the length of the assembly line and the amount of cost savings shows that the longer the assembly line, the less effective the online repair policy. This result was expected because when all machines, tools and operators are not 100% reliable, longer assembly lines will entail more room for errors, thereby increasing the probability of producing incomplete and defective parts. This result has also been confirmed by Robinson *et al.* (1990).

**Table 1** Average cost savings (%): arrangement of workers with respect to skill levels

| | *Average savings (%)* | | | |
|---|---|---|---|---|
| *m* | *Descending* | *Random* | *Equal* | *Ascending* |
| 10 | 98.73 | 94.38 | 86.11 | 84.20 |
| 20 | 97.23 | 93.59 | 84.59 | 77.82 |
| 30 | 95.12 | 92.52 | 83.00 | 72.68 |
| 40 | 91.85 | 90.73 | 81.35 | 68.73 |
| 50 | 87.43 | 89.47 | 79.64 | 66.12 |
| 60 | 80.34 | 88.37 | 77.88 | 64.03 |
| 70 | 72.08 | 87.21 | 76.08 | 62.67 |
| 80 | 61.77 | 86.01 | 74.26 | 61.59 |
| 90 | 51.18 | 84.53 | 72.41 | 60.84 |
| 100 | 40.43 | 82.82 | 70.55 | 60.64 |
| Mean | 77.62 | 88.96 | 78.59 | 67.93 |
| SD | 20.57 | 3.89 | 5.26 | 8.00 |

Note: Each figure is based on 50 test problems generated randomly.

In regard to *Q2*, Table 1 and Figure 3 show the effectiveness of the online repair policy under four different arrangements of assembly workers in accordance with their skill levels. The results show that an arrangement of workers in ‘descending’ order will bring substantial savings in shorter assembly lines ($m \leq 40$). The savings decline rapidly as the line becomes longer. In fairly long assembly lines ($m \geq 90$), this arrangement performed poorly among the four different arrangements. Overall, the performance of the ‘random’ arrangement was consistently higher and outperformed the other arrangements with an exception of shorter assembly lines ($m \leq 40$).

**Table 2** Average cost savings (%): the effect of unit failure costs

| | *Average savings (%)* | | |
|---|---|---|---|
| *m* | $C_s > C_e$ | $C_s = C_e$ | $C_s < C_e$ |
| 10 | 96.22 | 85.43 | 87.62 |
| 20 | 91.43 | 78.53 | 82.58 |
| 30 | 89.46 | 72.37 | 78.15 |
| 40 | 89.34 | 66.68 | 75.16 |
| 50 | 87.88 | 61.94 | 71.12 |
| 60 | 86.74 | 56.58 | 69.98 |
| 70 | 82.70 | 51.52 | 65.00 |
| 80 | 81.75 | 46.26 | 61.36 |
| 90 | 81.86 | 40.93 | 54.99 |
| 100 | 79.43 | 36.29 | 53.98 |
| Mean | 86.68 | 59.65 | 69.99 |
| SD | 5.23 | 16.29 | 11.28 |

Notes:
1 Each figure is based on 40 test problems generated randomly (*i.e.*, ten problems for 'random' arrangement, ten problems for 'ascending' arrangement, ten problems for 'descending' arrangement and ten problems for 'equal' arrangement).
2 A ratio of four to one has been used for the case of $C_s > C_e$ (*i.e.*, $C_s = 4$ and $C_e = 1$).
3 A ratio of one to four has been used for the case of $C_s < C_e$ (*i.e.*, $C_s = 1$ and $C_e = 4$).

**Figure 3** Comparison of four different arrangements

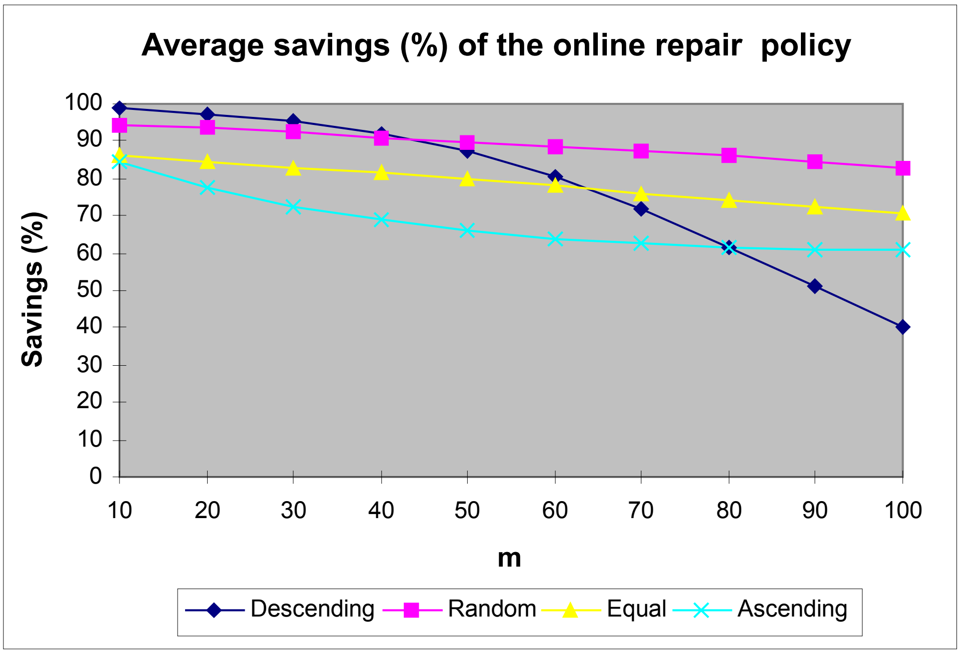
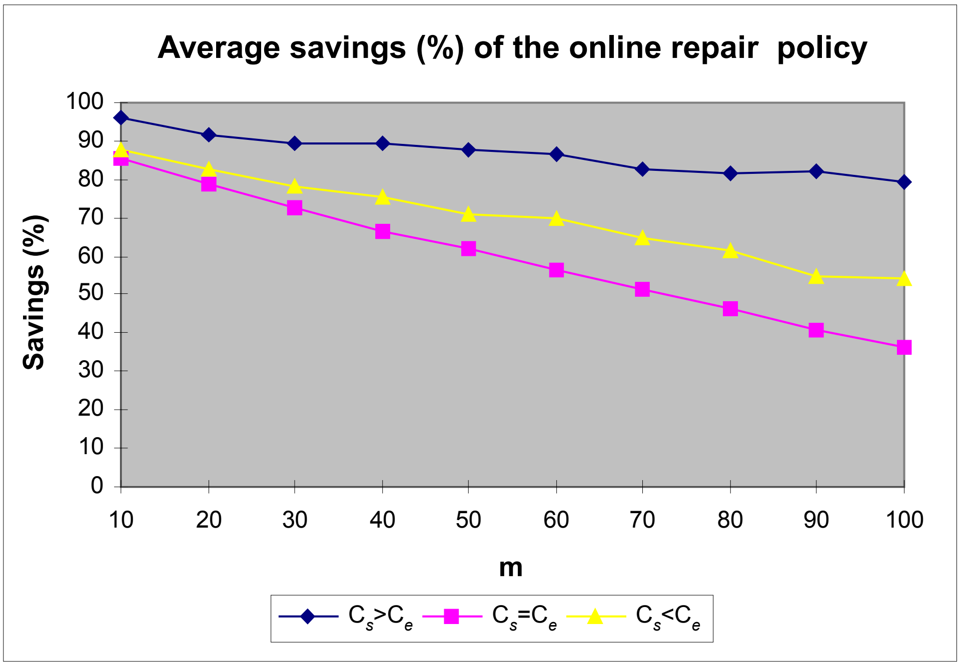


**Figure 4** Comparison of three different cases: the effect of unit failure costs




In regard to *Q3*, Table 2 and Figure 4 indicate that when $C_s$ is far greater than $C_e$, the average savings of the online repair policy become substantial, followed by $C_s = C_e$ and $C_s < C_e$. The savings are particularly high in shorter assembly lines. The gap among the three different cases becomes wider as the line becomes longer. In summary, the results suggest that the online repair policy should be the dominant repair policy, especially when a unit internal failure cost, $C_s$, is substantially higher than a unit external failure cost, $C_e$, as is the case under a traditional COQ framework (Feigenbaum, 1991).

## *5.3 Discussion*

In the previous section, we obtained the average cost savings (%) by assuming that $C_e$ and $C_s$ remain constant for both policies (*i.e.*, $C_s$ and $C_e$ of the offline repair policy are the same as $C_s$ and $C_e$ of the online repair policy). In typical factory settings, however, this may not be the case. As described before, when a defective part is shipped to the customers, it can incur external failure costs. Because the unit external failure cost, $C_e$, is assumed to be the same for both repair policies, the same $C_e$ has been used in the experiment. For normal scraps and losses that occur after parts are tagged irreparable, both policies may have similar cost estimates. In practice, however, it is highly likely that the offline repair policy will incur much higher Internal Failure Costs (IFCs). When a part is tagged reparable and requires a correction, the offline repair policy may be more costly than the online repair policy. Since all reworks are done at a separate repair shop, maintaining such a shop (or running a regular assembly line on an overtime basis, if necessary) would necessitate the retention of extra workers, floor space, machines and equipment, thereby incurring extra costs.

By contrast, the online repair policy requires workers to correct defective parts at their own workstations during the given cycle time. Some manufacturing firms even require workers to repair defective parts on their own time after work. Although workers are given the authority to stop the line and make necessary decisions to assure quality, workers are also responsible for the workmanship. Considering this, we could easily assume that the $C_s$ of the offline repair policy could be higher than that of the online repair policy. Therefore, it is also reasonable to assume that the average savings of the online repair policy might be much higher than the ones provided in the tables if we could get realistic estimates of $C_s$ and $C_e$ under the two different policies.

In this study we assumed a stabilised manufacturing process under which a line can be stopped whenever assembly operations cannot be performed in accordance with work standards or production requirements. In practice, however, the benefit of stopping a line may not be fully achieved if abnormalities typically occur at the later stages of assembly operations, or inspection and repair can be done effectively at a separate repair shop. This point has been partially validated in Tables 1 and 2. In the case of 'descending' arrangements, where highly skilled workers are placed in early stages of assembly operations and less-experienced workers are placed in later stages of operations, the savings decreased at a faster rate in longer assembly lines.

As mentioned earlier, prevention and appraisal costs were not factored into the computation of the quality failure costs in our study owing, in part, to the difficulty involved in generalising the concept. According to Feigenbaum (1991), prevention costs do not exceed 5% to 10% of the total quality cost and the appraisal cost is in the neighbourhood of 20% to 25%, while internal and external failure costs may represent about 65% to 70%. In general, it is conceivable to assume that the online repair policy requires more prevention efforts than the offline repair policy. Implementing an online repair policy not only requires a strong commitment by the top management but also necessitates far greater investments in employee education and training, quality planning activities, and product and process design improvements than an offline repair policy. However, such prevention efforts would, in turn, ultimately improve the reliability of the workmanship and inspection skills of the workers, thereby further decreasing internal and external failure costs.

It is also noteworthy that the online repair policy can reduce typical appraisal costs by delegating line-stop authority to workers. In a JIT production system that focuses heavily on the elimination of wastes to make the system lean, appraisal costs may be viewed as unnecessary waste resulting from a traditional quality management system that relies on end-of-line inspection and the offline repair policy. Costs pertaining to quality inspectors, inspection stations, tools and equipment can be eliminated by empowering workers and making each workstation an inspection and control point. In addition, correction of errors in earlier processing through the online repair policy can lower appraisal costs by eliminating or reducing the need for work-in-process and finished goods inspections.

Finally, intangible benefits of the online repair policy may also be carefully considered in assuring quality on an assembly line. In the online repair policy, every problem or abnormality that causes a line stop is documented using a confirmation form and analysed thoroughly by a group, including a help team. After the root cause of a problem is identified, permanent remedies which would prevent a recurrence of the problem are developed and fully implemented throughout the necessary workstations. The online repair policy allows companies to discover quality problems at an earlier stage, trace down the problems systematically, and implement countermeasures promptly.

The online repair policy also creates an induced learning environment. Workers and management become more aware of the causes and effects of problems that are detrimental to quality, and are consciously involved with problem solving. As a matter of fact, Womack *et al*. (1990) discovered that as workers were fully empowered to stop the line and they gained experience in identifying and correcting problems, their yields reached 100% and the assembly line practically never stopped.

## 6 Summary and conclusions

Our study was based on the premise that workers are the best sources of quality improvement and quality can be controlled and assured at the workstations by the workers themselves, rather than at the final inspection or at separate repair shops. In this paper, we have examined the effectiveness of two different assembly line repair policies on quality assurance. Despite the fact that the offline repair costs more (usually ten times) than the online repair, many manufacturing firms have been hesitant to adopt the online repair policy in assuring quality on an assembly line owing to its unproven savings potentials. To integrate the online repair policy with TQM concepts, we have developed two cost models from the perspective of quality failure costs. Conceptual backgrounds of two policies have been discussed and general frameworks have been proposed using flow charts. Through the computational experiment, we have demonstrated that the proposed framework can be a valuable performance measure for evaluating the contribution of the online repair policy to quality improvements. The computational results show that the online repair policy can bring substantial cost savings over the offline repair policy under different assembly line configurations. Regardless of the length of the assembly line and the workers' skill levels, placing workers '*randomly*' on an assembly line will result in consistently high savings. The results also showed that the savings could be considerable when a unit internal failure cost, $C_s$, was much higher than a unit external failure cost, $C_e$, as was the case under a traditional COQ framework.

Although our study has focused on cost savings, future research can be expanded to include increases in revenues and profits. Considering that the effectiveness of any quality improvement programme is determined by its ability to contribute to customer satisfaction and profits, it is not unreasonable to measure real profit gains when the savings of the online repair policy are achieved. However, because quality assurance is considered to be a long-term commitment, and long-run quality improvement and profitability are closely related, the overall impact of quality improvement should be carefully monitored and assessed over an extended period of time. As quality improves, productivity increases and the costs associated with poor quality decline. While quantifiable gains in productivity and costs savings can be easily measured, there may be some hidden, intangible benefits that are difficult to trace. For example, customers' perception of a company's products as being of high quality and its competitive posture, which may not be readily quantifiable, could result in higher profitability in the long run.

Finally, one thing that is missing in the current study, as well as in the literature on COQ, is a consideration of customer value that is directly tied to customer satisfaction levels. Current COQ research falls short of recognising 'invisible loss', which is not taken into consideration for calculating external failure costs. For example, 'invisible loss' may occur when dissatisfied customers bad-mouth the poor quality to other customers. In other words, costs resulting from tarnished reputation and lost customer goodwill should be included in this category. Although these costs are mostly nonquantifiable and difficult to trace, reasonable efforts should be made to reflect these costs to some extent when measuring the cost of poor quality.

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