Manufacturing Test Strategy Cost Model

Rosa D. Reinosa
Carlos Michel

Hewlett-Packard Company
1501 Page Mill Rd.
Palo Alto, California
United States 94304-1100

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. Although, industry methodologies may have strong similarities, they also highlight unique differences in the approach towards justifying a particular approach. The Test Strategy Project of the National Electronics Manufacturing Initiative, Inc. (NEMI) completed, in April 2003, the development of a Manufacturing Test Strategy Cost Model that could be utilized by Printed Circuit Assembly (PCA) manufacturers to benchmark and measure the financial impact of selecting a particular test strategy, perform trade-off analysis among various test strategies and gain visibility on the impact of field failures on warranty costs. This model embraces the best practices and methodologies used by the participating companies (Agilent Technologies Inc., Delphi Delco Electronics Systems, HP, Intel Corporation, Solectron Corporation and Teradyne Inc.). At the same time, the test cost model seeks to standardize and simplify the process of performing an economic evaluation of a manufacturing test strategy.

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. Electronic manufacturers are finding that they can no longer utilize a single test method to verify the quality of a PCA and are increasingly combining various electrical, structural and inspection test techniques. Through a technical assessment one can determine which method or combination of methods will provide the best test coverage. However, an electronic manufacturer will make a decision based on the results of the effectiveness of a test technique or sets of techniques, as well as, on the financial impact of a test strategy to a company's bottom line. 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.

Model Description

The model is available as an Excel spreadsheet and it is intended to be used on post-reflow PCA test strategies. It comprises of 4 major sections: Inputs, Defaults, Calculations, and Outputs Sections (See Figure 1).

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. Descriptions for each of the input variables are included in the comments embedded in each cell.

The table below (Table 1) summarizes a sample of one test strategy entered into the cost model that includes In-Circuit Test (ICT), Functional Test (FT), and Integration Test (INT).
The model can accommodate up to 9 test stages per strategy. The user will be asked to enter up to 2 strategies so that the comparison of investments vs. returns can be estimated.

Figure 1
Four Major Sections of the Test Cost Model: Inputs, Defaults, Calculations & Outputs.

The model provides the user with the ability to select Yield vs. DPMO of the PCA (See Figure 1). 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.

Test Strategy # 1	
Field Return Rate [%]:	1.41%
Number of Test or Inspection Stages:	3

	Stage 1	**Stage 2**	**Stage 3**
Type of Test/Inspection:	**ICT**	**FT**	**INT**

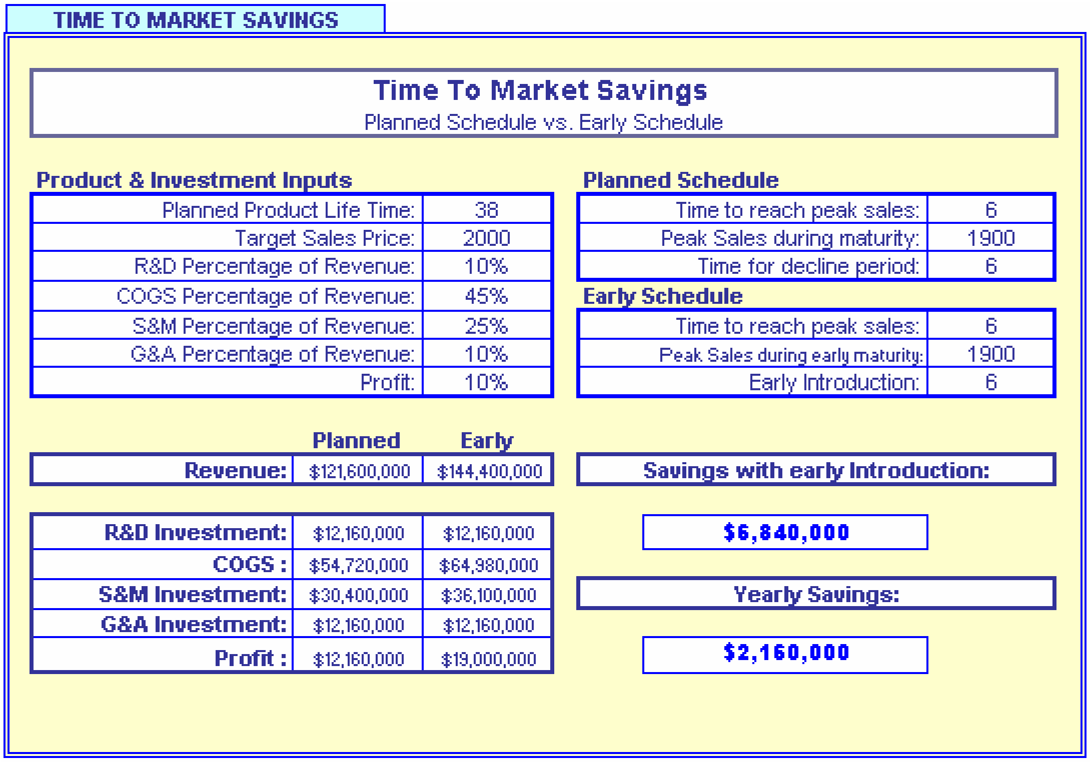
	ICT	**FT**	**INT**
Test Effectiveness [%]:	75.00%	72.50%	31.00%
Test Access Multiplier:	1	1	1
Test Time [min]:	0.47	3.6	5
False Reject Units:	2	2	2
False Reject Rate:	0.10	0.30	0.05
Number of Test Operators:	0.03	0.47	0
Annual Test Operator Cost [$]:	$6,000	$6,000	$6,000
Repair feedback loop [1 or 0]:	1	1	0
Repair Yield [%]:	95.00%	35.00%	100.00%
Re-test Cycles Permitted:	1	1	
Repair Cost [$/per defect]:	$0.20	$0.20	$0.00
Diagnostic Cost [$/per defect]:	$1.00	$7.00	$25.00
Equipment Cost [$]:	$9,143	$0	$0
Fixture Cost [$]:	$15,000	$110,000	$0
Programming Cost [$]:	$35,000	$75,000	$0
Annual Maintenance Cost [$]:	$610	$2,801	$0
Equipment Depreciation (years):	5	5	0

Table 1 Sample of Test Strategy Inputs

The following table is a snapshot of the package defect levels that are used for the PCA DPMO calculation. The user must enter the quantities of each package type that are present on the board under consideration. The defect level values were provided by one of the participating companies based on their experiences seen in production.

	Component Package Types	Defaults for structural DPMO Joint & Component		Defaults for electrical DPMO component
	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

The Cost Model also includes a Time To Market (TTM) Savings (See Figure 2) 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. There are 3 main areas in the TTM section of the model: Product & Investment, Planned Schedule and Early Schedule.



TIME TO MARKET SAVINGS

Time To Market Savings

Planned Schedule vs. Early Schedule

Product & Investment Inputs

Planned Product Life Time:	38
Target Sales Price:	2000
R&D Percentage of Revenue:	10%
COGS Percentage of Revenue:	45%
S&M Percentage of Revenue:	25%
G&A Percentage of Revenue:	10%
Profit:	10%

Planned Schedule

Time to reach peak sales:	6
Peak Sales during maturity:	1900
Time for decline period:	6

Early Schedule

Time to reach peak sales:	6
Peak Sales during early maturity:	1900
Early Introduction:	6

	Planned	Early
Revenue:	$121,600,000	$144,400,000
R&D Investment:	$12,160,000	$12,160,000
COGS :	$54,720,000	$64,980,000
S&M Investment:	$30,400,000	$36,100,000
G&A Investment:	$12,160,000	$12,160,000
Profit :	$12,160,000	$19,000,000

Savings with early Introduction:

$6,840,000

Yearly Savings:

$2,160,000

Figure 2 Time To Market Savings.

Defaults

The model includes a set of default values (See Figure 1) that can be utilized to estimate the financial impact of selecting a particular test strategy. The default values have been taken from the experiences of the NEMI member companies with medium complexity boards manufactured in the U.S. In order to obtain a closer estimate on the strategy's ROI it is best to utilize actual figures from past products.

Calculations

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

Yield

Defect escapes

Scrap Cost

Repair Cost

False Reject Cost

Diagnostic Cost

Re-Test Cost

Field Return Cost

Programming Cost

Maintenance Cost

Equipment Cost

Test Operator Cost

Yield Costs

Effectiveness

Yield Enhancement Savings

Time to Market Savings

Return of Investment Metrics.

Savings with Strategy 2.

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.

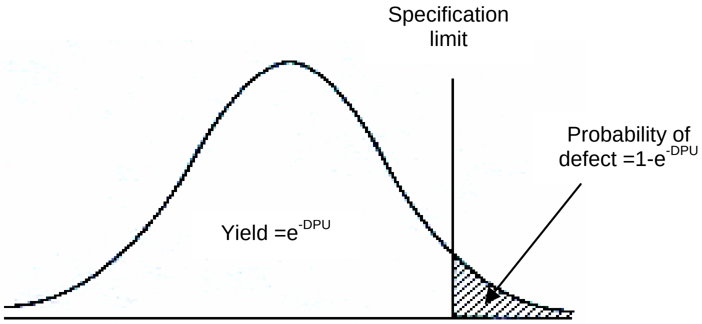


Figure 3 Yield Measurement

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

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.

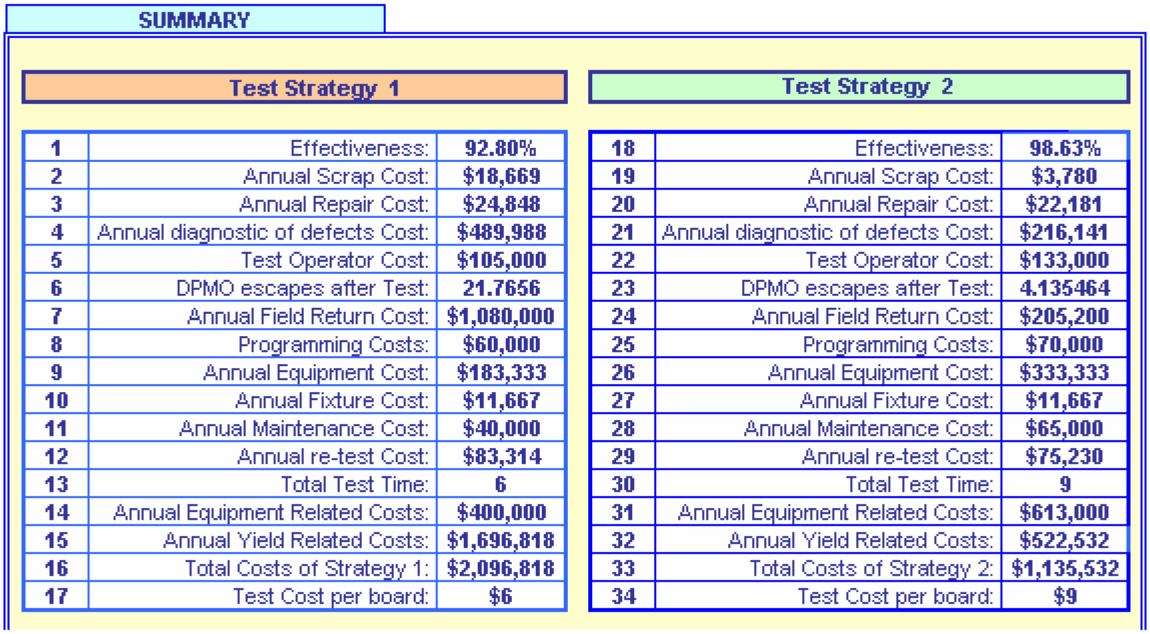
Where Di_n is the number of defects entering to strategy 'n' and Do_n is the number of defects escaping from strategy 'n'.

The remainder model calculations are described in the NEMI Test Cost Model User's Guide available at the NEMI website:

http://www.nemi.org/projects/TSCM/test_strat_cost_model.html.

Outputs

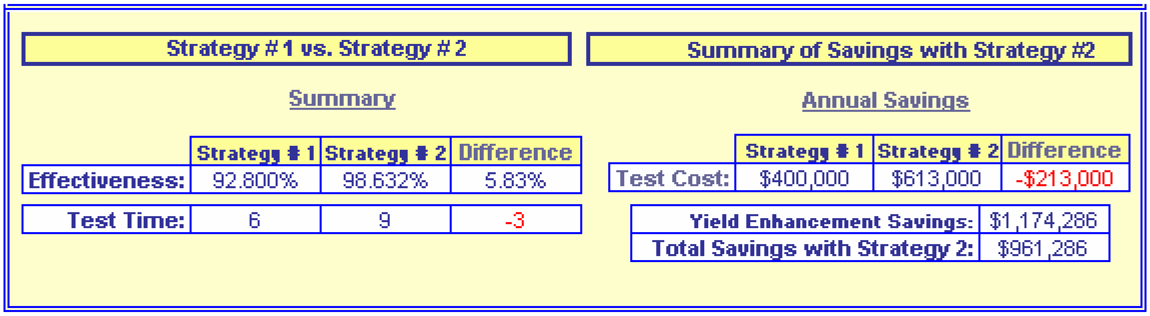
The output section of the model provides a summary of estimated costs vs. savings/ losses introduced by each of the test strategies under evaluation. A comparison of the costs of both strategies, as well as, the total savings introduced as a result of yield improvements or other process improvements provides the ability to determine which test strategy will bring the best return on investment for a company. A section of the outputs section focuses on providing a summary of the Return on Investment Metrics for the preferred strategy (See Figure 4a, b & c).



SUMMARY

Test Strategy 1			Test Strategy 2		
1	Effectiveness:	92.80%	18	Effectiveness:	98.63%
2	Annual Scrap Cost:	$18,669	19	Annual Scrap Cost:	$3,780
3	Annual Repair Cost:	$24,848	20	Annual Repair Cost:	$22,181
4	Annual diagnostic of defects Cost:	$489,988	21	Annual diagnostic of defects Cost:	$216,141
5	Test Operator Cost:	$105,000	22	Test Operator Cost:	$133,000
6	DPMO escapes after Test:	21.7656	23	DPMO escapes after Test:	4.135464
7	Annual Field Return Cost:	$1,080,000	24	Annual Field Return Cost:	$205,200
8	Programming Costs:	$60,000	25	Programming Costs:	$70,000
9	Annual Equipment Cost:	$183,333	26	Annual Equipment Cost:	$333,333
10	Annual Fixture Cost:	$11,667	27	Annual Fixture Cost:	$11,667
11	Annual Maintenance Cost:	$40,000	28	Annual Maintenance Cost:	$65,000
12	Annual re-test Cost:	$83,314	29	Annual re-test Cost:	$75,230
13	Total Test Time:	6	30	Total Test Time:	9
14	Annual Equipment Related Costs:	$400,000	31	Annual Equipment Related Costs:	$613,000
15	Annual Yield Related Costs:	$1,696,818	32	Annual Yield Related Costs:	$522,532
16	Total Costs of Strategy 1:	$2,096,818	33	Total Costs of Strategy 2:	$1,135,532
17	Test Cost per board:	$6	34	Test Cost per board:	$9

Figure 4a Summary of the estimated costs & savings



Strategy # 1 vs. Strategy # 2

Summary

	Strategy # 1	Strategy # 2	Difference
Effectiveness:	92.800%	98.632%	5.83%
Test Time:	6	9	-3

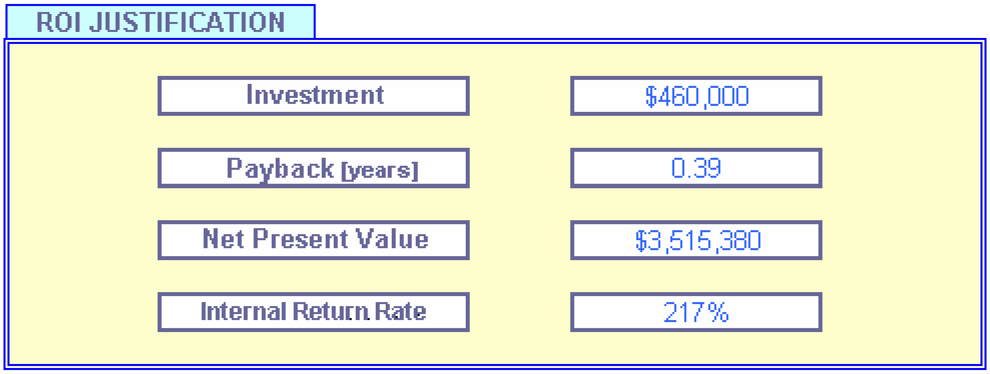
Summary of Savings with Strategy #2

Annual Savings

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

Yield Enhancement Savings:	$1,174,286
Total Savings with Strategy 2:	$961,286

Figure 4b Summary of annual costs & savings



ROI JUSTIFICATION

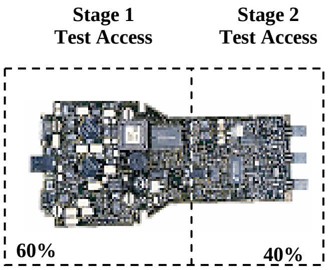
Investment	$460,000
Payback [years]	0.39
Net Present Value	$3,515,380
Internal Return Rate	217%

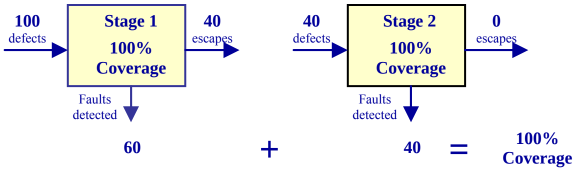
Figure 4c Summary of Return on Investment metrics

Model Considerations

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

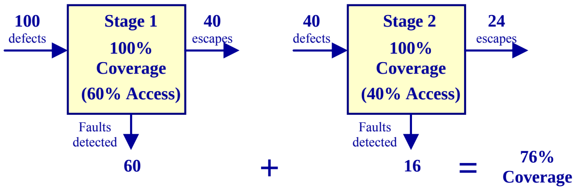
- The present tool models test coverage of each test stage as a multi-stage test, such that test coverage always overlaps from one stage to another. This model does not accurately represent results when multiple test stages are used in a complementary manner. For example, if test stage 1 had 100% coverage 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.

Current Use of the Model

Since the inception of the model each participating company has continued to validate its accuracy. The model's output has been proven to deliver conservative estimates on warranty costs.

In a recent study, conducted by Hewlett-Packard, the model's accuracy with respect to actual warranty cost impact was validated. The comparative analysis was conducted on a product that already had market history so that the actual warranty data could be compared to the model's estimated warranty impact.

The model estimates warranty costs based on the percent of field failures that result from test escapes.

Future Work

There are a number of potential model enhancements under consideration that could continue to improve the accuracy and usability of the model in the future:

- The creation and linkage to a DPMO database with an expanded set of package types and package defect levels which would increase the accuracy of the DPMO calculation.

- On-going validation of field related costs with actual warranty costs after a strategy has been selected.

- Validation of package defect levels used for DPMO calculation.

- Improvements on user's interface. Make the user's interface easier to navigate.

- Enable automatic sensitivity analysis features into the test cost model. The idea is for the model to automatically generate a variety of scenarios driven by user's input and that are also based on the most important strategy drivers. The model would also output a graphical view of the sensitivity analysis.

- Enable production capacity analysis features into the model. The cost model would automatically estimate the test resources needed to support each of the test strategies entered. It would also identify when test resources are under utilized or whether additional equipment is needed to satisfy the production volumes.

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 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 at the following URL:

http://www.nemi.org/projects/TSCM/test_strat_cost_model.html.

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References

“Management of DPMO metrics reduces the cost of PCB assembly”
Amit Verma
APEX 2003, Conference Proceedings

“One Billion Solder Joints …and Counting”
Stig Oresjo
Circuits Assembly, February 2001.

“Economics of Built-In Self-Test”
Louis Y. Ungar, Tony Ambler.
IEEE. Design and Test of Computers. 2001.

“Implementing Six Sigma.”
Forrest W. Breyfogle III.
Wiley Interscience, John Wiley & Sons Inc.