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Ergonomics Improvements of the Visual Inspection Process in a Printed Circuit Assembly Factory

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An ergonomics improvement study was conducted on the visual inspection process of a printed circuit assembly (PCA) factory. The process was studied through subjective assessment and direct observation. Three problems were identified: operators' eye problems, insufficient time for inspection and ineffective visual inspection. These problems caused a huge yearly rejection cost of US $298,240, poor quality, customer dissatisfaction and poor occupational health and safety. Ergonomics interventions were made to rectify the problems: reduced usage of a magnifying glass, the use of less glaring inspection templates, inspection of only electrically non-tested components and introduction of a visual inspection sequence. The interventions produced savings in rejection cost, reduced operators' eye strain, headaches and watery eyes, lowered the defect percentage at customers' sites and increased the factory's productivity and customer satisfaction.

occupational health and safety   eye problems   quality   productivity   cost savings

1. INTRODUCTION

Many studies have been conducted on sustained vigilance [1, 2, 3, 4, 5, 6, 7]. Mackworth's [1] experiment found that missed critical signals increased as time went on. Schmidtke's [2] investigation found that observation performance has the shape of an inverted "U" where performance increases when there are more signals per unit of time until it reaches an optimal signal frequency, after which observation performance decreases. Warm [3] and Warm et al. [4, 5, 6] did studies on some factors that affect vigilance performance such as the complexity of symbolic functions for signal detection, the use of head restraints and the types of auxiliary workload. Kroemer and Grandjean [7] summarised the results of the many studies on vigilance. One of the results was that the observation performance of a vigilance task decreased when the subject had to perform under unfavourable conditions. However, to date, there has been no research on the unfavourable conditions of a visual inspection task (which requires constant vigilance) in a printed circuit assembly (PCA) factory.

Several ergonomics studies have been conducted on the visual inspection process in the electronic industry. For example, Helander and Burri [8, 9] conducted a study of an ergonomics intervention at a factory of raw printed circuit boards (PCBs) and sub-assemblies of copier machines. They included some ergonomics interventions in the visual inspection (VI) of PCBs. However, VI of PCA boards (which includes the inspection of PCBs with electronic components on them) was not included in their study. Ntuen [10] carried out research into the

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workload modelling of PCB inspectors using fuzzy logic. Conversely, this paper presents ergonomics improvements to solve work problems faced by PCA inspectors, such as insufficient time for VI, eye problems and ineffective inspection. Hsu and Chan [11] conducted a study of the inspectors' performance and the personality of quality inspectors. That study focused on how personality traits, such as stability, enthusiasm, sensitivity and suspicion affected the inspection performance of PCBs. The present study measured the effects of work problems (faced by PCA inspectors) on inspection performance in terms of defect percentage at customers' sites. Bossemeyer [12] conducted a laboratory experiment to determine human lapses at VI of PCA boards. His focus was on the reduction of error rates and inspection time by applying the principles of Gestalt psychology. In the present study, ergonomics principles were used instead of Gestalt psychology to reduce error rates and inspection time in a factory.

Therefore, the objective of the present research was to conduct an ergonomics study on the VI process at a PCA factory. This study involved a medium-sized factory with six PCA lines, manufacturing PCA motherboards for computer peripherals, such as printers, projectors, network cards, disk drives, etc., with a revenue of about US $120 million per annum. The factory employed about 500 people. The management of the factory consisted of locals but the workers (operators) consisted of locals and immigrants from Indonesia, Bangladesh, etc. The principles of ergonomics were applied to the VI process and the resulting improvements in quality, productivity, cost-benefits and occupational health and safety (OHS) were documented in this paper.

The present research was a part of a series of ergonomics studies in PCA factories in Malaysia, an industrially developing country (IDC), with the purpose of helping the industry (which is one of the biggest industries in the country) to improve quality, productivity and OHS [13, 14, 15, 16, 17, 18, 19, 20, 21, 22]. The preliminary results of the study were presented in Yeow and Sen [20]. The final results are presented in this paper.

2. DESCRIPTION OF MANUFACTURING PROCESSES

The PCA manufacturing process in this study is shown in Figure 1. All PCA lines in the industry generally have similar processes, which consist of the following processes:

1. Surface mounted technology component placement (SMTCP) process: To machine-place surface mounted technology (SMT) components (integrated circuits/chip resistors/capacitors/inductors, etc.) on the PCB and to solder them to their electrical connections.
2. Manual component insertion (MCI) process: To insert through-hole (TH) components (electrolytic capacitors, transistors, resistors, etc.) manually into the PCB and solder them to their electrical connections. These components were much larger compared to the SMT components and their leads penetrated the boards, protruding from the opposite side.
3. VI process: To inspect visually the completed board for defects related to the physical components and the soldered connections using a magnifying glass or microscope.
4. In-circuit electrical test (ICET) process: To electrically test the soldered components and their circuit connections, e.g., to test the values of the resistors, capacitors and inductors for any errors.
5. Functional electrical test (FET) process: To test the completed board for its product functions, e.g., power-up test, printing test.
6. Other processes: Include inspections of incoming components, component preparation (cutting/forming leads of components, programming integrated circuits, etc.), manual soldering, mechanical assembly, packing, Quality assurance of outgoing products and rework of defective boards.

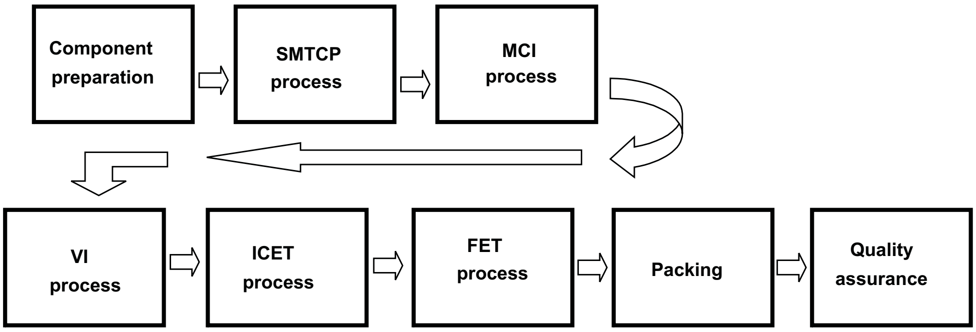

Figure 1. Printed circuit assembly (PCA) board manufacturing process. *Notes.* SMTCP—surface mounted technology component placement, MCI—manual component insertion, VI—visual inspection, ICET—in-circuit electrical test, FET—functional electrical test.

The VI Process has four operations, as shown in Figure 2. The first three operations are performed together in a continuous line after the SMTCP and MCI processes. The final inspection is performed last in the PCA manufacturing prior to packing.

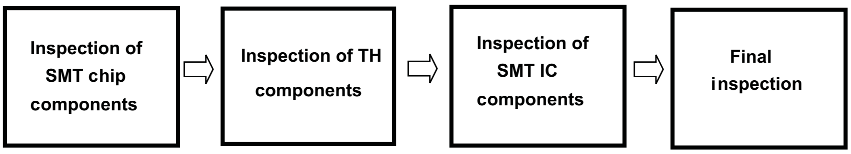

Figure 2. Visual Inspection (VI) process flow. *Notes.* SMT—surface mounted technology, TH—through-hole, SMT IC—Surface Mounted Technology Integrated Circuit.

In the SMT chip components inspection operation, operators use inspection templates (InspT) made up of a conductive material (as a conductive material would not have any electrostatic discharge [ESD] on the PCA board) to aid inspection. An InspT is a piece of cardboard, about the size of a PCA board, with rectangular or circular holes cut to expose the SMT chip components when the template is placed on top of the PCA board. The operators use a 3× magnifying glass, with a built-in lamp called Luxolamp, to inspect the exposed components for defects, such as damaged chips, missing chips, cold solder, insufficient solder, misalignment, etc.

In the TH components inspection operation, operators use an InspT and a Luxolamp to inspect for components, soldering and manual insertion defects, such as damaged components, dry solder, blow-hole solder, wrong components, wrong polarity, lifted components, tilted components, etc.

In the SMT integrated-circuit components inspection operation, operators use a 10–30× microscope to inspect the fine leads of the quad flat pack package integrated circuits for soldering defects, such as, misalignment, insufficient solder, lifted leads, etc.

In the final inspection operation, operators use a 3× Luxolamp to look for board defects, such as dirty solder flux, delamination, smearing stamps, etc. The operators also look for any mechanical assembly defects, such as improper gluing and attachment of bracket, screws, studs, etc., and chassis defects, such as cracks, scratches, poor printing, etc.

The operator uses the IPC-A-610C standard [23] as the acceptable or rejectable criteria for all inspections. This standard is very popular in the PCA industry and it is widely used. The operators have to rely on their memory of the standard to perform inspections.

All rejected boards are sent to the rework process for repairs and then sent back to the beginning of the VI process to be inspected again.

3. METHODS

3.1. Problem Identification

A general survey was conducted on the VI process to ascertain its major work-related problems. This was done by conducting a plant walk-through of the factory, particularly the VI process (refer to the direct observation [DO] method in Drury [24]). Unstructured interviews (also using Drury's DO method) were conducted with 8 employees of different ranks (2 managers, 2 engineers, 2 supervisors and 2 executives) from various departments (production, quality, engineering, training and customer service departments). Qualitative and quantitative data were collected, such as the VI process description, work instructions and the layout of the process, the operators' training method, major work-related problems faced in the process, the cost of customer product returns and possible root causes of the problems.

Also, 3 months' Archival Operation Records and Customer Feedback Data (AORCFD) [25], such as the cost of customer product returns and defect percentage were collected and analysed.

3.2. Detailed Study of the Major Work-Related Problems in the VI Process

Major work-related problems were identified and studied in detail using the methods documented in Table 1.

TABLE 1. Ergonomic Methods Used to Investigate Major Work-Related Problems in the Visual Inspection (VI) Process and Observations Made

Problems	Methods	Observations
Operators' eye problems.	Subjective assessment of problems at work (20 operators were interviewed).	High rating by operators of eye problems: 4.3 ± 0.3
		Operators were facing: • eye strain and headaches 50.5 ± 4.7 % of workdays per week, • watery eyes 29.3 ± 5.4% of workdays per week.
		High rating of fatigue of the upper extremities: 3.9 ± 0.7
	Direct observation of 20 operators for problem confirmation.	High rating by operators of glare from inspection templates: 4.1 ± 0.6.
		All operators used a magnifying glass too frequently, i.e., at an average of 7.34 ± 1.64 hrs/day[1]. They were using a magnifying glass for inspection of all components, regardless of their size.
		Breaks to rest operators' eyes were not allowed due to the continuous production line.
Insufficient time for VI, time stress.	Subjective assessment of problems at work (20 operators were interviewed).	High rating of insufficient time for conducting VI: 4.6 ± 0.3.
	Direct observation of 20 operators for problem confirmation.	100% of components (altogether 338 components/board) were visually inspected although 67.4% were electrically tested.
	Obtain cycle time through direct observation.	On average, operators inspected 7.5 ± 2.3 components/second.
Ineffective VI.	Direct observation of 20 operators on their methods of conducting inspection.	Random scan/search. None of the operators had a fixed or logical method for visual scanning of the whole board during VI.
		The inspected board was very large (130 x 208 cm).
	Subjective assessment of problems at work (20 operators were interviewed).	Random scan/search. None of the operators had a fixed method for visual scanning of the whole board during VI

Notes. $x \pm y \equiv$ average ± *SD*; 1—the figure was extrapolated from the 1-hr direct observation (of the 20 operators) to an 11-hr workday (excluding lunch and tea breaks).

Subjective Assessment (SA) [26] was done by conducting structured interviews with all 20 operators in the VI process.

The operators were all female Malaysian citizens, with an average age of 18.7 ± 2.2 years (minimum 14.6 and maximum 24.1 years old) and an average number of years of experience in the company of 3.6 ± 0.4 years (minimum 2.5 and maximum 4.3 years). This shows that all the operators were young and experienced, with no significant difference among them.

The structured interview questionnaire was designed using Sinclair's [26] subjective assessment method and tested on 3 operators before finalising. The interview questionnaire in the Appendix was used. There were 13 open- and close-ended questions altogether related to workstation design, work environment, work and OHS problems, work tools (e.g., magnifying glasses and inspection templates), quality, productivity, feedback, time constraints and the visual scanning method. The open-ended questions were used to identify the operators' work-related problems, find possible root causes of the problems and to obtain suggestions to overcome them. The close-ended questions were used with Likert's 5-point scale to describe the intensity of specific problems highlighted earlier during the plant walk-through and the unstructured interviews.

DO [24] was made of the VI process using videotape recordings (video camera model GR-AX20 manufactured by JVC, Japan) to confirm the findings of the subjective assessment and to further investigate the work problems.

One-hour of videotape recordings were made of each of the 20 operators at work in the VI process. This added up to a total of 20 hrs of recordings.

The recordings were analysed by playing them in slow motion to investigate a particular problem (e.g., high usage of a magnifying glass, glaring inspection templates, insufficient time for VI, an ineffective method for scanning during VI). The recordings were also played in fast motion to search for the occurrence of a particular incidence (e.g., searching for rest breaks). Cycle time of the VI process, in terms of the number of components inspected per second, was calculated from the recordings by taking the average of 20 operators.

3.3. Ergonomics Interventions and Follow-Up Studies

After the detailed study of the major problems in the VI process, ergonomics interventions were implemented. The problems were tackled one at a time to ensure a clear relationship between cause and effect, i.e., between each intervention and its effects on the problem.

Three to 12 weeks after the interventions, SA and DO were conducted again of the operators to determine the effectiveness of the interventions. Cycle time of the VI process was taken again. The cost of customer product returns and defect percentage data were collected again from customers. Table 1 summarises the methods used in the follow-up studies.

4. RESULTS

4.1. Major Work-Related Problems in the VI Process Based on the General Survey and Detailed Study

From the general survey and analysis of AORCFD (refer to section 3.1), it was found that there were three major work-related problems, i.e., operators' eye problems, insufficient time for proper VI and ineffective visual inspection. The problems are listed in Table 1.

The problems caused many PCA board defects at the customers' sites. The defect percentage was 2.7 ± 0.3%. The boards with defects were returned to the factory, which led to a huge yearly loss of about US $298,240. Those boards should have been detected in the VI process and rectified before reaching the customers. Also, the defect percentage was not acceptable as most customers expected a defect percentage of no more than 0.1%.

The observations of the problems from the detailed study are documented in the Observation column in Table 1. The observations are described in section 4.3 onwards.

4.2. Root Causes of Major Problems, Ergonomics Interventions Implemented and Their Results

Table 2 summarises the root causes of the problems, the ergonomics interventions implemented to rectify the problems and their results. The data in the Root Causes column (in Table 2) is derived from the Observations column in Table 1. The data in the Results column (in Table 2) is taken from the follow-up

TABLE 2. The Root Causes of Work-Related Problems in the Visual Inspection (VI) Process, Ergonomic Interventions Implemented and Their Results

Problems	Root Causes[3]	Ergonomic Interventions	Results
Operators' eye problems.	Too frequent use of a magnifying glass	Operators were instructed to use a magnifying glass only for inspection of small components.	Reduced usage of a magnifying glass to 4.36 ± 1.10 hrs/day (40.6% ↓)[1].
	High glare from Inspection Templates (InspTs)	Replaced InspTs with less reflective templates.	Glare from InspTs was minimised. Operators' rating on glare was reduced to: 2.6 ± 0.3 (36.6% ↓)[2].
		Changed the angle between viewer's line of sight and InspT to avoid specular reflection.	
	No short breaks to rest eyes.	Leaders were instructed to take over the line to allow operators short breaks whenever they felt tired.	Operators' rating of fatigue of the upper extremities was reduced to 2.8 ± 0.5 (28.2% ↓)[2]. The 3 interventions: • reduced eye strain to 14.4 ± 2.6% of workdays per week (36.1% ↓)[2], significantly different from the previous value using WSRT (p = .01), • reduced headaches to 5.3 ± 1.2% of workdays per week (45.2% ↓)[2], significantly different from the previous value using WSRT (p = .01), • reduced watery eyes to 7.5 ± 1.8% of workdays per week (21.8% ↓)[2], significantly different from the previous value using WSRT (p = .04), • reduced the percentage of PCA board defects at customers' sites by 1.3% after 3 weeks of implementation.
Insufficient time for VI.	Too many components to inspect per board.	Operators were instructed to inspect only electrically non-tested components.	Reduced the number of inspected components/second to 2.4 ± 0.3 (67.4% ↓)[1]. Reduced operators' rating on insufficient time for proper inspection to 2.6 ± 0.2 (43.5% ↓)[2]. The intervention reduced defect percentage at customers' sites by 0.8% after 12 weeks of implementation.
Ineffective VI.	No fixed or logical visual scanning method used during VI.	The large board was divided into 3 inspection areas and operators were instructed to inspect from left to right and from top to bottom.	The operators found it easier to inspect using the recommended sequence (ease of use rating: 4.2 ± 0.5)[2]. The intervention reduced defect percentage at customers' sites by 0.4% after 12 weeks of implementation.

Notes. $x \pm y$ ≡ average ± *SD*; WSRT—Wilcoxon Signed Rank Test; ↓ ≡ reduction. 1—data from the direct observation of the follow-up study (section 3.3). 2—data from the subjective assessment of the follow-up study (section 3.3). 3—the root causes were derived from the observations in Table 1.

studies. The interventions are described in the following sections.

4.3. Operators' Eye Problems

Before the ergonomics interventions were implemented, the operators in the VI process were experiencing eye problems (Likert Scale Rating [LSR] 4.3 ± 0.3), i.e., eye strain and headaches (50.5 ± 4.7% of workdays in a week) and watery eyes (29.3 ± 5.4% of workdays in a week).

These problems were due to the operators' excessive use of the magnifying glass (an average of 7.34 ± 1.64 hrs/day). Moreover, the operators were not allowed short breaks throughout the shift (other than two tea breaks and one meal break) due to the continuous production line that fed the PCA boards to them. This was confirmed through DO of all 20 operators (Table 1). Furthermore, the operators used very glaring (LSR 4.1 ± 0.6) InspTs, made of kapton (conductive material), with a reflective yellow colour (Figure 3a).

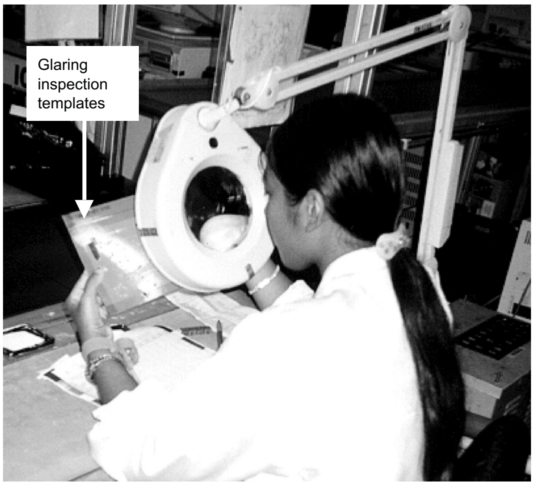

Figure 3a. An operator using inspection templates with very high glare.

The operators also experienced fatigue of the upper extremities (LSR 3.9 ± 0.7) due to long hours (11 hrs) of static work in the visual inspection task (such as carrying the boards during inspection).

Ergonomics interventions were implemented to rectify the eye problems and to reduce static work fatigue. The operators were instructed to use the magnifying glass only when necessary, especially for smaller SMT components (i.e., 0603 SMT component packaging) and this reduced the usage of the magnifying glass to 4.36 ± 1.10 hrs/day. Line leaders were instructed to allow operators to take frequent short breaks when the operators' eyes and arms were tired and to temporarily replace them so that the production line would not halt. The glare from the InspT was minimised by changing to a less-reflective material made of white-coloured paperboard with ESD coating (Figure 3b).

Figure 3b. Ergonomic improvement: the glare from the inspection templates was reduced by changing to a less reflective material.

In addition, the angle between the viewer's line of sight and the InspT was changed by tilting the InspT to avoid specular reflection (Figures 4a and 4b).

Three weeks after the ergonomics interventions, there were significant reductions in eye strain, headaches and watery eyes, glare from inspection templates, fatigue of the upper extremities and defect percentage at customers' sites. Eyestrain was reduced to an average of 14.4 ± 2.6% of workdays in a week (significantly different from the previous value using Wilcoxon

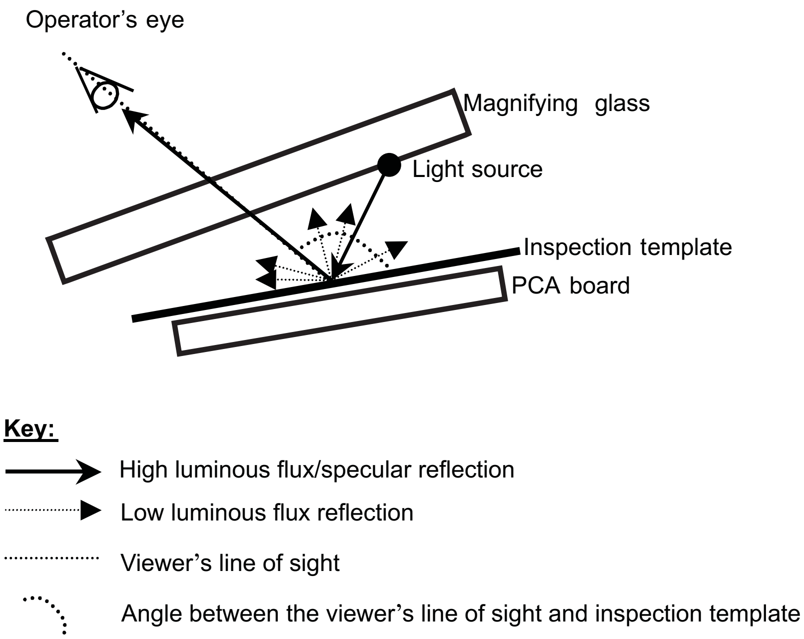

Figure 4a. Viewer's line of sight is at the specular reflection. *Notes.* PCA—printed circuit assembly. The inspection templates have mixed reflection [27].

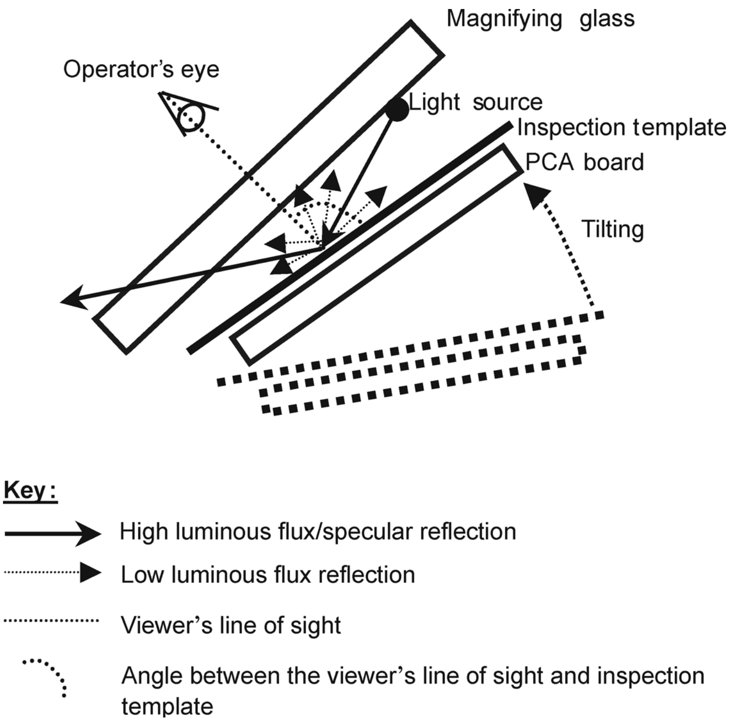

Figure 4b. Viewer's line of sight is avoiding the specular reflection. This is done by changing the angle between the line of sight and inspection template (tilting the template). *Notes.* PCA—printed circuit assembly. The inspection templates have mixed reflection [27].

Signed Rank Test [WSRT], p = .01). Headaches were reduced to an average of 5.3 ± 1.2% of workdays in a week (significantly different from the previous value using WSRT, p = .01). Watery eyes was reduced to an average of 7.5 ± 1.8% of workdays in a week (significantly different from the previous value using WSRT, p = .04). The operators' rating on glare was reduced to 2.6 ±

0.3 (LSR). Their rating on fatigue of the upper extremities was also reduced to 2.8 ± 0.5 (LSR). The percentage of PCA board defects at customers' sites was reduced by 1.3%.

4.4. Insufficient Time for Visual Inspection

Before the implementation of the ergonomics interventions, operators in the VI process did not have sufficient time for conducting VI effectively (LSR 4.6 ± 0.3). They had to inspect 338 components per board within 45 s to follow the speed of the conveyor. On average, the operators had to inspect 7.5 ± 2.3 components per second (based on the actual cycle time measurement from DO).

The ergonomics intervention was made by instructing the operators to inspect only the electrically non-tested components which reduced the percentage of inspected components by 67.4% (from 338 to 110 components per board). The electrically non-tested components were identified by using an inspection template (the components were exposed through the cut holes of the inspection template). The other components were electrically tested in the ICET station; thus VI was not required.

After 12 weeks, the intervention reduced the number of inspected components per second to 2.4 ± 0.3. This also reduced the operators' rating on insufficient time for proper inspection to 2.6 ± 0.2 (LSR). Furthermore, the intervention lowered the defect percentage at customers' sites by 0.8%.

4.5. Ineffective Visual Inspection Method

Before the ergonomics intervention, no operator in the VI process had a fixed or logical method for scanning the whole board (Figure 5a). Instead, they scanned/searched randomly (Table 1). The dimensions of the board were very large (130 × 208 cm), thus it was difficult to perform effective inspection by visually scanning randomly over the board.

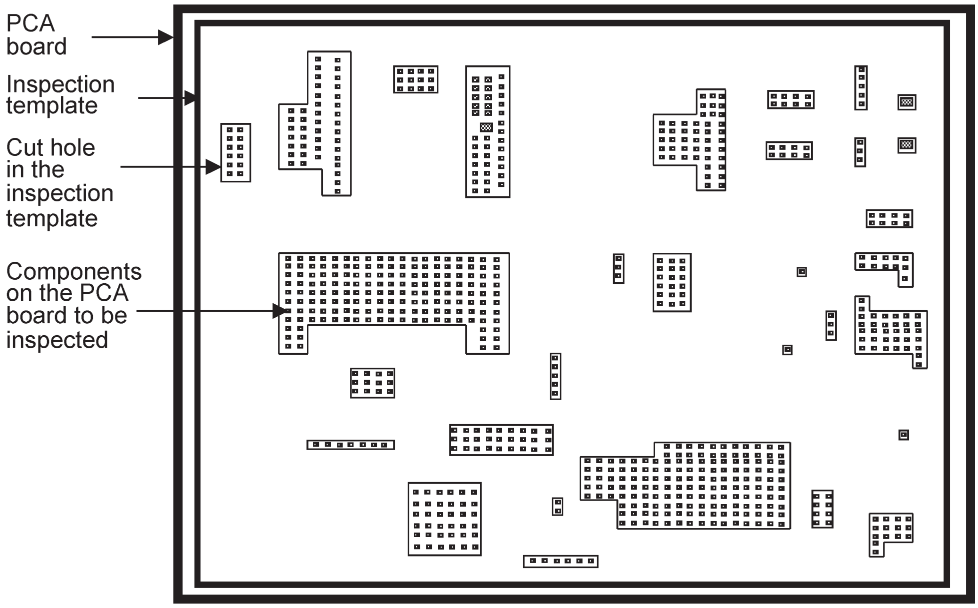

Figure 5a. Visual inspection was performed by scanning randomly. *Notes.* PCA—printed circuit assembly.

Ergonomics interventions were implemented to increase the effectiveness of VI so that more rejects could be captured at the VI process before reaching the customer. The large board was divided into three inspection areas by drawing two horizontal lines on the InspT. The operators were instructed to inspect by following a fixed sequence from left to right and from top to bottom (Figure 5b).

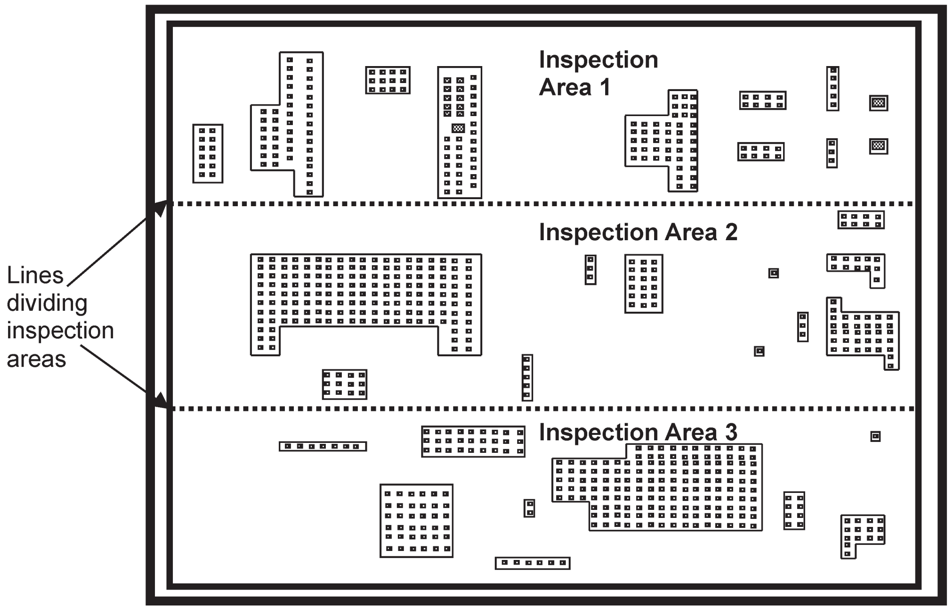

Figure 5b. Visual inspection was performed by scanning from left to right and from top (Inspection Area 1) to bottom (Inspection Area 3).

After 12 weeks, the intervention reduced the defect percentage at customers' sites by 0.4%. The operators reported that it was easier to inspect using the recommended sequence as shown by the high rating they gave to the ease of use (LSR 4.2 ± 0.5).

5. DISCUSSION

5.1. Significant Reduction in Defect Percentage, Savings in Customer Product Returns and Productivity Improvement

The ergonomics interventions in the VI process reduced the defect percentage at customers' sites by 2.5% (calculated from 1.3 + 0.8 + 0.4%) (Table 2). This was translated to a yearly savings of US $276,228 in customer product returns and a non-quantifiable improvement in customer satisfaction because better quality products were delivered.

Although there were still 0.2% defects going to the customers' site (which was above the target of 0.1% set by the customers), they were satisfied with the huge reduction of defects from 2.7 to 0.2%.

Moreover, labour productivity improved by about 9.0% since the operators spent less time in reworking rejects from customers.

5.2. Visual Search Strategies and Optimum Time

Tsao, Drury and Morawski [28] and Karwan, Morawski and Drury [29] found systematic search was more effective than random search. Many researchers [30, 31, 32, 33] discovered that performance feedback, consisting of feedback on inspection errors, inspection time, etc., improved inspection performance. Gramopadhye, Drury and Sharit [34] found that cognitive search using graphical displays combined with performance feedback could enhance VI performance. In this study, visual inspectors' performance improved with the use of VI sequence compared to random search. Performance feedback was practised, whereby inspectors were given feedback on the rejects from customers. However, it was difficult and not feasible in the shop-floor environment to provide cognitive feedback on the scanned patterns of the inspectors.

In this study, the operators complained of insufficient time (based on the high rating of insufficient time). After reducing the number of components inspected per board, the operators faced fewer problems of insufficient time for inspection (LSR on insufficient time reduced from 4.6 ± 0.3 to 2.6 ± 0.2) and their inspection performance improved. Drury [35] presented some models for defining the optimum time to be spent on inspecting a product. Bullimore, Howarth and Fulton [36] found inspection performance involved both speed and errors and people often made a trade-off between them. In addition, they found that inspection performance was affected by the long duration of inspection tasks where vigilance and tiredness might be involved. Although the 2.6 LSR was still significant (because it had to be borne by the operator every day), the author failed to get the factory management's permission to conduct further studies, i.e., to use Drury's [35] models and Bullimore et al.'s [36] findings to discover optimum inspection rates for the operators. This was because they were contented with the current result and afraid that such studies might jeopardise the quality of the production line.

5.3. Discussion on Operators' Eye Problem

Chromatic aberration of the eyes due to the use of a magnifying glass (with a thick lens) can cause visual fatigue which manifests itself as eye strain, headaches and watery eyes [7, 37]. This probably explains why these symptoms were reduced by reducing the use of a magnifying glass from 7.34 ± 1.64 hrs to 4.36 ± 1.10 hrs.

Even after the ergonomics interventions, there still remained significant eye problems, i.e., operators were still facing eye strain 14.4 ± 2.6% of the 5-workday week; the LSR for glare was 2.6 ± 0.3. It was suggested that the factory introduce job rotation to reduce the total exposure to these problems and to conduct periodic eye tests on the operators to monitor the effects of these problems. However, the management did not take the authors' advice because the figures after the ergonomics interventions showed great improvements from the previous figures. Furthermore, job rotation would require more personnel to coordinate this programme and to train the operators to learn other jobs. In addition, eye tests would require the service of experts, such as an optician, which was an added cost. The management was not willing to spend on these purposes.

5.4. Comparison of the Results with Helander and Burri's Studies

This study is compared with Helander and Burri's studies [8, 9], which are closest to this study. Their studies were also done in an electronics industry and included ergonomics interventions in VI (but they were not confined to VI).

This study reaped better results in injury reduction, i.e., 36.1% in eye strain (50.5–14.4%), 45.2% in headaches (50.5–5.3%), 21.8% in watery eyes (29.3–7.5%) compared to 21 and 19% (in either study the specific types of injury reductions were not mentioned) in Burri and Helander's [8] and Helander and Burri's [9] studies. However, this study had yield and labour productivity improvements (2.5 and 9.0%, respectively) lower than those of Helander and Burri's [9] (18 and 23%, respectively) and Burri and Helander's [8] (12 and 8%, respectively).

Nevertheless, the yearly savings for all three studies were significant, i.e., US $276,228 (this study), US $1,639,000 [8] and US $7,375,000 [9]. It is to be noted that this study was conducted in a medium-sized factory so savings were expected to be lower than those of the large factories in Burri and Helander's, and Helander and Burri's studies.

5.5. Poor Attitude Towards Ergonomics Studies

One lesson learned from this research which is useful for practical ergonomists is the management's intransigent attitude towards ergonomics studies. The irony is, even though excellent results had been shown in the interventions, the management did not sanction follow-up studies on inspection and eye problems. They feared that such studies would affect their output and were unwilling to spend funds on improving workers' OHS. This may be due to their poor understanding of ergonomics as it is a new field in IDCs [38]. Much education and justification are needed for any ergonomics programme to be successful in an IDC.

5.6. Limitations of the Study

Only a small number of operators (20) were involved in the ergonomics study because there were not many operators doing the VI task in the VI process. Taking samples from other factories was considered. However, an identical factory with similar operators, using the same type of inspection templates, producing the same products and facing the same problems could not be found.

Controlled experiments could not be carried out for all the ergonomics interventions due to insufficient VI operators in the factory (only 20 of them). Again, finding samples from another identical factory was difficult. This limitation was similar to the limitation found in the case of Helander and Burri's [9] study of a PCB factory.

Only aggregate results of the three interventions (reducing magnifying glass usage, changing to less glaring InspTs and allowing short breaks) in the operators' eye problems were taken (such as the percentages of eye strain, headaches, watery eyes and defects). This was because the factory management did not allow the time-consuming factor-by-factor experiments in the experimental design. They were very anxious to solve problems in the shortest possible time. Therefore, the study was unable to determine the exact contribution of each intervention to the reduction of those measurements.

This study was unable to examine the operators' eye movements during VI to measure visual fatigue. This was because the methods to measure eye movements, such as electro-oculography, corneal-reflection, limbus tracking, contact lens methods, pupil-centre corneal reflection and double purkinje image method [39] were too expensive to set up. The measuring instruments used (for these methods) were too costly for the factory in an IDC.

The reflectance before and after the change of the InspTs was too difficult to measure. Also, the glare indices of the InspTs were complicated to measure. This was because these measurements would change depending on the angle/position of the eyes with respect to the InspT [27]. Also, the measuring instruments were too costly.

6. CONCLUSION AND RECOMMENDATIONS

The ergonomics interventions considered in this study were simple and low-cost. The total cost of the interventions was about US $300 (a one-off cost), i.e., the cost of replacing all the InspTs in the factory. Yet, they reaped many benefits in terms of improving the operators' OHS, saving rejection costs for the management, enhancing the overall quality and productivity of the factory and increasing customer satisfaction with fewer rejections at customers' sites.

The results of the study in this paper are beneficial for the PCA industry since most PCA factories have similar manufacturing processes and machines as documented in section 2. They may face similar problems as found in this paper.

The study was conducted in a medium-sized factory with limitations in machines, manpower, capital and other resources. Therefore, their results may be particularly useful for Malaysian PCA factories because most of them are small to medium-sized companies, with the same limitations. It is recommended that similar studies be conducted in other PCA factories, especially those from other IDCs. They may likely receive many benefits in quality, productivity and OHS improvements and reduction in rejection cost.

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APPENDIX: The interview questionnaire to identify work-related problems in the Visual Inspection process.

(Note: The questionnaire was translated to the Malay language so that the operators could understand the questions better. The questionnaire was filled by the interviewer.)

Date:	***Age:***	***Right/Left Handed***	***Current Experience: years***
Subject #:	***Weight: kg***		
Operator #:	***Height: cm***	***Right/Left Eyed***	***Previous Experience: years***
Station #:	***Line #:***		

1. What are the difficulties that you face at work? What problems do you have while working at your workstation?

2. Do you find your work strenuous/monotonous/fatiguing/boring/discouraging?

	Low				High
Strenuous					
Monotonous					
Fatiguing (where: _________________)					
Boring					
Discouraging					
Others___________________________					

Why do you feel that way?
What modifications/arrangements will improve the situation?

3. What tasks/subtasks do you enjoy doing?
Most Enjoyable:
Second Most Enjoyable:
Third Most Enjoyable:

4. What tasks/subtasks do you hate doing?
Most Hated:
Second Most Hated:
Third Most Hated:

5. Are you comfortable with your workstation? Is the chair comfortable? Are you comfortable standing all the time (if the question is applicable)? Is the conveyor too high or too low? Do you have enough working space? Do you feel very uncomfortable wearing a wrist strap and ESD shoes?

	Very Uncomfortable				Very Comfortable
Workstation					
Chair					
Standing all the time					
Conveyor height					
Working space					
Wrist strap					
ESD shoes					

What modifications/arrangements will make you feel more comfortable?

6. Are you comfortable in your work environment? Do you find it too noisy and disturbing? Do you find it too smelly? Do you find it too dirty? Do you find it too dark?

	Very Uncomfortable				Very Comfortable
Work environment					
Noise					
Smell					
Dirt					
Illumination					

What modifications/arrangements will improve your work environment?

7. Do you have difficulties in using magnifying glass and inspection templates? Yes/No
If “no”, how do you use the magnifying glass and inspection templates (e.g., use for inspecting what components, frequency of usage, etc.)?

If “yes”, what kind of difficulties and why?
Do you find your inspection templates glaring?

Glare of Inspection Templates
1 – Imperceptible
2 – Just perceptible
3 – Just uncomfortable
4 – Just intolerable
5 – Intolerable

What modifications/arrangements will make your task easier/more productive/ less hazardous?

8. If you were a production manager, what modifications would you make in order of priorities?
i)
ii)
iii)

9. What do you think of the reject percentage related to your work?

	Very Low				Very High
Reject percentage					

What do you think are the causes of the rejects?
What modifications/arrangements will reduce the reject percentage?

10. Do you give feedback to your supervisor so that your task becomes easier/less time consuming? Yes/No

	Very Little				Very Much
Feedback					

If "yes", how do you give feedback?
If "no", why?

11. Do you face any eye problem or other Occupational Health and Safety (OHS) problem due to your work?

	Very Little				Very Much
Eye problem					
OHS problem					

If "yes", please elaborate on the type, intensity/frequency of the problems.
What modifications/arrangements will make your work safer and less hazardous?

12. Do you face much time constraint/insufficient time in performing visual inspection? Yes/No

	Very Little				A Lot
Time constraint/`insufficient time					

Time constraint/insufficient time
If "yes", please elaborate on why.
What modifications/arrangements will improve the situation?

13. Do you follow any sequence in your visual scan/search during the inspection?
If "yes", please explain your sequence.
If "no", how do you perform your visual scan/search?