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USING YIELDED COST AS A METRIC FOR MODELING MANUFACTURING PROCESSES

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ABSTRACT

Yielded cost is defined as cost divided by yield and can be used as a metric for representing an effective cost per good (non-defective) assembly for a manufacturing process. Although yielded cost is not a new concept, it has no consistent definition in engineering literature, and several different formulations and interpretations exist in the context of manufacturing and assembly.

In manufacturing, yield is the probability that an assembly is non-defective. To find the effective cost per good assembly that is invested in the manufacturing or assembly process, cost is accumulated and divided by yield.

This paper reviews and correlates existing yielded cost formulations and presents a new method that enables consistent measurement of sequential process flows. This new method views the yielded cost associated with an individual process step (step yielded cost) as the change in the process's yielded cost when the step is removed from the process. This approach is preferred because it incorporates upstream and downstream information and because it provides a specific process step's effective cost per good assembly that is independent of step order between steps that scrap defective product (i.e., test steps).

Conventional wisdom dictates that the best way to improve a process is to increase the yield of the lowest yield step. The new approach developed in this paper produces an auxiliary cost that can be used to determine the best method of improving processes that, for complex processes, does not always correspond to improving the lowest yield step.

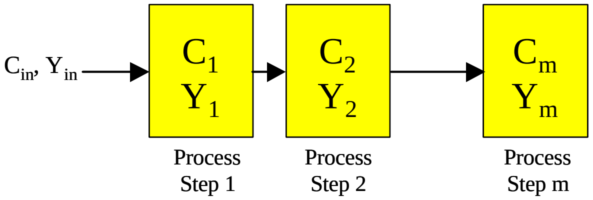
Simple and complex assembly process examples are presented to demonstrate the interpretation of yielded cost. The new approach is applied to a microwave module (MWM) manufacturing and assembly process example.

Keywords – cost, yield, yielded cost, design to cost.

I. INTRODUCTION

To date, industry has left yielded cost (cost divided by yield) formally undefined and has not fully embraced its meaning, usefulness and ramifications. For many years, however, engineers have incorporated yielded cost in manufacturing cost analyses as a method of measuring the cost of processes. It has been referred to under several different names, such as yielded die cost in electronics (Matsuno, 1988) or total test cost (Schuelke, 1989), and its application has depended upon the specific manufacturing process under analysis. As a result, much of its value as a general diagnostic and quality evaluation metric was lost. If defined properly, however, yielded cost could be used to consistently and accurately determine the effective contribution of individual process steps to entire processes, and could thus identify critical steps. Manufacturers could then improve process quality and performance-price ratios (Dance, 1992) and use yielded cost to improve manufacturing and assembly processes.

Yielded cost, in general, is described as *cost divided by yield*, Figure 1. One can appreciate the value of this definition by considering an example: if $C_{in} = 0$, $Y_{in} = 1.0$, setting $C_i = 100$ and $Y_i = 0.9$ for m = 3 steps in Figure 1, gives $C_Y = \$300/(0.9^3) = \$412$ per good assembly. This measurement of "process yielded cost" is valuable because it represents an effective cost per good assembly after three process steps, which helps in evaluating the quality of the process.



$$\text{Yielded Cost, } C_Y = \frac{\text{Cost}}{\text{Yield}}$$

$$C_Y = \frac{\text{cost per part}}{\text{fraction of good parts}} = \frac{C_{in} + \sum_{i=1}^{m} C_i}{Y_{in} \prod_{i=1}^{m} Y_i}$$

Figure 1. A simple sequential process flow consisting of m process steps

A close look at the electronic and mechanical systems cost modeling literature indicates that cost divided by yield appears frequently, examples include integral passive modeling (Power, 1999), yield prediction and associated cost for printed circuit packs (Sultan, 1986), integrated optical chips (Marz, 1996), VLSI floorplanning (Domer, 1994), flip chip and wire bonding (Lau, 2000), expected profit models for multi-stage manufacturing systems (Barad, 1996), and the implementation of inspection costs for optimal lot sizing (Grosfeld-Nir, 1996). Actual references to the specific concept of yielded cost have also appeared in the literature, mostly as a means of developing cost models. Matsuno *et al.* (Matsuno, 1988) addresses yielded cost in a paper on the development of a yield and cost-forecasting model for monolithic microwave integrated circuits (MMICs). References (Matsuno, 1988; Schuelke, 1989; Marz, 1996; Domer, 1994; and Lau, 2000) define values called "costs" with yields in the denominator. Although none of these references define the concept incorrectly, previous work as a whole has inconsistently applied yielded cost, and has therefore limited the potential usefulness of the concept. In addition, the usefulness has also been stifled because no attempt has been made to correlate step yielded costs (defined later) to process yielded costs. It is important to accurately determine step yielded costs so that manufacturers can target and improve low quality steps in the process. In order to address these issues, this paper will evaluate existing definitions and derive a more appropriate yielded cost metric.

Section II of this paper guides the reader through process flow examples to demonstrate the meaning of yielded cost and compare alternative definitions. Section III explains how the components of a specific process step's yielded cost (step yielded cost) are distributed and applies the yielded cost approaches to an actual microwave module (MWM) process flow. Section IV extends yielded cost metrology to a general case and concludes with a result on how to most efficiently improve a process. Section V concludes the paper with some general comments.

II. CALCULATING YIELDED COST

In process-flow analysis, manufacturing operations are typically analyzed as a series of fabrication and assembly steps, each with specific costs and yields. The step costs typically account for material, assembly, and scrapping costs (Bloch, 1992) while the yields are determined through sampling (Santana, 1987) with some tolerance (Rhode, 1987). Process yield is defined as the number of usable assemblies after manufacturing divided by the number of assemblies that start the manufacturing process.

One way to characterize the quality of a process is with yielded cost. Process yielded cost, C_{Ytotal}, characterizes the quality of the entire process under consideration and is defined as the total cost invested per assembly divided by the total process yield. Step yielded cost, C_{Ystep}, represents the effective cost contribution of a step towards the entire process. Although process yielded cost has been used consistently in the past, step yielded cost has not. Therefore, an appropriate method of computing step yielded cost must be found. The criteria used for evaluating these methods are: 1) one must be able to be collect step yielded costs in some way to get process yielded cost, 2) step yielded costs must account for upstream and downstream information for each step, and 3) step yielded costs must be independent of step order between "scrapping steps." In scrapping steps, assemblies are removed from the process (i.e., test or inspection steps).

Collection of step yielded costs is necessary because the sum of effective cost contributions should represent the effective cost of the entire process itself. Incorporating upstream and downstream information is necessary because step yielded cost should account for a step's effect on *all other* process steps and all other process steps' effect on the step under consideration. Lastly, independence of step order for steps between scrapping points is necessary because the contribution should be the same no matter where a step is in a process. This is explained in Part C of this section. Four approaches to calculating step yielded cost have been identified: the *itemized*, *iterative*, *cumulative*, and *omission* methods. The collection criterion was met with the *cumulative* and *omission* methods while it was not met with the *itemized* and *iterative* method. Additionally, the *omission* method was found to satisfy the second and third criteria.

The general *itemized* approach, a new method, simply defines C_{Ystep} as the cost of the step divided by the yield of the step. In Figure 1, with this definition, the C_{Ystep} values are $C_{Yin} = C_{in}/Y_{in}$ and $C_{Y1} = C_1/Y_1$. The C_{Ytotal} after step 1 would then be $C_{in}/Y_{in} + C_1/Y_1$. Since this is not equal to the actual process yielded cost after step 1, $(C_{in}+C_1)/Y_{in}Y_1$, this approach does not satisfy the first criteria (C_{Ystep} values cannot be collected to get C_{Ytotal}). Furthermore, in the iterative approach used by Matsuno *et al.* (Matsuno, 1988), the incoming yield is assumed to be unity and the yielded cost after some step i, $C_{Yi\text{-}(i+1)}$, is the previous yielded cost, $C_{Y(i\text{-}1)\text{-}1}$, plus the cost of step i, C_i, all divided by the step yield, Y_i:

$$C_{Yi\text{-}(i+1)} = \frac{C_{Y(i\text{-}1)\text{-}i} + C_i}{Y_i} \qquad (1)$$

C_{Ystep} for step i is defined as the difference between the yielded cost before and after step i. This approach also does not satisfy the first criteria (C_{Ystep} values cannot be collected to get C_{Ytotal}).

B. Cumulative Approach to Yielded Cost

Similar to the iterative approach, the *cumulative* approach (SavanSys, 2001) similarly defines C_{Ystep} as the yielded cost after the step minus the yielded cost before the step; however, yielded cost is defined as in Figure 1, not by (1).

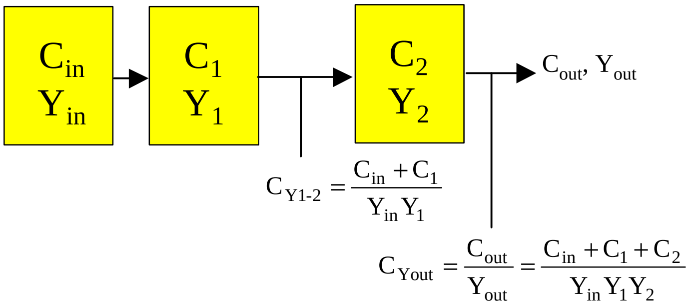


Figure 2. *Cumulative* approach: multiple step process

Using the cumulative method, the C_{Ystep} values in Figure 2 are given by,

$$C_{Yin} = \frac{C_{in}}{Y_{in}} \qquad (2)$$

$$C_{Y1} = C_{Y1\text{-}2} - C_{Yin} = \frac{C_{in}(1 - Y_1) + C_1}{Y_{in}Y_1} \qquad (3)$$

$$C_{Y2} = C_{Yout} - C_{Y1\text{-}2} = \frac{(C_{in} + C_1)(1 - Y_2) + C_2}{Y_{in}Y_1Y_2} \qquad (4)$$

With the assumption that no processing occurs before step “IN,” the total cost and yield after step “IN” would be equal to C_{in} and Y_{in} respectively. Thus, equation (2) also represents the yielded cost following step “IN” and can be used to compute C_{Y1} and C_{Y2}, as was done in (3) and (4). This approach is reasonable because C_{Ystep} values, (2), (3), and (4), can be summed to get C_{Yout} shown in the figure. However, the C_{Ystep} values are blind to downstream information by the nature of this calculation (i.e., the effects of processing that takes place after the current step). For example, the expression for C_{Y1} in (3) does not include C_2 or Y_2 and thus does not consider the affect of step 2 on step 1. With a decrease in Y_2, a higher proportion of cost invested in step 1 would be spent on assemblies that will be made defective in step 2. So, ideally, C_{Y1} should change if the yield or cost of step 2 were changed. Additionally, the *cumulative* method’s C_{Ystep} values are not independent of step order. If step “IN” and step 2 of Figure 2 are switched, then C_{Y1} would change in such a way that C_{in} will become C_2 and Y_{in} will become Y_2. Thus, because the *cumulative* method does not consider downstream information and its values are not independent of step order, it falls short of completely describing step yielded cost.

C. Omission Approach to Yielded Cost

Another new method, the *omission* approach measures C_{Ystep} as the difference between C_{Ytotal} computed with the step in the process flow and C_{Ytotal} computed without the step in the process flow. The step yielded costs calculated with this method thus represents the change in C_{Ytotal} by removing the step from the process flow. Under this definition, the yielded cost of the first step in Figure 2 would be,

$$\begin{aligned} C_{Y1} &= \frac{C_{in} + C_1 + C_2}{Y_{in}Y_1Y_2} - \frac{C_{in} + C_2}{Y_{in}Y_2} \\ &= \frac{C_{in}(1 - Y_1) + C_1 + C_2(1 - Y_1)}{Y_{in}Y_1Y_2} \end{aligned} \qquad (5)$$

which satisfies the downstream argument in the previous section by including the additional C_2 and Y_2 terms. Similar to the *cumulative* approach, these C_{Ystep} values can be collected to get C_{Ytotal}. If the numerator of (5) is separated, the second term, the cost of the first step divided by the process yield, represents the *base cost* (the cost invested in the step of interest). The first and third terms, which each have a step cost multiplied by the fraction of assemblies made defective in the step of interest, represent *auxiliary* costs. Therefore, this C_{Ystep} value obtained with the *omission* approach, represents the change in C_{Ytotal} when removing the step from a process flow, and, can be broken down into base cost and auxiliary cost components. Because these base costs and auxiliary costs are independent of step order, the step yielded cost is also independent of step order.

If (6) is the sum of all step yielded costs for Figure 2, then the sum of the base costs term $(C_{in} + C_1 + C_2)/Y_{in}Y_1Y_2$ equals the process yielded cost, C_{Yout} from Figure 2. The additional terms in this line of (6) represent the sum of the auxiliary costs.

Thus this method gives C_{Ystep} values that can be collected, according to the criteria set previously.

$$C_{Yin} + C_{Y1} + C_{Y2}$$

$$= \frac{C_{in} + (1 - Y_{in})(C_1 + C_2)}{Y_{in} Y_1 Y_2} + \frac{C_1 + (1 - Y_1)(C_{in} + C_2)}{Y_{in} Y_1 Y_2}$$

$$+ \frac{C_2 + (1 - Y_2)(C_{in} + C_1)}{Y_{in} Y_1 Y_2}$$

$$= \frac{C_{in} + C_1 + C_2}{Y_{in} Y_1 Y_2} + \frac{C_{in}(2 - Y_1 - Y_2)}{Y_{in} Y_1 Y_2}$$

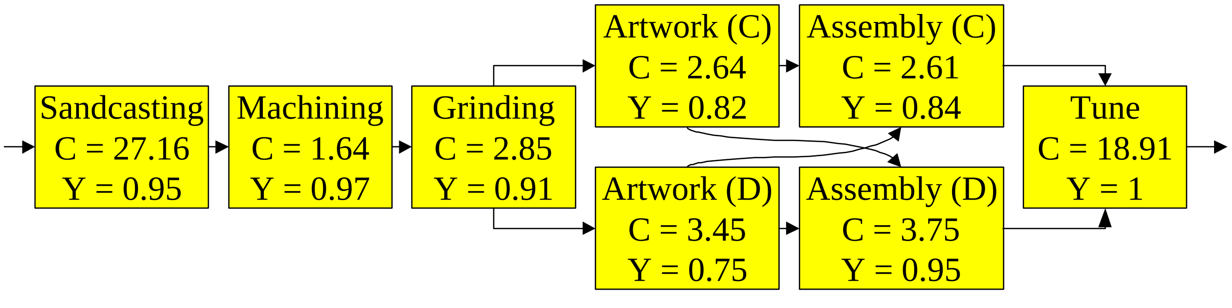
$$+ \frac{C_1(2 - Y_{in} - Y_2)}{Y_{in} Y_1 Y_2} + \frac{C_2(2 - Y_{in} - Y_1)}{Y_{in} Y_1 Y_2} \qquad (6)$$

In addition, these C_{Ystep} values are independent of step order and incorporate upstream and downstream information via the auxiliary costs. For example, in (5), upstream information appears in the C_{in} term and downstream information appears in the C_2 term. The C_{in} term represents the incoming auxiliary cost on assemblies to be made defective in the first step. That is, there will be some amount of cost invested into assemblies before they enter the first step. The assemblies made defective in the first step waste this cost by a factor of $(1\text{-}Y_1)$. Likewise, the C_2 term represents the auxiliary cost of the second step on assemblies made defective in the first step. Like the first case, there will be assemblies made defective in the first step that will absorb cost from the second step. Thus the *omission* approach calculates C_{Ystep} values that incorporate upstream and downstream information with its auxiliary cost terms (the last three terms in (6)). Furthermore, this approach defines C_{Ystep} values that are independent of step order. In (5), for example, C_{Y1} will not change if the order of steps is changed. This is because base cost and auxiliary cost terms are both independent of step order. The base costs only depend on the cost of the base step and the process yield while the auxiliary cost terms all have the same auxiliary yield factor, $(1\text{-}Y_1)$. It is also intuitive that the step yielded costs are independent of step order because of how they are calculated, as the change in process yielded cost when removing a step. Since this method defines step yielded costs that incorporate upstream and downstream information and that are independent of step order for steps between scrapping points, the *omission* approach is the most appropriate of the four methods considered in this paper for the measurement of step yielded cost.

III. DISTRIBUTION OF STEP YIELDED COST BY OMISSION APPROACH

To see how the *omission* approach distributes C_{Ystep}, consider the example shown in Figure 3. This process was obtained from (Minnis, 1999) and (Lam, 1995) and represents the manufacturing process for a microwave module (MWM). The MWM consists of a flat mechanical aluminum substrate (7”x 3” x ¼”, 0.5 lb) that is clad with a Teflon dielectric layer. Two electrical components are then mounted on the substrate with epoxy and a power module is surface mounted.

The process steps represent the manufacturing locations that were selected on the basis that they have the capability of performing the desired task. The data for first three steps was obtained from (Lam, 1995) and the last three from (Minnis, 1999), where both sets of data are for the same process flow. For the artwork and assembly steps, two different manufacturing locations were capable for completing each step, thus four different process flows were possible (C-C, C-D, D-C, D-D). A manufacturability assessment was then performed to calculate the system cost, yield, and lead-time for each of the four possible process flows. The results appear in the table of Figure 3, which are slightly different from those reported in (Lam, 1995) since more steps were incorporated into this example. One way to evaluate the best process flow in terms of cost and yield is to use yielded cost (the last row of the table in



Process Flow	C-C	C-D	D-C	D-D
Process Yield	0.58	0.65	0.53	0.60
Process Cost	55.81	56.95	56.62	57.76
Process Yielded Cost	96.48	86.99	106.36	95.87

Figure 3. Process flow and corresponding yield and cost information for MWM example (Lam, 1995; Minnis, 1999). The process flow is not actually branched. Four different combinations of Artwork and Assembly are considered.

Step that creates defects

Step where cost is incurred

	Sandcasting	Machining	Grinding	Artwork Gen.	Assembly	Tune
Sandcasting	**96.81**	2.55	8.64	17.62	4.84	0.00
Machining	0.12	**2.50**	0.22	0.45	0.12	0.00
Grinding	0.22	0.11	**4.36**	0.79	0.22	0.00
Artwork Gen.	0.20	0.11	0.36	**4.03**	0.20	0.00
Assembly	0.29	0.15	0.51	1.04	**5.73**	0.00
Tune	1.44	0.76	2.58	5.26	1.44	**28.88**
Total	99.09	6.18	16.66	29.20	12.56	28.88

Figure 4. Distribution Matrix for step yielded costs

Figure 3). Using this approach, it is found that the C-D flow has the lowest yielded cost and is the best available choice.

Figure 4 shows how base costs and auxiliary costs are distributed among process steps for the C-D process flow. The diagonal elements in bold represent base costs while the remaining elements represent auxiliary costs. The sum of the base costs and auxiliary costs in each column are the step yielded costs, and are shown in the "total" row.

The step names on the left side of Figure 4 represent where costs are incurred. For example, the upper left value (row 1, column 1) represents the base cost of the sandcasting step, which is found with an expression analogous to the second term of (5). The next value to the right (row 1, column 2) represents the proportion of money spent by the sandcasting step on assemblies that will eventually be scrapped, due to the defects introduced by the machining step. This term, an auxiliary cost, would be found with an expression analogous to the first or third term of (5). This is the money wasted at the sandcasting step due to the machining yield: the lower the machining yield, the more money wasted in the sandcasting step. From this matrix, it can be seen that, aside from the sandcasting and tuning rows, the auxiliary costs are relatively low. This is reasonable since the costs of the machining, grinding, artwork generation, and assembly steps are low, and thus there is less opportunity to waste money. On the other hand, the auxiliary costs appearing in the sandcasting and tuning rows are higher because of the relatively higher costs of these steps. Also, notice how in these rows the auxiliary cost increases as the yields of the steps that create defects decreases, that is, costs increase from machining, to sandcasting and assembly, to grinding, and then to artwork.

To make the most effective change in process yielded cost for this example, one should decrease the largest auxiliary cost, \$17.62. This can be done either by decreasing the cost of the sandcasting step or by increasing any step yield. However, in terms of improving step yields, it turns out to be most efficient to increase the lowest yield in a process, shown by (7).

$$\frac{d(C_Y)}{dY} = \frac{d(CY^{-1})}{dY} = -CY^{-2} \qquad (7)$$

Equation (7) shows that the rate of change of yielded cost is more negative at lower yields. Thus, yielded cost drops more quickly with increases in yield at lower step yields. It is thus most efficient to improve the artwork generation yield as apposed to any other step yield for improvement in this system. Additionally, the fact that the artwork generation step has the lowest yield and the highest auxiliary costs are no coincidence. For linear process flows, like this example, a higher proportion of cost will be wasted on assemblies due to the artwork generation because the it contributes the most to making assemblies defective.

Although it is most effective to increase the yield of the artwork generation step over any other step yield, there still remains the decision of whether to do this or to decrease sandcasting step cost. Figure 5 shows the effects of decreasing cost and increasing yield on process yielded cost. A set reduction in sandcasting cost will give equal reductions in yielded cost at any given point (i.e., the slope of this curve is constant). However, the slope of the second curve changes with step yield and thus the marginal benefit of increasing yield is greater at lower yields. Since adjusting yields and costs are unrelated and their effect can only be compared on an application - specific basis, one should evaluate the improvements available by individually adjusting sandcasting cost and artwork generation yield to determine the best solution.

IV. YIELDED COST METROLOGY EXTENDED TO GENERAL PROCESS FLOWS

Conventional wisdom for effective process improvement is to improve the step with the lowest yield, as described in the previous section. However, this study finds that this may not be generally true, and that sometimes processes are best improved by increasing a yield that may not necessarily be the lowest in the process. Consider the example (Figure 6).

The process in Figure 6 consists of two parallel sub-processes that conclude with testing. Each sub-process combines together in a soldering step and a packing step. Each test step has a cost and yield, similar to that for other process steps, but also has a fault coverage fraction (f_a and f_b) that represents the fraction of faults detected by the test step. The test step will scrap defective assemblies and will pass non-defective assemblies to the soldering step.

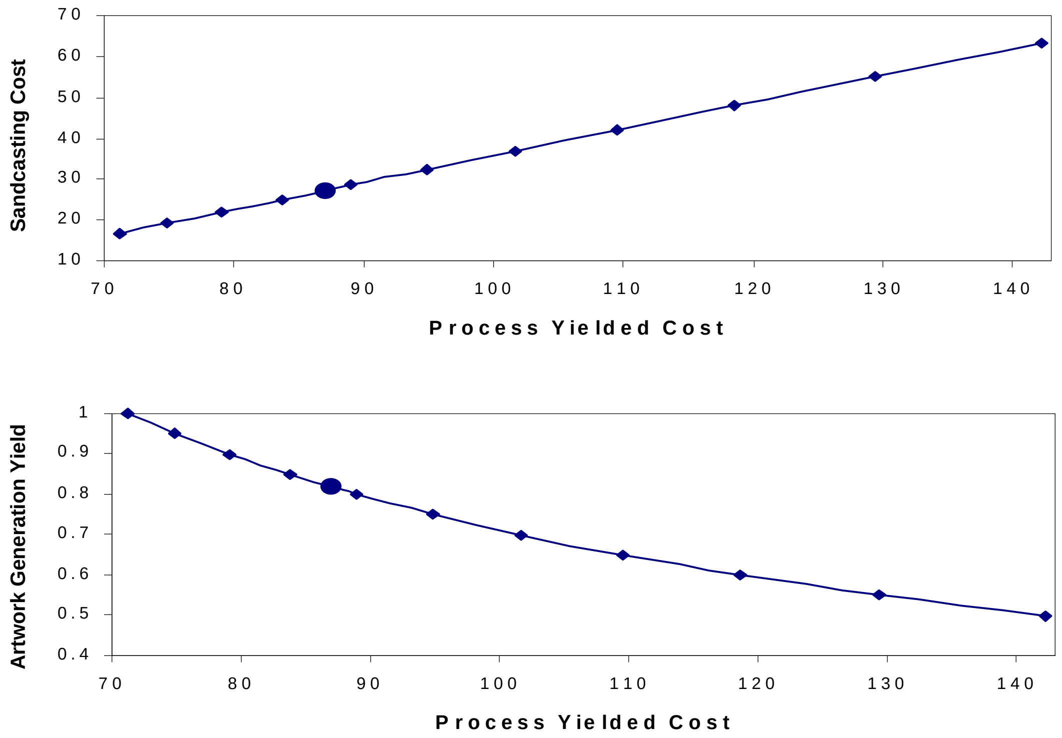


Figure 5. Sandcasting cost effects and artwork generation yield effects on process yielded cost. The large point represents the original conditions for sandcasting cost and artwork generation yield shown in Figure 3.

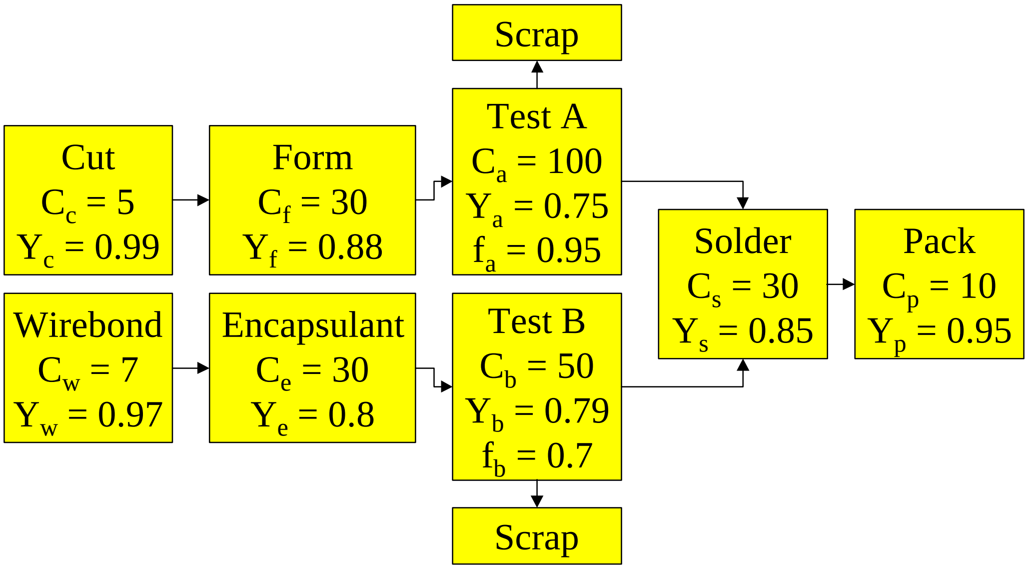


Figure 6. Branched process flow with test steps

Step that creates defects

Step where cost is incurred	Cut	Form	Test A	Wirebond	Encaps.	Test B	Solder	Pack
Cut	**13.35**	1.60	3.34	0.12	0.86	-1.50	2.00	0.67
Form	0.80	**80.09**	20.02	0.73	5.19	-9.03	12.01	4.00
Test A	2.67	32.03	**266.95**	2.43	17.29	-30.09	40.04	13.35
Wirebond	0.01	0.11	-2.17	**17.57**	3.51	3.69	2.64	0.88
Encapsulant	0.04	0.48	-9.31	2.26	**75.29**	15.81	11.29	3.76
Test B	0.06	0.80	-15.52	3.76	25.10	**125.48**	18.82	6.27
Solder	0.03	0.34	-6.61	0.49	3.46	-6.03	**53.45**	2.67
Pack	0.01	0.11	-2.20	0.16	1.15	-2.01	2.67	**17.82**

Figure 7. Distribution Matrix for step yielded costs for process shown in Figure 6

The process cost and yield for this type of process (from Becker, 2001) are given by equations (8) and (9). A step yielded cost matrix (shown in Figure 7) was formed as discussed in Section III.

$$C_{total} = \frac{C_c + C_f + C_a}{(Y_c Y_f Y_a)^{f_a}} + \frac{C_w + C_e + C_b}{(Y_w Y_e Y_b)^{f_b}} + C_s + C_p \qquad (8)$$

$$Y_{total} = (Y_c Y_f Y_a)^{1-f_a} (Y_w Y_e Y_b)^{1-f_b} Y_s Y_p \qquad (9)$$

To find the best solution to improving the system, an efficiency ratio can be used, where the ratio equals the change in process yielded cost divided by the change in auxiliary yield for a particular step. The best solution would be to improve the yield of the step that provides the highest efficiency ratio. From the table in figure 7, the highest auxiliary cost is $40.04 (Solder column and Test A row). A reduction of $10 of this value (which was achieved by increasing the yield of the soldering step) led to an efficiency ratio of 736.05. The next highest auxiliary cost is $32.03 (Form column and Test A row). A similar reduction of $10 in this value led to an efficiency ratio of 410.32. In the next five $10 adjustments of auxiliary costs, no efficiency ratios were found that were greater than 736.05. Thus, to best improve this process, one should increase the solder yield since it produces the highest efficiency ratio. Notice, that the Solder yield is not the lowest yield in the process.

V. GENERAL POINTS ON YIELDED COST

In the calculation of the C_{Ystep} components, several interesting points must be made. First, it is possible that some auxiliary costs can be negative due to test steps (e.g., see Figure 7) since test steps effectively *increase* process yield by removing bad parts. Second, the auxiliary cost components overlap with their corresponding base costs. From the first example, the auxiliary cost of the sandcasting step due to machining yield overlapped the base cost of the sandcasting step. Only base costs should then be added to get process yielded cost for this reason – to avoid double counting auxiliary costs. Auxiliary costs simply serve to represent the proportion of cost that is wasted due to step yields. Finally, assemblies can be made defective in multiple steps. For example, the assemblies made defective in sandcasting, can be made further defective in machining. Thus, auxiliary costs are not always strictly unique.

In Figure 8 each step yielded cost was plotted against the assembly step yielded cost for the example in Section III where the cost of the assembly step was increased from $0 to $196 in

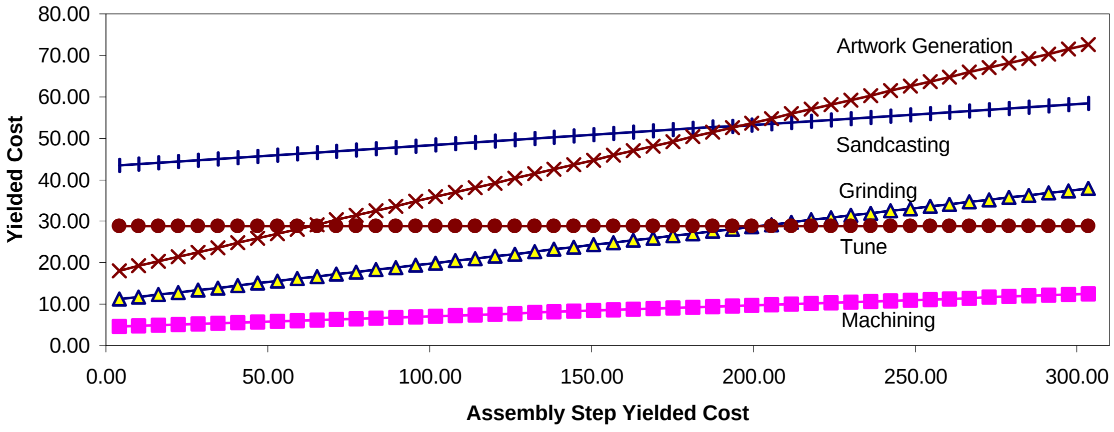


Figure 8. Effect of assembly step cost changes on relationship between $C_{Yassembly}$ and other C_{Ystep} values

increments of \$4 (the actual process has $C_{assembly}$ = \$3.75). As shown by the equally horizontally spaced points in Figure 8, the change in assembly C_{Ystep} is linear. This is because, with everything else being constant, a change in step cost brings and equal change in process cost. Since the expression for process yielded cost without including the step is

$$C_Y = \frac{C_{total} - C_{assembly}}{Y_{total}/Y_{assembly}} \tag{10}$$

a change in yielded cost of the process without including the assembly step is zero. Thus the only factor involved with the change in assembly step yielded cost is the process yielded cost with the assembly step, which changes linearly with cost. Therefore, the other yielded costs change linearly and their slope is (1-Y_{step}). To decrease the slopes, one needs to increase the yield while changing step costs shifts the curves up or down.

VI. SUMMARY

This paper defines and explains yielded cost for simple and complex sequential process flows. By analyzing existing yielded cost methods, a new model was developed that provides more accurate information on the effective cost per good assembly for process steps. Two of the existing yielded cost models, the *itemized* approach and *iterative* approach, were not used because the C_{Ystep} values cannot be readily accumulated. Another model, the *cumulative* approach, had C_{Ystep} values that did not incorporated upstream and downstream information and were not independent of step order. The *omission* method, proposed here, was found to be the most complete approach because it defined C_{Ystep} values that incorporated upstream and downstream information and that were independent of step order. Models were developed for the *omission* method and it was demonstrated on a MWM manufacturing process.

To most efficiently improve any process flow, one should tradeoff the outcome achieved through increasing the yield associated with the highest efficiency ratio (change in process yielded cost divided by change in step yield) or decreasing the cost associated with the highest auxiliary cost, according to the tradeoff curves (Figure 5). These auxiliary costs can be found in distribution matrices produced by the *omission* method, which are especially useful in displaying how yielded costs are distributed among individual steps in a process flow.

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