Test Strategy Cost Model Innovations

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Abstract

The selection of an adequate set of test and inspection techniques to verify the quality and functionality of a product, as well as, the integrity of the manufacturing process can be a complex task. This selection process would normally require a detailed technical assessment on the effectiveness of each test technique, trade-off analysis among alternate test techniques/platforms and an economic evaluation of the various options available. In industry today, there are many methodologies utilized to derive the Return-On-Investment (ROI) analysis of a particular manufacturing test strategy. The Test Strategy Cost Model of the National Electronics Manufacturing Initiative [1], Inc. (NEMI) completed, in April 2003, has been enhanced based on the feedback received from users of the model and on experiences of the authors when applying this model to analyze current product test strategies.

Introduction

A paper describing the first version of the NEMI test cost model was presented at the Board Test Workshop (BTW03) in 2003 [2]. Since then, the test strategy cost model has evolved in many areas in order to expand its usability, increase its accuracy, and efficiency.

This paper describes all the new features incorporated in the model and presents a real case study for helping the users understand the process/methodology used when applying the test cost model.

Background

The NEMI Test Strategy Project was organized to address the loss of physical access and fault coverage at In-Circuit Test (ICT) caused by the physical space constraints of increasingly dense interconnections and electronic packaging designs. Project activities were organized into three working groups: test coverage analysis, test vehicle analysis and test strategy cost model. The test strategy cost model can help drive quick decisions by demonstrating the value of adding or removing test stages vs. utilizing sampling strategies vs. 100% inspection methods. Users of the model can determine the drivers of making a test strategy a viable option such as PCA volumes, PCA costs, investments vs. returns, etc. by comparing two test strategies.

Addition of DPMO default values from NEMI study.

The test strategy cost model described in this paper provides the user with the option to select Yield or DPMO (Defect per Million Opportunity) data from the PCA test strategy under evaluation.

The test cost model has the ability to perform the calculations with either DPMO information from the PCA or with Yield data from the test and manufacturing process history of the PCA.

If the yield of the PCA is not known, the user can either utilize a historic yield for a similar product, a default yield provided by the model or launch the DPMO calculator which is embedded in the model and which utilizes the types, quantities and defects levels of all electronic packages that make up the PCA, number of joints on the board and yield at the first test stage of the first strategy.

The following table (table 1) is a snapshot of the package defect levels that are used for the PCA DPMO calculation. The DPMO default values provided in the table are based on a study performed by Stig Oresjo [3] in 2001.

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	DPMO	Structural DPMOJ	Structural DPMOC	Electrical DPMOC
4	Leaded (Gullwing)	200	100	100
5	Leaded (Gullwing)	500	100	100
6	Leaded (Gullwing)	700	100	100
7	Leaded (Gullwing)	1000	100	100
8	Leaded (Gullwing)	10000	100	100
9	Leaded (Gullwing)	15000	100	100
10	Jlead	300	100	100
11	Eutectic BGA	100	100	100
12	Eutectic BGA	150	100	100
13	NonEutectic BGA	150	100	100
14	CSP	100	100	100
15	Column Grid	100	100	100
16	1206 SMT	400	200	100
17	0805 SMT	150	300	100
18	0402 SMT	150	400	100
19	0201 SMT	200	400	100
20	1206 Wave	400	500	100
21	0805 Wave	150	1000	100
22	0402 Wave	150	2000	100
23	SMT Connector 1	2000	100	100
24	SMT Connector 2	2000	100	100
25	Res/Cap Pack 1	100	200	100
26	Res/Cap Pack 2	100	200	100
27	PTH/Wave 1	2000	200	100
28	PTH/Wave 2	2000	200	100
29	PTH/Wave 3	2000	200	100
30	PTH/Wave 4	2000	200	100

Table 1 DPMO levels based on 2001 study

The National Electronic Manufacturers Initiative (NEMI) completed a DPMO study [4] in 2004. In this study 11 companies and manufacturing sites contributed with DPMO data. The outcome of this project is a database containing number of defects, opportunities and DPMO levels at the termination, placement, component and assembly levels based on a volume of more than 300k boards from 380 different board types.

The DPMO levels from the NEMI database are embedded in the test cost model. Through an option window at the inputs section the user can select to utilize (for the model calculations) default data from the following options:

1) Yield. Users can select this option when yield data from the manufacturing and test process is known (i.e. for a test strategy currently in use). Normally this option is utilized when the user is running the model to analyze the tradeoffs in cost and coverage of adding a new test stage to an existing test strategy for a product currently in manufacturing.

The following two options can be used when yield information is not known, like in the case when defining the test strategy for a new product to be introduced in manufacturing.

2) DPMO defaults 1. When this option is selected the user must enter the quantities of each package type that are present on the board under consideration. The model then will calculate the overall DPMO (and yield) values based on the DPMO default levels provided in the study performed by Stig Oresjo [3] in 2001.

3) DPMO defaults 2. When this option is selected, as in option 2 - *DPMO defaults 1*, the user must enter the quantities of each package type that are present on the board under consideration. The model then will calculate the overall DPMO (and yield) values based on the DPMO default levels provided in the NEMI DPMO study [4] completed in 2004.

Automated Sensitivity Analysis

This new feature is driven by user's input. Users of the previous version of the test cost model wanted to have an automated capability for conducting sensitivity analysis when considering a variety of implementation scenarios based on the selection of key strategic drivers. These strategic drivers are Volume and Coverage; therefore two new modules for the automated sensitivity analysis were added to the test cost model: Annualized Volume Analysis and Coverage Analysis.

Annualized Volume Analysis

In the automated volume sensitivity analysis the user can enter up to 10 values (or checkpoints) for the annual volume to be analyzed. These 10 volume-checkpoints can be selected by default. The default volumes are shown in the figure below (table 2).

#	Annual Volume
1	500
2	2,000
3	10,000
4	30,000
5	50,000
6	100,000
7	200,000
8	500,000
9	750,000
10	1,000,000

Table 2 Volume default values

The model then, will automatically calculate the savings obtained with the proposed test strategy on each of the

10 checkpoints (volumes) provided by the user (or the default volumes, if selected). This new automated feature is very useful when users of the model want to verify at what point (in volume) makes economical sense to modify a current test strategy by adding new test stages (and test equipment) or improving, at additional cost, the coverage of the current strategy. It helps test strategists to answer the question: What is the volume required to profitability implement a proposed test strategy?

The model automatically calculates the equipment needed to test each of the 10-checkpoint volumes. The test cost of any additional equipment is calculated and taken into consideration in the analysis as well (refer to section *Automated Capability Analysis* on this paper).

The output of the Annualized Volume Analysis is presented in a graphic in which the savings of the proposed strategy are displayed for each of the 10 volume-checkpoints selected by the user. Below is an example of the output provided by the model (figure 1).

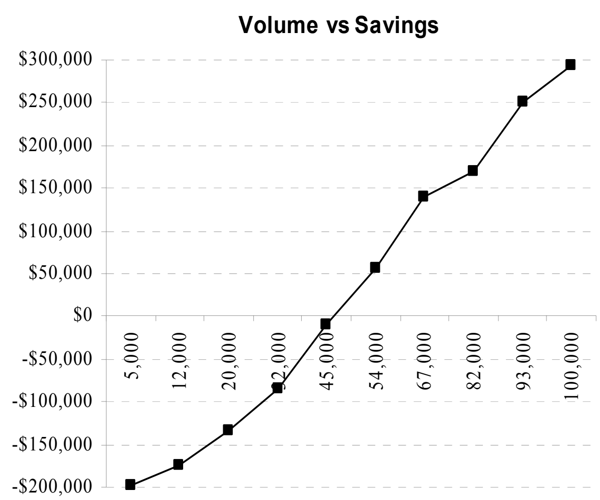


Figure 1 Example of the output of the Annualized Volume Analysis

Coverage Analysis

Similarly to the Annualized Volume Analysis an option for an Automated Coverage Analysis is available. In this new module the test cost model calculates the savings obtained with the proposed test strategy (as compared with the current test strategy) at 10 different checkpoints or coverage values. Although each of these 10 coverage values represents the coverage of the overall test strategy, the user can modify the coverage of each individual test stage and then the model will automatically calculate the overall strategy coverage (see table 3).

Checkpoint	Coverage & Cost	Test Stage		
		AXI	ICT	FT
1	Coverage	98.5%	75%	99.3%
	Cost	-----	-----	-----
…	Coverage	98.5%	80%	99.3%
	Cost	-----	$1,500	-----
10	Coverage	98.5%	85%	99.3%
	Cost	-----	$5,000	-----

Table 3 Up to 10 checkpoints or coverage values

In this part of the analysis the user must enter the delta cost (or savings) associated with the incremented (or decremented) coverage at each test stage of the strategy (see table 3). These associated costs are reflected on the savings displayed on the analysis result.

The output of the Automated Coverage Analysis is presented in a graphic in which the savings of the proposed strategy are displayed for each of the 10 coverage-checkpoints selected by the user. Below is an example of the output provided by the model (figure 2).

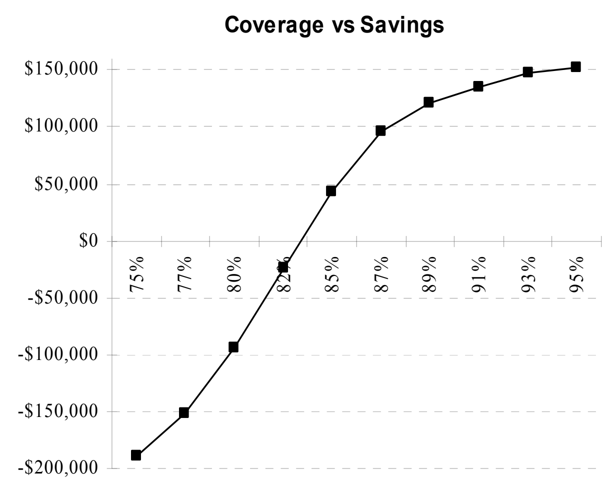


Figure 2 Example of the output of the Automated Coverage Analysis

Automated Capability Analysis

There is another new module on the test cost model that includes an intelligent feature to estimate the production capacity based on the production volume, test time and line throughput.

With this new feature the test strategy cost model automatically estimates the test resources needed to support each of the test strategies being considered. In addition, the model provides visibility to test equipment requirements based on production volumes.

Case Study

The following is a case study that shows the process of collecting/completing the inputs of the test cost model and understanding the outputs of the model. The purpose of this section is to help the users understand the organizational issues and the methodology utilized when applying this model.

This case study is based on a project in which the model was applied in order to analyze the cost/savings and yield/coverage tradeoffs of adding and Automated X-ray Inspection (AXI) stage into a current test strategy (for a product currently in manufacturing in Hewlett-Packard) composed of In-Circuit Test (ICT) and Functional Test (FT) only.

Although the input values presented in this paper are the same as the model default values (the real product and manufacturing values are not shown here) the conclusions of the present case study are still valid as the methodology described here is the same methodology as the one applied in the project.

Inputs

Through the input section, the user enters all the variables that describe the key PCA manufacturing process financial metrics such as Annual PCA Production Volume, PCA cost and Field Return Cost (per board) and the test stages for the various alternative options.

The first step is to select whether to use DPMO or Yield data for the calculations in the model. Since we already had a manufacturing history for this product we selected to use yield information

Some of the most difficult values to obtain are values related with warranty costs (Field Return Cost and Field Return Rate).

Field and warranty organizations had to be involved in the process and mountains of data were analyzed before we could get a reliable input for the Field Return Cost and Field Return Rate for just a single product.

The table below (Table 4) summarizes the inputs for both, the current and the proposed test strategies that include Automatic X-ray Inspection (AXI), In-Circuit Test (ICT) and Functional Test (FT). The model can accommodate up to 10 test stages per strategy.

Test Strategy # 1	
Field Return Rate [%]:	1.00%
Number of Test/Inspection Stages [1-10]:	2

	AXI	**ICT**	**FT**
Test Effectiveness [%]:	90.00%	80.00%	80.00%
Test Access Multiplier:	1	0.8	1
Test Time [min]:	3.00	1.00	5.00
False Reject Units:	0	1	2
False Reject Rate:	1000.00	100.00	0.05
Number of Test Operators:	1	1	2
Annual Test Operator Cost [$]:	$28,000	$35,000	$35,000
Repair feedback loop [1 or 0]:	0	1	1
Repair Yield [%]:	90.00%	90.00%	90.00%
Re-test Cycles Permitted:		3	3
Repair Cost [$/per defect]:	$1.00	$1.00	$1.00
Diagnostic Cost [$/per defect]:	$1.00	$5.00	$35.00
Equipment Cost [$]:	$450,000	$500,000	$50,000
Fixture Cost [$]:	$0	$20,000	$15,000
Programming Cost [$]:	$10,000	$30,000	$30,000
Annual Maintenance Cost [$]:	$25,000	$20,000	$20,000
Equipment Depreciation (years):	3	3	3

Table 4 Test Strategy Inputs

The board and field return costs were obtained from the market history data of the product. All the other required information was available except for the X-ray inspection stage of the new strategy for which data history didn’t exist.

In order to obtain such data an AXI test effectiveness study was performed with the assistance of our test partner, who programmed the AXI equipment and ran five hundred boards on their tester. That is how accurate numbers for the test coverage and the test time (as well as for the rest of the inputs) were obtained.

The Cost Model also includes a Time to Market (TTM) Savings module that can be selected to estimate the cost savings for an early market entry or losses for delays introduced during the new product introduction phase. But since this product is already in the market the Time to Market section of the model was not selected.

Calculations

The following represent the key calculations that are included in the test cost model:

Yield	Re-Test Cost	Yield Costs
Defect escapes	Field Return Cost	Effectiveness
Scrap Cost	Programming Cost	Yield Enhancement Savings
Repair Cost	Maintenance Cost	Time to Market Savings
False Reject Cost	Equipment Cost	Return of Investment Metrics.
Diagnostic Cost	Test Operator Cost	Savings with Strategy 2.

Internally the test cost model uses DPMO data to perform all the calculations. However in some cases, like in the present case study, when manufacturing history exists, yield information is easier to obtain and the test cost model must automatically translate yield data into DPMO information.

Following are the formulas and the rationale behind the formulas utilized in the test cost model to perform yield and DPMO calculations.

A) Yield Calculation. Yield is the area under the probability density curve between tolerances. From the Poisson distribution this equates to the probability with zero failures. Mathematically, this relationship is described by Equation 1.

$$Y = P(x=0) = \frac{e^{-\lambda}\lambda^{x}}{x!} = e^{-\lambda} = e^{-\frac{D}{U}} = e^{-DPU}$$

Equation 1 Yield

Where λ is the mean of the distribution and x is the number of failures. This relationship is shown pictorially in Figure 3.

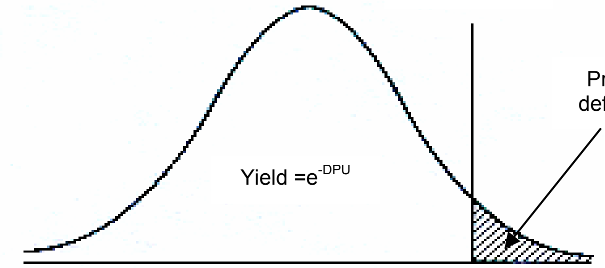


Figure 3 Yield Measurement

More information on yield can be found on the test cost model User's Guide [1] and on reference [5].

B) DPMO (Defect Per Million Opportunities) calculation. Some organizations give focus only to the rate of defects at the end of a process. A defect level per unit calculation, however, can give additional insight into a process by including the number of opportunities that exist for a failure to occur. A defect level per unit metric considers the number of opportunities for failure within the calculations. A pareto chart of the defects or fault spectrum by DPMO can give insight to where test process improvement efforts should focus. The *DPMO* of the process is calculated using Equation 2.

$$DPMO = \frac{D}{O} \times 10^{6}$$

Equation 2 *DPMO* formula

Where *D* is the defects on board and *O* is the total opportunities for defect. In the spreadsheet, *D* is calculated as the sum of the structural defects (D_S) plus electrical defects (D_E):

$$D = D_S + D_E$$

Equation 3 Defects on Board

Structural and electrical defects are calculated with the number of components and joints on the board, the structural and electrical *DPMOc* (components) and *DPMOj* (joints) and with the structural and electrical multiplier:

$$D_S = \frac{(C_B \times S_C \times M_S) + (J_B \times S_J \times M_S)}{10^{6}}$$

Equation 4 Structural Defects

Where:

C_B = Components on Board.
J_B = Joints on Board.
S_C = Structural DPMOc.
S_J = Structural DPMOj.
E_C = Electrical DPMOc.
M_S = Structural Multiplier.
M_E = Electrical Multiplier.

$$D_E = \frac{C_B \times E_C \times M_E}{10^{6}}$$

Equation 5 Electrical Defects

The electrical and structural multiplier can be modified by the user in order to reduce or increase the electrical and structural number of defects on the board. For example, if there is a known design problem with the component, a structural multiplier of 2 or 3 will increase the defects on that component to reflect the design problem.

C) DPMO calculation using Yield data. If a user lacks the DPMO data, the yield data can be utilized to backward calculate the DPMO by utilizing Equation 2. However, the defects on board (*D*) are calculated utilizing the following method. From equation 1 we know that the yield is:

$$Y_n = e^{-D_F}$$

Equation 6 Yield at stage n.

Where D_F is the number of defects found at test stage n.

Test coverage can be defined as:

$$T_C = T_E \times T_A$$

Equation 7 Test Coverage

Where T_E is the test effectiveness and T_A is the test access. The number of defects found on a particular test stage is:

$$D_F = T_C \times D$$

Equation 7a Defects found.

Where T_C is the test coverage at that particular stage, and D is the number of defects on the board. By substituting equation 7 into equation 7a, D_F can be obtained.

$$D_F = T_E \times T_A \times D$$

Equation 8 Defects Found at stage n

and substituting equation 8 into equation 6:

$$Y_n = e^{-T_E \times T_A \times D}$$

$$-\ln(Y_n) = T_E \times T_A \times D$$

$$D = -\frac{\ln(Y_n)}{T_E \times T_A}$$

Equation 9 Defects on Board

$$DPMO = -\frac{\ln(Y_n)}{O \times T_E \times T_A}$$

Equation 10 DPMO calculated from yield data

Once that the DPMO and Yield calculations are completed, the model then calculates two other important values: the defects escaping out of each test stage and the test effectiveness of each test as well for the overall strategy

D) Defect escapes. The *DPMO* calculated on B) or C) is used as the number of defects entering to test strategy 1 and test strategy 2. The yields of the test stages are calculated using the formula of equation 6. The defects entering to following stages are the defects that escape from previous stages.

The defects that escape from a test stage can be defined as the total defects on board minus the defects found at that particular stage:

$$Do_n = Db - Df_n$$

$$Do_n = Db - (Tc_n \times Db)$$

$$Do_n = Db(1 - Tc_n)$$

Equation 11, Defect escapes from stage n.

Do_n is the number of defects that escape from stage ‘n’, Db is the number of defects on the board, Df_n is the number of defects found at stage ‘n’ and Tc_n is the test coverage at stage ‘n’.

E) Test Effectiveness. The effectiveness of each test strategy is defined in the model as the relationship of the defects that enter to the strategy and the defects that escape from that strategy.

$$T_{En} = \frac{Di_n - Do_n}{Di_n}$$

Equation 12, Test effectiveness of strategy n.

Where Di_n is the number of defects entering to strategy ‘n’ and Do_n is the number of defects escaping from strategy ‘n’.

Using the formulas above to calculate the defect escapes in our case study the model shows the following comparison of the defect escapes for the current and the proposed strategy.

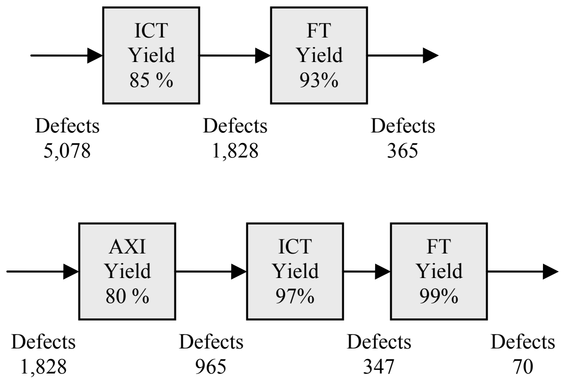


Figure 4 Test Defect Escapes

The remainder model calculations are described in the NEMI Test Cost Model User's Guide [1] in the appendix called 'A Case Study'.

Outputs

The output section of the model provides a summary of estimated costs vs. savings/ losses introduced by each of the test strategies under evaluation. A comparison of the costs of both strategies, as well as, the total savings introduced as a result of yield improvements or other process improvements provides the ability to determine which test strategy will bring the best return on investment for a company. Figure 5 shows the outputs of the model for the present case study.

Summary of Savings with Strategy # 2

Annual Savings

	Strategy 1	Strategy 2	Difference
Test Cost	$400,000	$613,000	**-$213,000**

Yield Enhancement Savings:	$99,195
Total savings with strategy 2:	**-$113,815**

Figure 5 Summary of annual costs & savings

From the outputs of the model it can be observed that it doesn't make economical sense to add the Automatic X-ray Inspection stage to the current test strategy. According with the cost model calculations the recurring and non-recurring costs of the new test stage are higher than the potential savings generated by the coverage improvement obtained with the addition of the AXI stage.

To find out when will make economical sense to invest in an AXI test stage for the current strategy is necessary to look into the volume-forecast (table 5) for this particular project.

Year	Annual Volume
2001	5,000
2002	12,000
2003	20,000
2004	32,000
2005	45,000
2006	54,000
2007	67,000
2008	82,000
2009	93,000
2010	100,000

Table 5 Forecasted Volumes

Using these ten values as volume-checkpoints for the Automated Annualized Volume Analysis in the cost model, we get the following results:

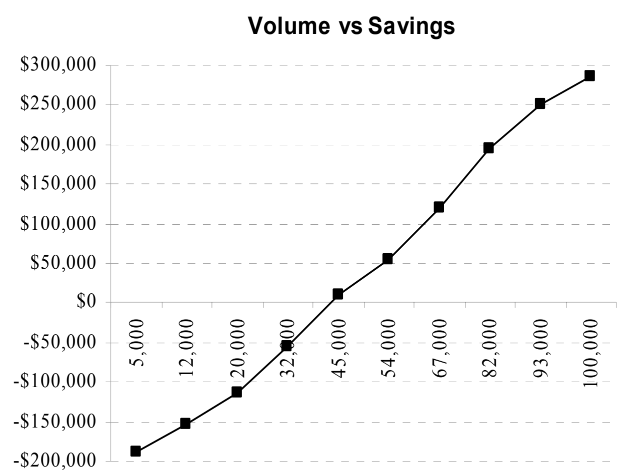


Figure 6 Results of the Annualized Volume Analysis

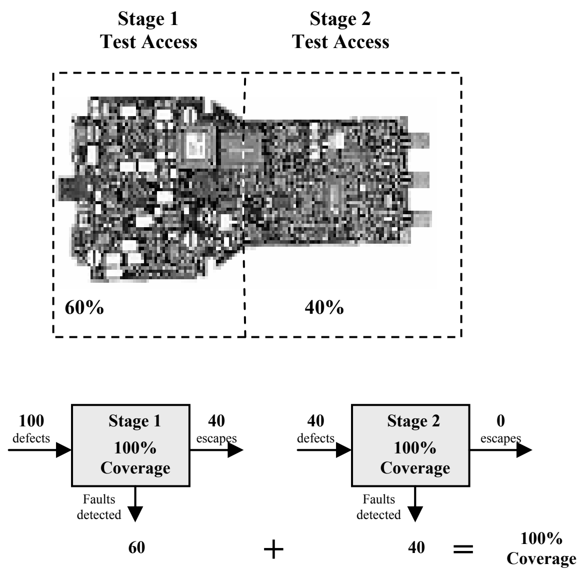
Conclusions of the case study

By observing the results of the test cost model calculations it can be concluded that, for the current annual production volume, the overall cost of adding AXI into the current test strategy are prohibitive, but for 2005 and beyond (with annual volumes above 45K) it is recommended to implement the X-ray station since for that volumes the return will be greater than the investment.

Model Limitations

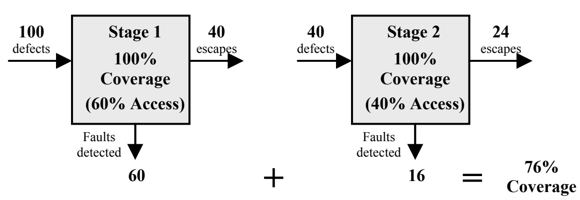
- The list of package types and their defect levels are not representative of all package types currently available in industry.

- The present tool models test coverage of each test stage as a multi-stage test, such that test coverage always overlaps from one stage to another. This model does not accurately represent results when multiple test stages are used in a complementary manner. For example, if test stage 1 had 100% coverage of all defects on 60% of the board that it can access and test stage 2 had 100% coverage of all defects on 40% of the board that it can access, the model would not deliver accurate results.



Actual Coverage

Instead of giving a result that represents 100% coverage, the model would deliver only 76% coverage of the board. The model was constructed in this manner in order to simplify the calculations. Users of the model need to take these limitations into account when considering complementary test coverage.



Coverage Calculated by the Test Cost Model

- In a test process there are true failures and false failures. When we have a diagnostic process, the following things can happen with the failures detected at a particular test station :

  1. A *true failure* diagnosed as a *true failure*.
  2. A *true failure* diagnosed as a *false failure*.
  3. A *false failure* diagnosed as a *true failure*.
  4. A *false failure* diagnosed as a *false failure*.

  In this test cost model we are assuming a 100% diagnostic yield, which means that any diagnostic performed is always able to catch failures. In other words, in the present tool we are only considering cases 1 and 4. The economic impact of the false failures (case 4) is reflected on the test cost model in the calculation of the diagnostic and re-tests costs.

Future Work

There are potential model enhancements to the tool suggested by users of the test cost model and that are under consideration that could continue to improve the accuracy and usability of the model in the future. For example, the model is not designed to handle system testing where a number of cards are brought together in a box and then the box is shipped out to a customer. Including this type of capabilities will increase the cost model's flexibility.

Conclusions

The NEMI test cost model was created with the intent of enabling decisions when considering trade-offs between manufacturing test techniques. The model is intended to be used by engineers or managers that are responsible for making decisions on test strategies for their company.

The tool can be utilized to justify the economic investment made when selecting a test strategy. The utilization of actual data in the model will drive accuracy onto the calculations. Therefore, the cost model results will be credibly and trusted. The model has been created to justify test strategies in a high volume production environment. However, the model can still be utilized in low volume production environments when the equipment is shared by various production lines. This scenario, however, would require a greater deal of calculations, multiple runs of the model and sensitivity analysis.

Today's estimates of ROI of manufacturing test strategies generate different results because they are not based on common financial drivers. The NEMI Test

Strategy Project members would like to see an industry wide adoption of the model. Standardization of the economic analysis of production test strategies will bring consistency to the overall approach for determining the financial impact of various test techniques. The model is available to industry (free of charge) on the NEMI website [1].

References

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