Calculating Total Cost of Ownership in Electronics Manufacturing

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Abstract

Total cost of ownership is a financial estimate designed to help consumers and enterprise managers assess direct and indirect costs commonly related to software or hardware. It is a form of full cost accounting. However, in the world of electronics manufacturing are there any standardized, generally applicable values and guidelines that apply to the determination of the cost-of-ownership of SMT equipment, or software that manufacturers can refer to in order to make decisions that will carry them through the future?

This presentation takes a comprehensive look at the many factors to be considered when purchasing equipment such as purchase price, value retention, operating costs, output quality, ease-of-use, availability, and real performance. We will also discuss the total costs of ownership directly related to the factory flow of projects and processes and, thus, profitability. We will pay special attention to the extent to which the individual factors are truly relevant for the cost-of-ownership computation.

Based on this analysis, the presentation will cover typical COO examples in various manufacturing environments ranging from high-volume to mid-volume and low-volume environments in low-cost and high-cost countries. The presentation will introduce newly developed COO tools that let you make exact and objective COO computations in the electronics industry.

In particular, the presentation will shine light on the question to what extent placement costs have a significant impact on the overall manufacturing costs. It will also do away with some myths and assumptions around cost-of-ownership in electronics manufacturing.

Brief discussion of past work in this area

Total Cost of Ownership or TCO is a subject that has been explored by many different groups in the electronic assembly industry. Several different cost models have been proposed for analysis by different groups, many of them original equipment manufacturers representing varying disciplines such as process equipment suppliers – pick and place equipment manufacturers – and test equipment manufacturers.

It would be a large task in itself to review each of these models, suffice it to say that each one of them performed rather complex computations of several differing interacting factors that go into producing a TCO result. However, the particular background of the “Source” for the computation in many cases served to influence the perspective upon which TCO is looked upon, and hence the decision for which factors would be included and the relative weighting that each would carry. The result being that each different method while in its self serves to illustrate a particular perspective on the cost drivers, none of the models could easily be used to compare with or validate another.

Also, due to the complexity of these models, and as a result of attempts to protect some of the IP work that went into creating these models, it became very difficult for the outside observer to comprehend or validate the underlying methodologies. This only served to divide opinions and lead to reluctance within the manufacturing community to accept one particular model over another, or even to put much faith in the results of any particular calculation.

Any one wishing to explore TCO with any particular model had therefore to choose whichever model matched their particular situation and use that model with a lot of careful consideration and comprehension. Care had to be taken to ensure that any result was only used to establish the weighting and sensitivity of each particular input to the TCO. Additionally, if certain pre- conditions were controlled the chosen model could be used to compare the TCO between different manufacturing systems.

Amidst this confusion there was a recent attempt by the IPC to bring some clarity and standardization to this field. This took the form of an initiative to develop an independent standard for calculating cost of ownership within surface mount manufacturing. Please see Fig 1 a picture of the first draft of this initiative.

DRAFT

IPC
COST OF OWNERSHIP FOR SURFACE MOUNT TECHNOLOGY MANUFACTURING EQUIPMENT METRICS

1 Purpose

1.1 The purpose of this guide is to provide standard metrics for evaluating unit production cost effectiveness of factory equipment subsystems in the Surface Mount Technology (SMT) industry. The guideline is appropriate for application to any type of equipment processing SMT boards or panels.

1.2 The guideline establishes a well-defined practice to facilitate an understanding of equipment-related costs by providing definitions, algorithms, methods, and default examples necessary to build a full or constrained cost of ownership (COO) calculator. A number of constraint types are defined.

2 Scope

2.1 The definitions provide a metric that can be applied to any factory equipment system, but are specialized to SMT printed circuit board production.

assess several different options based on their financial impact.

2.7 This guideline does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this guideline to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

3 Referenced Standards

3.1 *SEMI Documents*

SEMI E35-0701 Cost of Ownership for Semiconductor Manufacturing Equipment Metrics

SEMI E35.1 — Guide for Cost of Equipment Ownership Comparison Metric

NOTE 1: IPC has explicit permission from SEMI to use these documents as the basis for IPC XXX Standard.

Figure 1 – an extract from the IPC Draft on Cost of ownership

True to IPC principles, this initiative included multi-disciplinary and cross- industry representation. This initiative so far has not come to conclusion. Perhaps as a reflection of the complexity of the subject matter, and the fact that both within SMT and also the surrounding processes to surface mount there are many levels of interaction that can influence cost of ownership. However, even at this stage one useful outcome of the initiative was to establish the broad scope of possible inputs that can influence TCO within surface mount. This is conceivably not complete, but it could be the best attempt so far to get industry wide agreement on this difficult subject.

The rest of this paper will illustrate the efforts taken by one particular participant in this original IPC initiative to explore this area more fully even if in isolation. Possibly this further exploration of this subject will help any future IPC standardization efforts in this area.

<u>Basis for this particular model</u>

There is an old saying **"One persons Scrap may be another ones Treasure"** this may be true when considering TCO since there are so many different line and equipment configurations, matched with an infinite variety of product complexities and production characteristics, all further influenced by a particular set of operating characteristics and business objectives. For example, one enterprise may be influenced by the desire to drive out all costs of production maximizing economies of scale in an ultra-high volume production concept. But another enterprise may be focused on readily available capacity and maximum flexibility to produce any new product on a line where capability is more important than utilization.

To this end the TCO model has to be sufficiently broad in scope to span as many different types of enterprise and business objectives. However, to clarify and simplify the tool an ability is inbuilt to disable some of the Key Value Drivers (KVD) when not appropriate to a particular enterprise.

Taking this newly established set of basic inputs from the draft IPC initiative a new TCO model was developed. The hierarchy of the TCO can be illustrated in Figure 2 showing how a TCO number expressed in a currency value per product produced is made up of three Fundamental drivers, with each of the key value drivers that contribute to them, and all of the basic value drivers that contribute to each of these KVD.

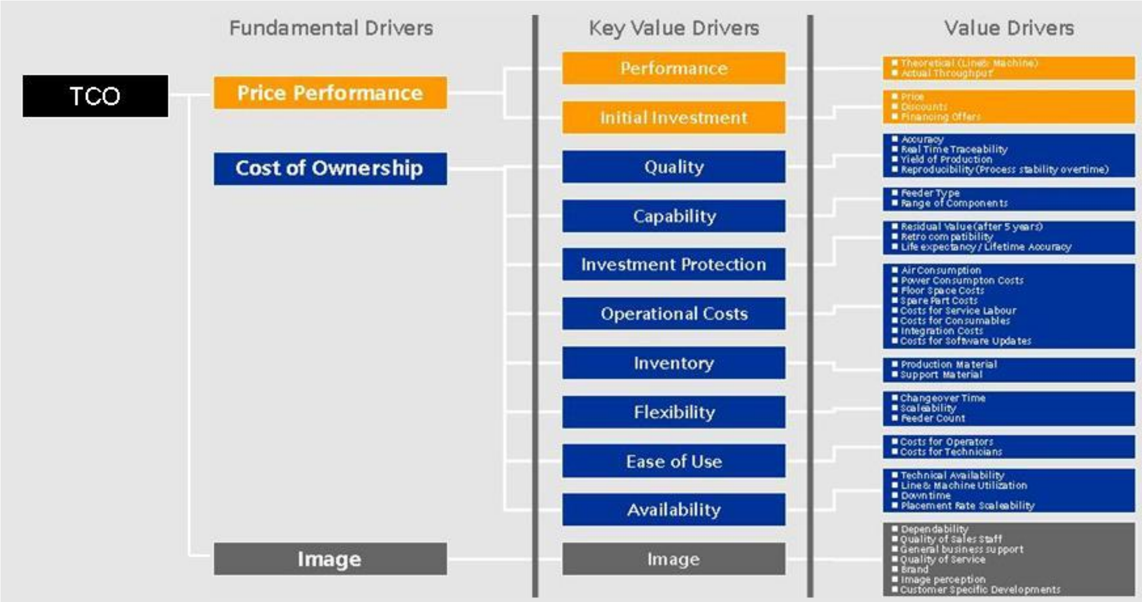

Figure 2 Showing the Driver structure for the TCO calculation

In Figure 3 two KVD "Performance" & "Quality" are further explained with regard to the structure of all the contributing factors that are considered in the calculation.

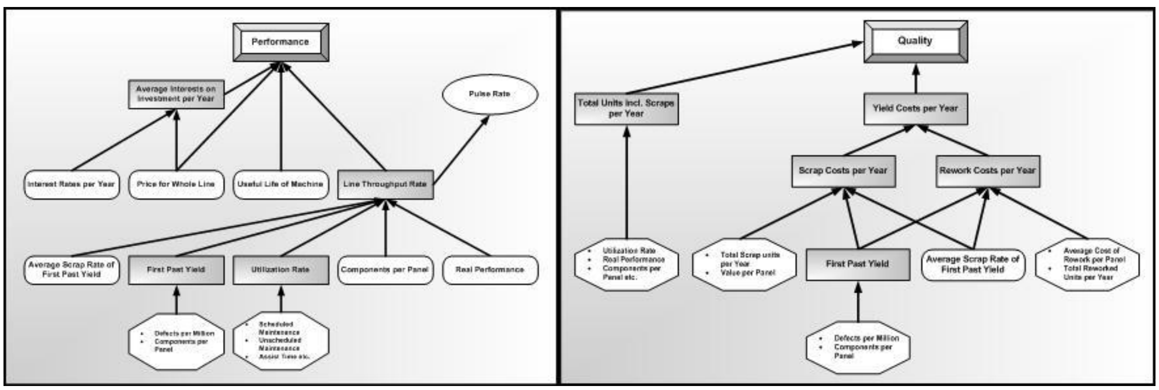

Figure **3 Showing the hierarchy of the KVD "Performance" & "Quality"**

This would be a very long and boring paper if it was attempted to detail every level of logic and calculation within this tool, which may be better explored with a particular investigation during a point to point interaction. It should be sufficient to detail the key inputs as explained in Fig 2, and the key outputs as illustrated in Figure 4

Fixed Costs			
Solution	Line 1		Line 2
II Initial Investment for Line and Equipment	$1,694,192		$1,694,192
SUCM Software update costs per year	$16,942		$16,942
TSC Spare part costs per year	$23,147		$23,147
REV Residual value after useful life	$300,000		$300,000
TCF Total fixed costs per year	$318,927		$318,927

Yield Costs			
Solution	Line 1		Line 2
SCY Scrap costs per year	$132,600		$212,160
RCY Rework costs per year	$32,487		$51,979
YC Yield costs per year	$165,087		$264,139

Recurring Costs			
Solution	Line 1		Line 2
LCY Labor costs per year	$92,945		$92,945
UCY Utility costs per year	$10,614		$10,614
FCY Floor space costs per year	$698		$698
COCY Cost of consumables per year	$11,690		$11,690
YCP Yearly capital costs for all products	$232		$232
TRC Total recurring costs per year	$116,179		$116,179

Total Costs			
Solution	Line 1		Line 2
TCY Total costs per year	$600,193		$699,245
LTR Line throughput rate (faultless panels per year)	662,337		661,939
ACP Average cost for one Placement	$0.00091		$0.00106
TCO Total Cost of Ownerhsip per panel*	$0.90617		$1.05636

*Excluding interest rates and expenses for PCBs and components

Figure 4 TCO outputs

The Key outputs are: - **TCO** per panel & **ACP** Average cost for one placement.
These are derived from a total cost per year **TCY** & a line throughput of faultless panels per year **LTR.**
The cost factors are derived from three major areas of **fixed costs, recurring costs**, & **yield costs**.

There is the ability to set basic costs for a particular region and currency, however this tool is truly a comparative tool for the reasons mentioned earlier, it allows comparisons to be made between one particular set of conditions and another. The tool can be used to illustrate which key inputs have the most effect on TCO per panel, and also to do sensitivity analysis to determine what some level of change in one or more particular factors will do to the TCO result.

Analysis of three differing production concepts using this TCO tool

The TCO tool discussed above was used to model three different production situations as follows; - a **high-mix low-volume line** similar to a NPI facility, a **high-volume-line** suitable to produce any product in volume, and an **ultra-high volume line** that could be used in a dedicated manner for a "Consumer" type product. Each production situation line concept differed from the other in equipment set, capability, and other basic input factors; however the intent of the comparison was to **compare within each line concept** the effect of a limited set of changing conditions. Comparisons between the line concepts may be interesting, but it does require a more detailed consideration than this paper will discuss.
Some basics constants were maintained throughout the analysis as follows in figure 5

Basic constants	Total initial line cost	Line residual value after five years	Working hours	Number of operators	Line effective placement rate comp. per hr
High Mix	$ 1,281,968	$ 200,000	24 hrs, 6.5 day wk, 50 wk yr	2	30,000
High Volume	$ 1,694,192	$ 300,000	24 hrs, 6.5 day wk, 50 wk yr	2	100,000
Ultra High Volume	$ 3,200,000	$ 500,000	24 hrs, 6.5 day wk, 50 wk yr	5	300,000

Figure 5 Basic constants for each line

In all cases basic utility costs and labor rates were taken from typical values that may be found in Mexico (Same conditions for all lines and variations)
Figure 6 shows the relative dimensions of the costs splitting out labor rates for the high volume line (at 50 Defects Per Million Placements (DPM) and other factors set to nominal)

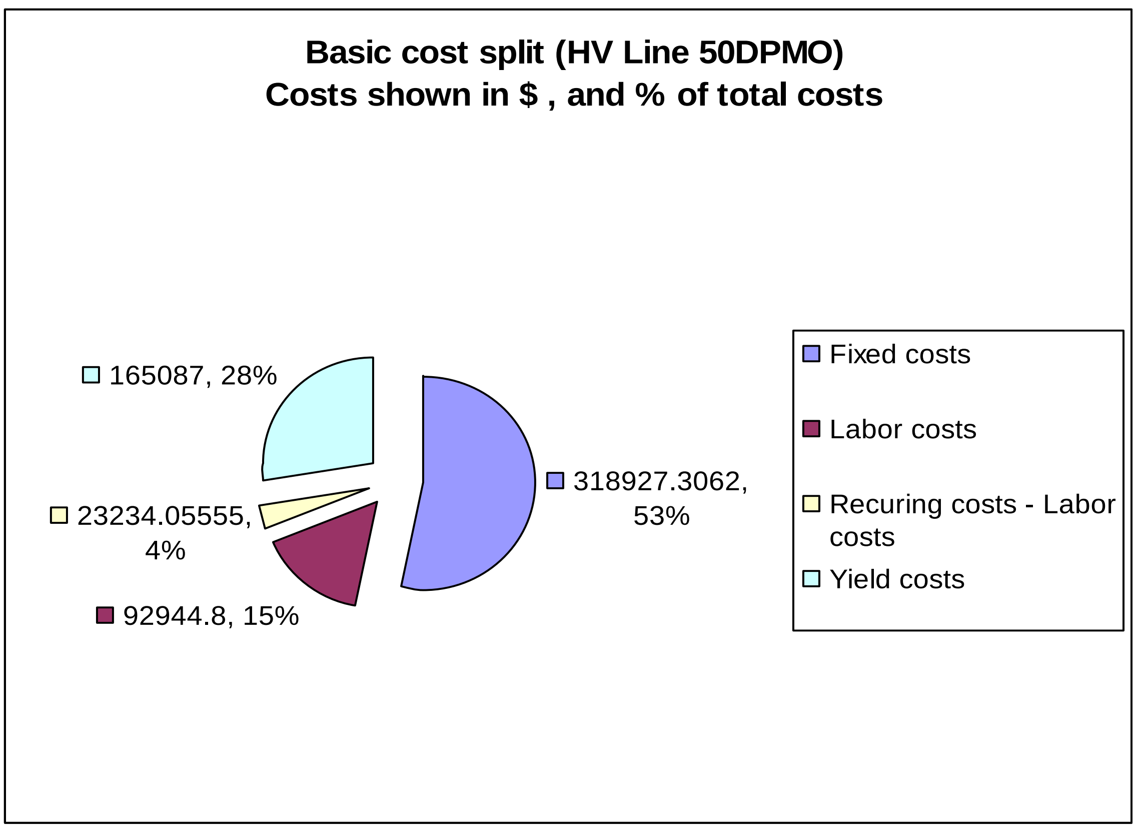

Figure 6 basic cost split for HV line at 50DPM

Labor costs were not included as a key variable for this paper, but an idea of its significance can be estimated from Figure 6. Take into account that the basic labor rate can be estimated at around four times more or four times less than used here if considering a higher or lower labor cost region than Mexico.
Three particular factors were used to illustrate their effect on TCO; - **process quality** (measured in defects per million (Placements) DPM), **equipment utilization** (measured in a % below a preset value), and **total line cost** (measured as a % higher than a pre-calculated value). These factors were adjusted over ten different levels to show their effect on TCO and to allow each factors effect to be compared on the same graph.
The range of variation is illustrated in Figure 7

	Factor change in ten increments between: -		
	DPM	Utilization	Extra Price
High Mix	20 to 290 DPM	50% to 28%	0% to 18%
High Volume	20 to 290 DPM	85% to 63%	0% to 18%
Ultra High Volume	20 to 290 DPM	85% to 63%	0% to 18%

Figure 7 Lines and Factor levels

<u>Results of the analysis</u>
As discussed before the TCO results are most relevant when comparing different factor changes within one line type, the results are illustrated in figure 8

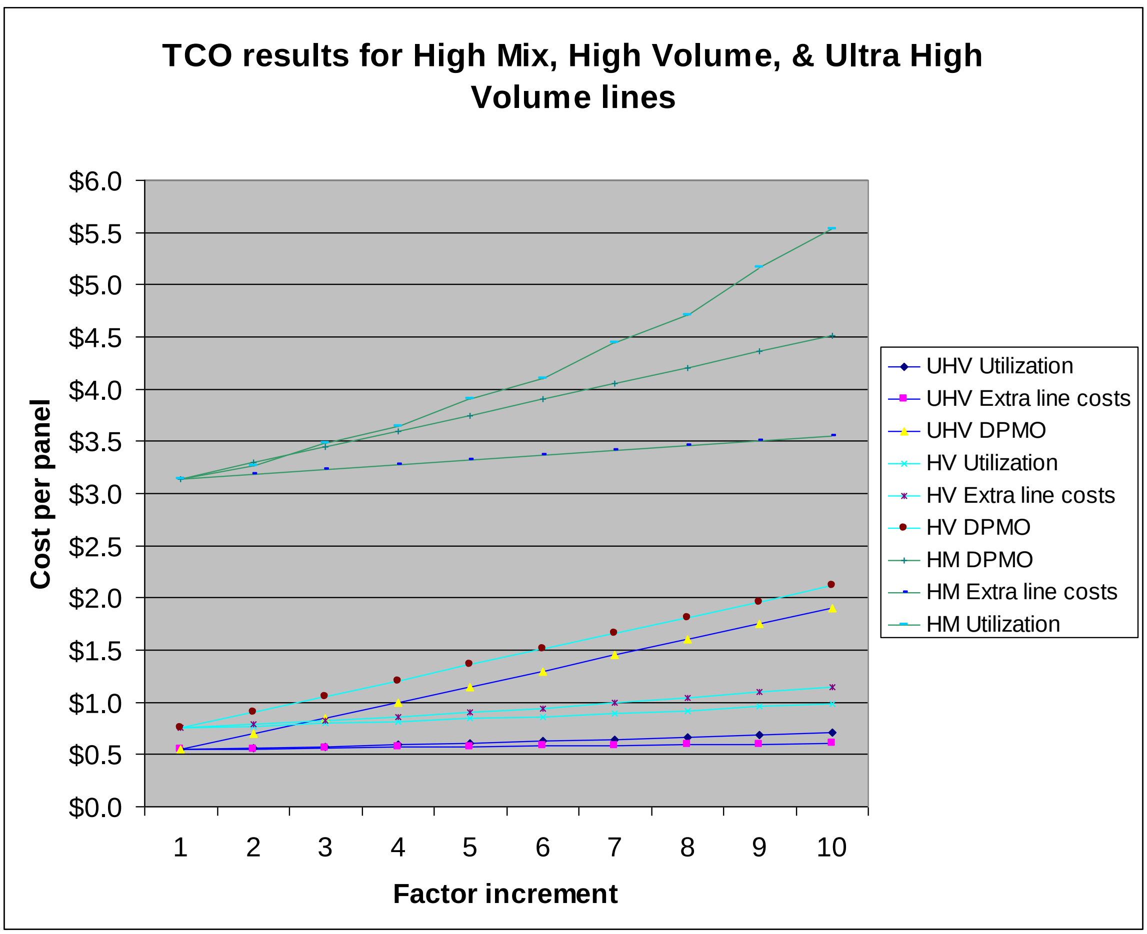

Figure 8 TCO shows costs per panel over three factors – ten levels - and three line concepts

In all cases only one factor is changed at a time, but from the results of the analysis we can see that for the two lines (high-volume, & ultra-high-volume) the most significant factor (within the range of change explored) was process quality level DPM.

For the high-mix line utilization level was the factor effecting cost per panel most.

This difference in the most significant factor can be understood from the fact that process quality was directly affected by volume produced since it was a defect per million produced metric. The high mix line had a significantly lower designed production capability and started with a lower initial utilization level than the other two lines. Consequently, for a similar process quality level fewer defects are produced and therefore fewer yield costs are incurred. Also, the fixed costs and labor costs become more significant in conjunction with the lower quantity of panels produced.

Some basic inputs to yield costs are shown in figure 9

1. Input Project Configuration

Solution	Line One	Line Two
CPP Components per panel	1000	1000
CPS Changeovers per shift	0.00	0.00
NPSS New product setup per shift	0.00	0.00
VPP Value per panel	200.00	200.00
ACR Average cost of rework per panel	1.00	1.00
COC Cost of consumables per panel	0.02	0.02
DPM Defects per million	50	80
FPY First pass yield (% defects)	95.00%	92.00%
ARR Average reworkable rate of first pass yield	98.00%	98.00%
ASR Average scrap rate of first pass yield	2%	2%
TPQ Total product qualification idle time (h/week)	0.0	0.0
TPE Total process engineering idle time (h/week)	0.0	0.0

2. Line Speed

Solution	Line One	Line Two
RP Real performance in (components per hour)*	100,000	100,000
NPS Number of panels processed per shift	680	680
TUS Total units including scraps per year	663,000	663,000
TSU Total scrap units per year	663	1,061
TRU Total reworked units per year	32,487	51,979

Figure 9 inputs to yield costs

From Figure 9 you can see that some basic inputs such as: -
1000 components (placement opportunities for defects) per panel, $200 per panel scrap costs, $1 rework cost for all defective panels, and 2% of all failed boards (so for 90% yield only 0.2% of all panels produced are scrapped)
These basic assumptions are very conservative and in many cases the rework costs and scrap rates may be significantly higher which would only serve to exacerbate the significance of yield costs (Or process quality) to TCO.

To understand what this analysis is telling us we must first validate the levels that were chosen for the key variable inputs; -

DPM process quality 20 to 290 defects per million placements

Questions such as what is best in class process quality performance and what is typical process quality performance are very good ones that require a little qualification to answer since component complexity levels and process equipment capability levels are not static over time. For component placement we should choose a component that has been around for at least the last several years so let's use 0402 discrete devices as a benchmark. Also, let's establish what is best in class process performance for such a device in today's modern equipment.

Based on the observation of many volume production lines across multiple industry segments it could be said that today's modern placement equipment can achieve DPMO levels of less than 20 DPMO. This does require best in class process and equipment engineering but is none the less achievable. But what is typical or average? That is a harder question to answer since it depends on the level of engineering knowledge, age and condition of equipment. Several years ago 0402 devices were only just becoming commonplace, now today's equipment is designed for the challenges of devices such as 0201 or 01005 which are more than a factor of four more complex. This means that for 0402 devices equipment today is much more capable than equipment designed more than several years ago, even in best maintained conditions!

Many studies have been made into process performance trying to establish what is best in class, what average is, and what "Typical" is. It is the Authors considered opinion that even with modern equipment, combined with poor process engineering and poor equipment maintenance (over the long term) DPMO levels of up to or exceeding 290DPMO can be expected. Indeed combine aged equipment with poor process knowledge and defect levels far in excess of this are possible. As such it is the author's belief that a range of 20 to 290 DPM is acceptable for this analysis allowing the reader to define where in that range his process performance is and hence the weighting that has on TCO.

Line utilization levels

Again this measure of line productivity could require further explanation as to what goes into making up "utilization"?
However, the main point here is that for both the high-volume line and ultra-high- volume line a level of 85% was chosen, with a variation from that point to 22% below that level (so more than 25% less productive than the initial level).
In the authors opinion this amount of variation is reasonable to expect when contrasting best in class performance with a less focused and driven approach to productivity. The exact levels are subject to definition, but the range of variation is perhaps valid, and again it is for the reader to understand where his productivity stands for the analysis.
For a high-mix line it is generally expected that due to more activities in product changeover and NPI activities, the productivity of such lines is significantly below a volume lines production. Hence a level of 50% utilization was chosen with a 22% variation below that level used for the analysis. Again, this may be expected to be typical of what may be found in real cases and once again the reader can judge where in that range his line lies.

Total line price

This is an even harder measure to define; one could just as well ask "What is the price of a car?" Well that would depend on such things as what make of car are we talking about? What accessories and extras are included in that cars specification? What level of negotiation was applied in the purchasing process etc….
The same is true of a production line. For the sake of this analysis a nominal value for a line was used with a range of variation from zero to plus 18% more. This level of variation allows us to observe the effect of variation in pricing depending on perhaps different line options being used to effect better productivity such as higher speed placement heads, or better changeover software tools, etc…
The main point is to contrast line pricing variation against process costs and utilization levels.

<u>Fully depreciated equipment or "Is there such a thing as a free lunch?"</u>

A further useful analysis would be what effect would there be of using equipment that is several years old and therefore fully depreciated, compared to new equipment? This is a good question to pose as the average age of equipment in the field may be more than several years old with all the implications that may have on: -

- **Process quality factors (original equipment capabilities vs. today's product complexity levels, the condition of this aged equipment due to the wear and tear of time and use).**
- **Increased maintenance costs to support this aged equipment.**
- **Increased staffing costs due to larger or more lines and less capable equipment.**
- **Lower utilization levels due to the aged concepts of the equipment (changeover methodology or component replenishment on the fly).**

For this analysis the high volume line was chosen as the comparison line, the fully depreciated line was chosen as a typical line of equipment seven or more years old which would certainly be beyond any normal depreciation cycles (Normally five to seven years) Both lines were of a design that they would both produce 100,000 components per hour output in real product. The following base differences were set in the TCO tool as can be seen in figure 10; -

Pre set factor	New line	Depreciated line
DPM Level	20	80
Component vision & ID errors	0.02%	0.50%
Number of operators	2	3
Total line price	$1,694,192	0
Annual line software maintenance & spare parts costs	$40,089	$62,866
Number of placement machines	2	4

Figure 10 base differences between the new line and the depreciated line

DPM Level
It is assumed that the line is building products of technical complexity for today's products and not a product from several years ago, also it is assumed that no major retro fitting and upgrading of the depreciated equipment is done (This would add significant costs) In both cases it is assumed that process optimization is at optimal levels for the equipments capabilities.

Vision and ID errors
Similar to DPM level the amount of components lost through attrition is set at basic levels for the condition of the equipment and the component complexity of today's product. A nominal cost for these lost components is set and it is assumed that expensive components are controlled to a higher level or are reworked rather than lost.

Number of operators
The new line has one less operator than the fully depreciated line, this is justified by the fact that this line has fewer machines on it, and newer equipment tends to require less operator intervention due to progressive improvements that will have been designed into newer generation of equipment.

Total Line price
A nominal line price of all equipment on the line (Printers placement, ovens etc) is taken at $1,694,192 for the new line, and a zero value price associated with the fully depreciated line.

Annual software and spare parts costs
A higher cost for this is attributed to the fully depreciated line due to the fact that it has more equipment and the condition of equipment several years old may actually demand more spare parts (Newer generation of equipment should have designed into their concept more robust systems)

Number of placement machines
Since equipment that is several years old is used for the fully depreciated line it is configured with more machines, this reflects the trend for higher placement speeds over time within one machine frame.

Figure 11 shows the output of the TCO calculation of the new line vs. the fully depreciated line; -

Fixed Costs

Solution	New Line	Depreciated line
II Initial Investment for Line and Equipment	1,694,192 €	0 €
SUCM Software update costs per year	16,942 €	26,866 €
TSC Spare part costs per year	23,147 €	36,000 €
REV Residual value after useful life	300,000 €	0 €
TCF Total fixed costs per year	318,927 €	62,866 €

Yield Costs

Solution	New Line	Depreciated line
SCY Scrap costs per year	53,040 €	212,160 €
RCY Rework costs per year	32,487 €	129,948 €
YC Yield costs per year	85,527 €	342,108 €

Recurring Costs

Solution	New Line	Depreciated line
LCY Labor costs per year	92,945 €	125,237 €
UCY Utility costs per year	10,614 €	21,397 €
FCY Floor space costs per year	698 €	1,117 €
COCY Cost of consumables per year	11,690 €	0 €
YCP Yearly capital costs for all products	232 €	5,801 €
TRC Total recurring costs per year	116,179 €	153,552 €

Total Costs

Solution	New Line	Depreciated line
TCY Total costs per year	520,633 €	558,527 €
LTR Line throughput rate (faultless panels per year)	662,735	661,939 €
ACP Average cost for one Placement	0.0008 €	0.0008 €
TCO Total Cost of Ownerhsip per panel*	0.7856 €	0.8438 €

*Excluding interest rates and expenses for PCBs and components

Figure 11 TCO output of new line versus fully depreciated line

Since each line was configured to have roughly the same base capacity the main drivers in TCO are fixed costs, recurring costs and yield costs.

Based on the assumptions and pre set conditions mentioned earlier, the fully depreciated line (which had no capital equipment depreciation costs) does actually come out as the more expensive production option. The major driving factor in this comparison is of course fixed costs versus yield costs. However, in this case the fully depreciated line costs were 7.5% higher.

This shows that careful analysis and investigation are warranted when making equipment replacement analysis. Not only is the purchase price of the new equipment and costs of spare parts and refurbishment important, also current process performance levels alongside careful analysis of product complexity levels matched with new and original equipment performance specifications and realities.

In some cases process performance levels of several hundred DPM may be encountered when matching a modern complex product with equipment that is one or two generations of design old and perhaps a little worse for the wear of time. This, as demonstrated earlier, can have a dramatic effect on TCO!

In many cases a well maintained and appropriately refurbished machine is capable of performing well alongside modern products with reasonable component complexity levels. However, if the equipment is suffering from its years of use, and perhaps the most complex products have to be produced in volume, a detailed analysis of current process performance levels and equipment conditions may warrant equipment replacement.

In Conclusion

In today's competitive environment it is well advised that engineers, and other leaders in manufacturing decision making, should understand all of the factors that have an input into TCO. Indeed, as has hopefully been demonstrated in this paper, this is a complex subject with many potentially interacting factors that can affect TCO. As such, it is useful to have a TCO tool (as demonstrated in this paper) available for careful analysis of the particular critical factors and what level of sensitivity these factors have towards overall TCO for each particular case.

The particular factors and levels of variation that were chosen in this study should be significant to all interested parties. It should be up to the individual to decide for themselves what factors are truly significant for them and what levels of performance they currently have or could hope to achieve.
This paper has hopefully reinforced the points: -
That process quality can become a very important cost factor.
Fully depreciated equipment is not always the bargain that it first appears to be.
Total Cost of Ownership is a complex subject that can mean different things to different people.

The author invites everyone to explore this subject further and hopefully validate some of the suggested significant factors.
This may be a subject worthy of some further collective work under the auspices of the IPC or some other such responsible body.
It may also be interesting to expand the analysis to cover the processes that surround SMT such as test and assembly.