MANAGEMENT OF SUPPLY CHAINS AND OPERATIONS

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Title: Management of Supply Chains and Operations Term Paper: Automation of Populated Printed Circuit Boards Operation Verification

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INTRODUCTION

The manufacturing process of printed circuit boards (PCB) can be classified into three phases. First the unpopulated circuit boards must be manufactured. This is the fiberglass (FR-4) portion of the completed product that all the components are soldered to and connects the soldered components together with copper traces. The next phase of the process is populating the circuit boards. During this phase, solder paste is applied to each of the circuit board pads, then all the components of the PCB are placed on their designated position, and finally the populated board are put through a temperature-controlled oven to melt the solder paste and solder the components to the circuit board. The last phase of the manufacturing process involves programming the PCB if required and verifying that the populated PCB is operating as intended. The verification and testing process is used to catch defects in populated boards before the boards are installed into a product and or shipped off to a customer. The testing process adds to the prevention cost of manufacturing but is necessary to ensure consistent quality in the final product. During the testing process, boards that fail the testing procedure incur expense to internal failures. This is a less costly expense than external failure of the products. Once a board is installed into a product, troubleshooting failures becomes a much more difficult and thus expensive process because of the increase in time required to resolve an issue. This is because the system becomes more complex with the addition of other components and the increased possibility of failure sources. The incurred expense is even greater once the product has shipped to the customer because shipping costs are also included into the total manufacturing cost. It is for these reasons that catching failures internally is important, and a good test procedure is necessary to do so.

The company I have been employed at for the last 5 years performs the programming and verifying phase of the manufacturing process manually either by technicians or engineers for all their PCBs. The testing process is documented onto a printed test procedure. The test procedure has a series of steps that are required to test all the necessary functionality of the device under test (DUT). In addition to the test procedure, each board has a unique testing kit that includes necessary harness, fixtures, and or other auxiliary equipment that isn't a standard piece of testing equipment. Every test procedure begins by creating a label containing the part number and a unique serial number. The label is attached to the DUT and the correlated information is written to the test procedure. Next, each step of the test procedure is completed sequentially, and the step is marked as either passing or failing. Some of the test procedure steps also require that information be acquired regarding the step involved such as voltage or temperature. If the board passes every step of the procedure, the board is stored in inventory until it is required to be installed into a product. If the board fails at any point during the procedure, the cause of failure is recorded on the test procedure and the board and corresponding test procedure is given to the engineering department for evaluation. The time required for each test procedure varies depending on the complexity of the board and the level of involvement required in the test procedure. This method of manual testing has room for improvement and automation may be used as a viable solution to improve testing. The considerations that should be made before implementing automation will be explored in the next sections.

LEVELS OF AUTOMATION

Automating a process doesn't always mean that the process becomes void of any human interaction. Several different scales are used to measure the level of automation implemented, each with varying levels of automation and qualifying criteria. The table in Figure 1 shows a 10-

level automation scale (LOA) proposed by Sheridan, T. B., & Verplank (Sheridan and Verplank). A higher level of automation corresponds to a process that requires less interaction with a human operator. A level-1 automated process has no automated assistance and relies entirely on the human operator. A level-1 system is the same as an unautomated manual system. On the other side of the spectrum, a level-10 automated system is the highest level possible and requires no human interaction. Progressing from a level-1 system to a level-10 system decreases the amount of human interaction required for the system at each consecutive level.

Level	Explanation
1	The computer offers no assistance; humans must do it all.
2	The computer offers a complete set of action alternatives and
3	Narrows the selection down to a few or
4	Suggests one, and
5	Executes that suggestions on humans approve, or
6	Allows humans a restricted time to veto before automatic execution, or
7	Executes automatically, then necessarily informs humans, or
8	Informs them after the execution only if they ask, or
9	Informs them after execution if it, the computer, decides to
10	The computer decides everything and acts autonomously, ignoring humans

Figure 1 Levels of Automation (Safsten, Winroth and Stahre)

The selection of the level of automation that best suites a task is also dependent on the function that is being automated (Safsten, Winroth and Stahre). Some tasks may be better suited for a person to complete as automating such a task would be very difficult to implement properly. Such tasks are those that are subjective such as aesthetic qualities. A table of tasks proposed by Paul M. Fitts that are best suited for a human or best suited for a machine can be seen in Figure 2. The class of the function being automated can be broken down into four different classes; information acquisition, information analysis, decision selection, and action implementation (Parasuraman, Sheridan and Wickens). The level of automation is directly correlated to the class of the function that is being automated. Selecting the right level of automation is critical to the success of implementing an automated system. The difficulty and cost associated with implementing a higher level of automation may not outweigh the benefits associated with it. The time required to develop an automated system and the cost of the hardware required for its construction must be considered. This concept will be discussed in the next section.

Men are better at	Machines are better at
Detecting small amounts of visual, auditory, or chemical energy	Responding quickly to control signals
Perceiving patterns of light or sound	Applying great force smoothly and precisely
Improvising and using flexible procedures	Storing information briefly, erasing it completely
Storing information for long periods of time and recalling appropriate parts	Reasoning deductively
Reasoning inductively Exercising judgment	

Figure 2 Man VS Machine Proficiency (Fitts)

MANUAL VS AUTOMATED TESTING SIMPLE COST MODELING

Manual testing of a product is a time-consuming and tedious process that requires a large investment in human resources. Training an individual to have the skills required to perform the test and the time of the actual test itself both contribute to the human resource expense involved in the task. By minimizing the time and minimizing the skill required to perform a task, the cost incurred by performing the task can be reduced. Both time and skill requirements can be reduced with the implementation of an automated system.

When verifying a product by performing a test procedure, there is an associated cost of quality, specifically prevention cost, to the test being performed. Verifying that the product is performing as required before it reaches the customer reduces the likelihood that an external failure will occur. Performing these verification tests also adds to the total quality of the product by verifying that performances and feature specifications are being met.

The cost of testing can be expressed as

$$C_P = T_P(R_E * t_{E,testing} + R_T * t_{T,testing})$$

where C_P is the cost of performing the test, T_P is the total number of products tested, R_E is the hourly rate of the engineer performing the test, t_E is the time required by engineering for the testing procedure, R_T is the hourly rate of the technician performing the test, and t_T is the time required for the technician to perform the test in hours. For most test procedures, R_E will be equal to zero as the test procedure can be performed entirely by the technicians.

Once a test procedure is automated, the adjusted cost of performing the test can be expressed as

$$C'_P = T_P(R_E * t'_{E,testing} + R_T * t'_{T,testing}) + C_D$$

where $t'_{E,testing}$ is the adjusted time required by an engineer to perform the test, $t'_{T,testing}$ is the adjusted time for a technician to perform the test, and C_D is the cost of developing the automated testing system. The cost of developing the automated system can be expressed as

$$C_D = R_E * t_{E,development} + C_H$$

where C_H is the cost associated with the hardware to fabricate the automated testing system. The difference between automated and manual cost of production, $\Delta C_P = C'_P - C_P$, can thus be expressed as

$$\Delta C_P = T_P\left[R_E\left(t'_{E,testing} - t_{E,testing}\right) + R_T\left(t'_{T,tesing} - t_{T,testing}\right)\right] + C_D$$

The equation for ΔC_P will result in a negative value when the cost of testing manually exceeds the cost of development plus the cost of using an automated testing solution. The crossover point between the two equations relies on the total time involved during the automated testing procedure to be less than that of the manual testing procedure.

Setting $\Delta C_P = 0$ and solving for T_P gives the number of products that must be manufactured so that the cost from developing the automated testing system is equal to the cost of continuing to test the product manually. If the number of products tested using an automated testing fixture is less than the solved value of T_P, then continuing to test the product manually is a more cost-effective solution. Otherwise, if the number of products tested is greater than the solved value of T_P, then creating the automated testing fixture will be a cost saving solution. The equation for the number of products that must be tested for the automated testing system to be cost effective is as follows

$$T_P = \frac{-C_D}{[R_E(t'_{E,testing} - t_{E,testing}) + R_T(t'_{T,tesing} - t_{T,testing})]}$$

$$= \frac{-(R_E * t_{E,development} + C_H)}{[R_E(t'_{E,testing} - t_{E,testing}) + R_T(t'_{T,tesing} - t_{T,testing})]}$$

The plot in Figure 3 shows the production cost of automated testing vs manual testing of products as a function of number of products tested. The intersection of the two plots is solved in the previous equation that solved for T_P. Note, the plot assumes that $t'_{E,testing}$ is less than $t_{E,testing}$ and that $t'_{T,tesing}$ is less than $t_{E,testing}$. The intersection on the Y axis (Production Cost Axis) of the comparative testing plot is C_D.

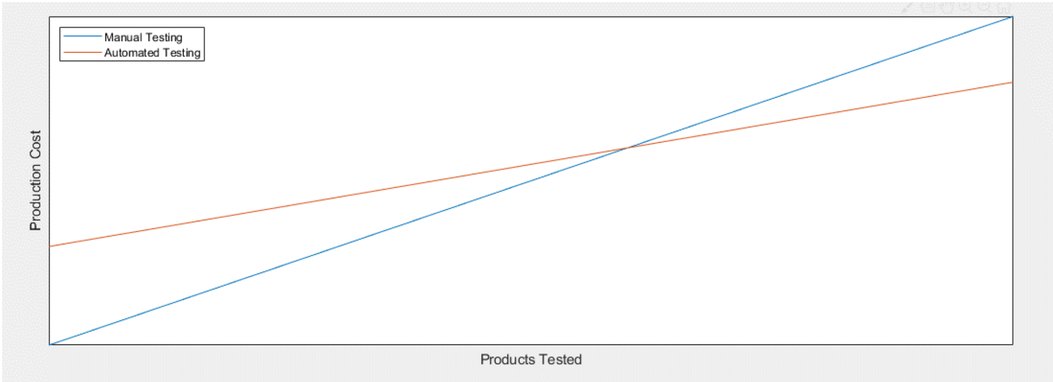

Figure 3 Production Cost - Manual VS Automated Testing Plot

QUALITY TRACKING

In an entirely manual testing system, the quantified measurements taken are logged on the test procedure associated with the DUT. Such data logging has no associated value beyond the single item being tested. Analysis of the performance of a product cannot be performed because the data is not available in an easily accessible tabular form. Tabularizing past data would be very time consuming but would allow for analysis of variance of key performance specifications. Such an analysis would provide insight into possible sources of error and or performance specifications that could be improved upon. It's for this reason that logging quantitative performance specifications is important. The logging of data can be achieved in a time efficient manor with the use of automation. Each product should have a unique part number and the performance specifications from the test produce can be easily tracked with an automated procedure. An automated system can generate a comma separated value (CSV) table after a testing session. This CSV data could then be added to a database were a quantitate analysis of the data could be performed.

The tabulation of information allows for manufacturing processes and product quality to more easily be improved. This is because with data that can be analyzed, methods such as Six Sigma or DMAIC can be implemented to improve passing product yield rates. Without performance or characteristic data, it would be very difficult or impossible to use such quality improvement methods. This is why it is important to implement an accurate and consistent data acquisition system into any level of automation, even in a level 1 system in which the human operator is performing all of the tasks.

ASSOCIATED ERROR

A major factor of the quality of the test procedure being implemented is the quality of the measurements being taken. As the quality of measurements decrease, the likelihood that a product outside of acceptable standards will pass a test will increase. This can result in complications and or failures later in production or failure of the product after it has been shipped to a customer. Both situations will have a greater cost associated with it relative to catching the failure earlier in the products life-cycle. Thus, it is important that the quality of measurements during a test be of a sufficient standard. Regardless of the measurement being taken, all measurements have some degree of uncertainty that may come from a variety of sources (The University of North Carolina at Chapel Hill). The measurements typically associated with circuit board production verification include parameters such as voltage, capacitance, frequency, and temperature. All these measurements are limited to the resolution of the tool being used and the interaction of the tool and the DUT. During manual testing, variance in measurement is compounded between the variance of the tool and the variance of the measurement technique used. Other sources of variance when acquiring electrical parameter measurements can include parasitic sources such as thermoelectric voltages, tribo-electric effects, electrochemical, and magnetic fields. The equipment used to acquire the measurements can also induce variance in the measurement due to factors such as the bandwidth of the tool, input resistance, input capacitance, and line inductance (Meettechniek). Because of all the possible sources of variance while taking electrical measurements, it is critical that proper measurement techniques are used. Improper technique can yield results that are not representative of the actual parameters being analyzed. This is a potential issue when the measurements are being performed by a human operator. The likelihood of error from a human operator increases when the operator is experiencing physical and or mental stress. The likelihood of error associated with operator stress is known as technical error probability (TEP) (Fruggiero, Fera and Lambiase). The graph in Figure 4 illustrates an example of the correlation associated with hours performing a task and the probability of error. The general trend of the plot increases as hours of performing the task increase. This is as expected with a human operator because the longer they are performing the same task the more fatigued they will become. This upward trend in error probability is consistent even when breaks are provided to reduce fatigue as exemplified by the case studies presented in *The Role of human fatigue in the uncertainty of measurement* by Fruggiero, Fera and Lambiase. As a result of this, reliability in the associated test reduces as hours performing the test increases.

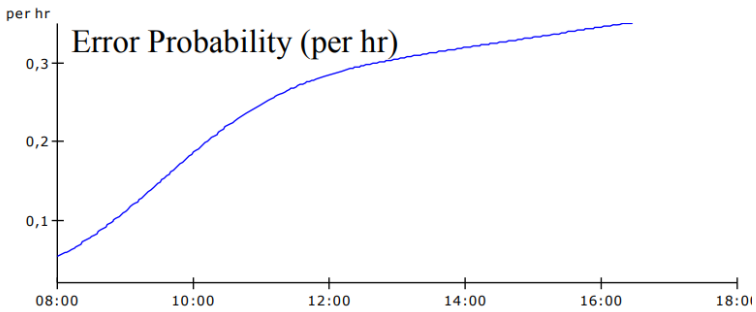

Figure 4 Error Probability VS Hours Performing a Task (Fruggiero, Fera and Lambiase)

By automating a task, the error probability as a function of hours performing the task is greatly reduced as a function of time that the test is performed. The automated system will not experience fatigue and thus the measurements will be much more consistent. The causes of variance in an automated system are those associated with the tools used to acquire the measurements. This source of variance is relevant to both manual and automated testing, but automated testing almost entirely removes variance from human operators.

LIMITATIONS AND CONSIDERATIONS

Though automation can provide better testing results, there also exists risks and limitations associated with the implementation of an automated testing system. A major limitation of automation is that not everything can be automated (Malve and Sharma). Simple tasks that require visual inspection such as orientation of polarized components or aesthetic attributes like the printing of the silkscreen can be performed by a human with little to no training. Implementing such visual processing into an automation system is very technically difficult and requires the knowledge of expects to implement correctly. This makes an automated visual inspection feature very expensive and time consuming to implement.

Another limitation associated with the implementation of automated testing is the difficulty in maintenance of test automation (Malve and Sharma). Typically, an automated testing system will be very specialized to a single product or even a single variant of a product. Designing a testing system that is modular enough to be used on different products will likely not be cost effective as this would require the testing system to be very complicated. Another option is to design a testing system with many features that can test all the features associated with a set of products. This would also require the development of a very complicated testing system that the users of the system may have difficulty using. If the operator finds the testing system difficult to use, the likelihood of error increases and the associated benefits of automation are diminished. A testing system designed to test a single product may still need to be able to test multiple variants of a single product. Software changes may affect standard operation as well as performance changes that may be specific to the variant of the product. This requires either multiple variants of the testing system or software associated with the testing system that can acount for variants in the product. Again, this adds complexity to the design as well as complexity to operation by the operator.

CONCLUSION

I believe that my employer could benefit from automating some of their circuit board testing procedures, however all the circuit board testing should not be automated. The boards in which the characteristics being tested can easily be quantified should have an entirely automated system for testing. Board testing procedure that would benefit from being automated should be limited to those that require only steady state measurements and or communication verification that a machine can easily verify. The steady state measurement can be performed with analog to digital converters and communication to the board can be verified with a microcontroller with purpose-built software. The test procedures that require analog temporal dependent measurements should be performed manually by a technician or engineer. Measurements that would make the board ineligible for an automated test procedure would include things such as video signal, dynamic power control signals, and acoustic observations of switching devices.

All the test procedures should incorporate a better data logging procedure to track performance. The current method of printing test procedures and hand writing performance measurements is very wasteful and does not supply any analyzable data. Measurements should be logged into a data base and performance measurements should be correlated to the unique serial number of the board the measurements came from. Implementing such a system would enable trouble shooting for entire products to be more easily performed as data corresponding to the characteristics of all the subcomponents would be easily accessible. Currently, acquiring the test procedure for a specific board is very impractical and time consuming. Because all the test procedures are stored in filing cabinets, finding a single specific test procedure would be an exercise in futility. It's for this reason that the entire test procedure is simply repeated when a product is under suspension of being faulty. This system is wasteful and has significant room for improvement.

Each board should be evaluated to determine which level of automation is best suited. Once an appropriate level of automation is determined, the cost to develop an automated system should then be approximated. Finally, the time and cost of manual testing should be compared to the cost and adjusted time of the automated system. Only if the cost savings associated with automation outweighs the cost involved with its implementation should automation be used.

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