MODELING AN SMT LINE TO IMPROVE THROUGHPUT

Gregory Vance
Rockwell Automation, Inc.
Mayfield Heights, OH, USA
gjvance@ra.rockwell.com

Todd Vick
Universal Instruments Corporation
Conklin, NY, USA
vickt@uic.com

ABSTRACT
One of the major challenges for an electronics assembly manufacturing engineer is determining how an SMT machine will impact throughput. Typically an SMT equipment supplier will ask for a few (5-10) products to simulate the throughput capability of their machine. Unfortunately, if the engineer works in a high-mix low-volume environment, he may need to know the impact of a new machine on 1,000 or more products. Currently there are no simulation tools to effectively model this. This is confirmed in the 2015 IPC International Technology Roadmap for Electronics Interconnections, which states "*In order to better deal with the demands for increased interconnection density and respond to market demands for better return on capital investment in assembly equipment, there is a need within the manufacturing industry for continued improvement in tools and software for modeling and simulation. Needs in this area include better methods of load balancing and improved machine utilization? The tools for determining the balance on assembly lines will need to be flexible to handle the mix of assembly types that manufacturers now face.*" [1]

Rockwell Automation partnered with Universal Instruments to develop a tool to model a large quantity of products and the impact of varying SMT line configurations. The information used for the modeling includes placements per panel and components placed per hour. With these tools, an electronics assembly plant can be analyzed to identify improvement opportunities and perform "what if" analysis to model impact of machine changes.

Key words: SMT, components per hour, CPH, utilization, high-mix, low-volume

GOALS FOR THE SMT LINE MODEL

1. Determine the right machine for the product mix.
2. Determine if products are running as fast as they should.
3. Determine if electronics assembly products are built on the optimal line configuration? This is crucial in plants with multiple line configurations.

DEVELOPMENT OF THE SMT MACHINE MODEL

Discovery that machine cycle times were poor

After sample product simulations were run by Universal Instruments, it was discovered that observed cycle times were 2-3 times longer than simulated cycle times. This led to focused effort to understand why.

A kaizen event was held to map out the process and observe product builds. Several items that impacted the product cycle time were uncovered. These items were:

1. Component library placement speed slowed down.
2. Imbalance between placement beams/heads due to not having enough nozzles to pick and place the required component packages for the products.
3. Bypassed nozzles and spindles.
4. Large quantity of placements from a single component input.
5. Panel transfer rate into and out of the machine slowed down.
6. Poor optimization and component split between machines on an SMT line.
7. Operator variation in responding to the process.

The most significant item impacting cycle time was not having the necessary quantity of nozzles available for the mix of component packages for the products that machine/line was building. To maximize flexibility to move products between lines, machines of the same type were equipped with a standard nozzle configuration. The nozzle configurations were changed only when a new component package was needed.

To address this problem, a regular nozzle review was implemented to ensure the machines have sufficient nozzles available to optimize the machine programs.

Products were reviewed for the above issues. As items were addressed, the observed cycle times were reduced to align with the simulated cycle times.

Realization that cycle time does not represent SMT machine utilization

Cycle time represents how a product is running compared to a benchmark, but does not reflect utilization of a machine based upon its throughput capability. For pick and place machines, throughout can be measured in components placed per hour (CPH).

$$CPH = \frac{Placements\ per\ Panel}{Panel\ Cycle\ Time\ (hr)}$$

Manufacturers provide CPH specifications for SMT machines in two ways. The first method is what is often called "Maximum CPH" [2] which represents the maximum speed the manufacturer was able to achieve and the second is based on "IPC 9850" [3] which has CPH categorized by package type. The "placements per panel" required to run these tests are shown in Table 1.

Table 1. Sample of range of placements per panel to run IPC and manufacturer tests.

Source	Test	Placements Per Panel
IPC 9850	QFP-100	36
IPC 9850	QFP-200	30
IPC 9850	BGA-228	36
IPC 9850	1608C (0603C)	400
IPC 9850	SOIC-16	80
Manufacturer	Maximum CPH	?

The "IPC 9850" performance tests are useful to compare equipment models and manufacturers to each other but they do not necessarily represent the products manufacturers are building. This complexity can be understood by comparing Table 1 to the sample product complexity of global product mix in Table 2.

Table 2. Sample range of placements per panel versus count of assemblies and forecasted panel volumes.

Range of Placements Per Panel	Count of PCBA Assemblies By Side	6 Month Panel Volume Forecast	Panel Volume %
0-299	1,250	682,380	44%
300-599	766	523,832	34%
600-899	401	178,584	11%
900-1199	212	96,884	6%
1,200-1,499	60	59,540	4%
1,500-1,799	21	10,593	1%
1,800-4,500	31	7,134	0.5%
Total	2,741	1,558,947	100%

The idea of using simple regression to develop a model of "placements per panel" to CPH began to develop. This relationship was first studied using production history.

Machine mathematical model for CPH

A report was available that contained panels built and total time to build a work order. This report was used to calculate the average CPH per panel for an SMT machine model. A scatter plot with a smoother line was used to view the relationship between the variables for a machine model. The smoother line is a line fitted to the data to explore the potential relationships between two variables, without fitting a specific model, such as a regression line.

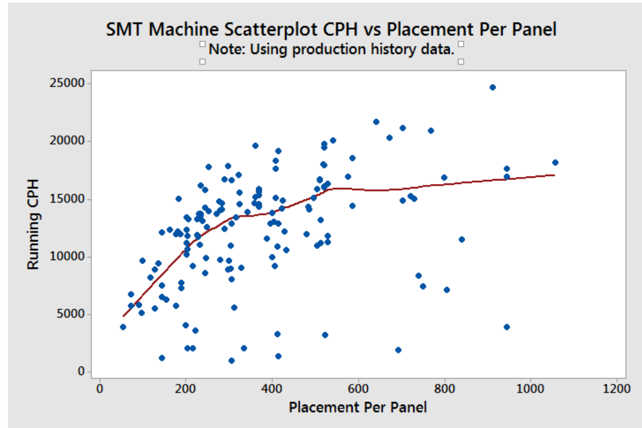

Figure 1. Scatter plot of CPH versus Placements per Panel from production data.

There is a relationship between "placements per panel" and CPH but there are points that do not follow the smoother curve. The other observation is that actual CPH values vary greatly compared to the specification value the manufacturer stated.

Since production data was used to model this relationship, all of the problem areas outlined earlier represent part of the performance and added noise in the model. Another idea was to use generic product simulation data from the manufacturer. The product simulation information included:

1. Quantity of placements per panel
2. Simulated cycle time for SMT machine
3. CPH (Calculated)

This would filter out the noise from production and machine configuration issues and could then be used to establish a realistic CPH equation.

With the simulated cycle time data, the relationship between "placements per panel" and CPH was then studied.

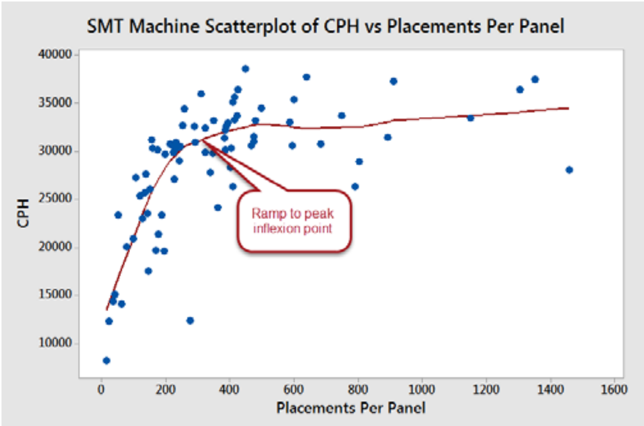

Figure 2. Scatter plot of CPH versus Placements per Panel from SMT Machine product simulations.

The scatter plot revealed a relationship between "placements per panel" and CPH. Using the Pearson Correlation Coefficient, the strength of the relationship is assessed. At 0.536 it is considered moderate and P-Value of 0.000 means the relationship is statistically significant. This indicates that "placements per panel" is a good predictor of CPH.

Using the scatter plot, the inflexion point where the red smoother curve flattens out is determined. The CPH values for "placement per panel" data points beyond this inflexion point are averaged and labeled the "Max CPH" for that model machine. For this SMT machine, the "Max CPH" is 32,311 and is achieved at 300 or more "placements per panel". The "Max CPH" is closer to the machine's IPC 9850 1608 4 board test of 37,000 CPH [2] with some simulations performing at the IPC 9850 1608 4 board test rate.

Simple regression was used to create a fitted line plot to generate an equation for the sloped part of the curve up to the "Max CPH" value. For this SMT machine, a quadratic equation provided the best fit.

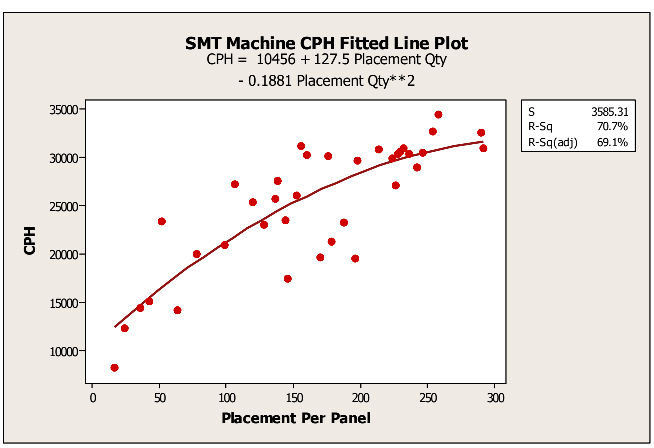

Figure 3. Fitted line plot of SMT Machine CPH predicted by Placements per Panel for less than 300 placements per panel

When performing regression analysis, the R-Square and residual plots need to be reviewed to determine how well the equation fits the raw data.

The R-Sq term shown in the fitted line plot represents how much of the variation the predictor (placements per panel) is accounted for by the CPH equation. The closer to 100%, the better. This model's R-Sq (adj) term is 69%. Since the model is intended to be used as a barometer of how well a product is running on a given SMT machine, this R-Sq term is acceptable.

The difference between the data points and fitted line are called residuals. Residuals represent the error or amount of variation not explained by the regression equation. There are four items to check to confirm that there are no unusual data points in the model. These are:

1. Normal Plot – Residuals form a straight line.
2. Histogram – Residuals appear to form a normal curve.
3. Versus Fits - Residuals are contained in a straight band, with no obvious pattern in the graph.
4. Versus Order – Residuals appears to be in statistical control.

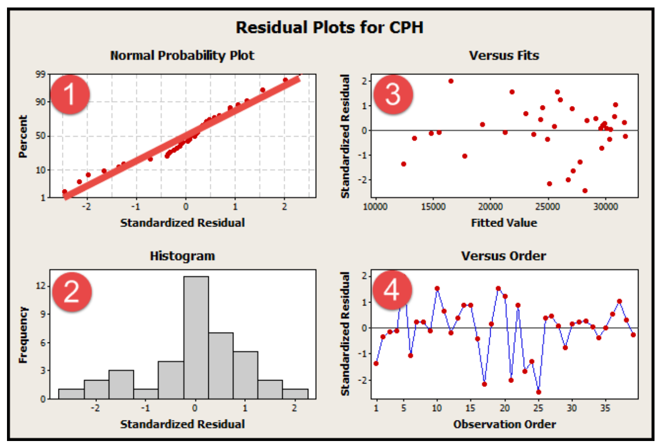

Figure 4. SMT Machine CPH Residual Analysis

This process of reviewing the "placements per panel" versus CPH, identifying the "Max CPH" and modeling the ramp to "Max CPH" with a regression equation (linear, quadratic or cubic) was completed for all other SMT machine models Rockwell Automation uses.

FINAL LINE MODEL

The line model consists of three sections:

1. Plant product inputs.
2. Product CPH & cycle time computations.
3. Product impact analysis.

Plant product inputs are:

1. Product number.
2. SMT line name. (Important if there are multiple line configurations in a plant.)
3. Process side of the product – Top or Bottom

4. Forecasted product panel volume (PPV), 4 to 6 months forecast is recommended to capture low volume products. The product panel forecast is totaled to determine the Total Panel Volume forecasted for the plant (TPV).
5. Placements per panel from each SMT machine on the line.
    a. For better resolution for future "what if" analysis, it is recommended to define placements per panel from each machine by feeder width (4 mm, 8 mm, 12 mm, etc.)
    b. Total placements per panel can be calculated.
6. Product Observed Cycle Time (POCT) that represents the observed cycle time constraint for that product on an assembly line.

Plant Product Inputs							
Product	Line	Side	Panel Forecast (PPV)	SMT 1 Placements	SMT 2 Placements	Total Panel Placements	Observed Cycle Time (POCT)
P841	1	Top	6,800	102	44	146	35
P1134	1	Bottom	9,000	428	342	770	76
P1146	1	Bottom	6,800	214	128	342	34
P862	1	Bottom	1,300	68	76	144	50
P1124	1	Bottom	6,931	682	282	964	97
P1151	1	Bottom	8,500	336	144	480	42
P797	1	Top	56	35	70	105	36
P798	1	Top	80	105	0	105	32
P1152	1	Top	4,358	342	66	408	66
P1142	1	Bottom	900	778	228	1,006	89
P1129	1	Top	1,067	1,632	264	1,896	166
P783	1	Bottom	24	324	6	330	53
P1148	1	Top	48	1,394	598	1,992	115
P1140	1	Bottom	640	540	238	778	69
P1126	1	Bottom	559	1,200	384	1,584	205

Figure 5. Line Model Inputs

CPH & Cycle Time Computations:
1. Regression equations and "Max CPH" for each SMT machine type on the line.
    a. With the actual placements per panel the product CPH (PCPH) and cycle time (PCT) for the product is calculated. These are considered to be the potential of the product being produced on that line when the line running.
    b. The sum of the machines "Max CPH" on a line represents the Line CPH.
2. Typical panel transfer time into the work nest of the SMT machine. Typical between 2 – 6 seconds.
3. Typical stencil printer and oven panel to panel takt time.

			CPH & Cycle Time Computations							
			SMT Machine 1			SMT Machine 2			Typ. Panel Transfer	Typ. SP/Oven Panel to Panel
			Max CPH			Max CPH				
			32,311			13,976			Time (sec)	CT (sec)
									4	30
Product	Line	Side	Comp	CPH (PCPH1)	Cycle Time (PCT1)	Comp	CPH (PCPH2)	Cycle Time (PCT2)	Constraint Cycle Time (LCCT)	Is Stencil Printer/Oven Constraint?
P841	1	Top	102	21,504	17	44	7,496	21	30	Yes
P1134	1	Bottom	428	32,311	48	342	13,976	88	92	No
P1146	1	Bottom	214	29,127	26	128	11,238	41	45	No
P862	1	Bottom	68	18,256	13	76	8,922	31	35	No
P1124	1	Bottom	682	32,311	76	282	13,976	73	80	No
P1151	1	Bottom	336	32,311	37	144	11,951	43	47	No
P797	1	Top	35	14,688	9	70	8,655	29	33	No
P798	1	Top	84	19,839	15	21	6,472	12	30	Yes
P1152	1	Top	342	32,311	38	66	8,476	28	42	No
P1142	1	Bottom	778	32,311	87	228	13,976	59	91	No
P1129	1	Top	1,632	32,311	182	264	13,976	68	186	No
P783	1	Bottom	324	32,311	36	6	5,804	4	40	No
P1148	1	Top	1,394	32,311	155	598	13,976	154	159	No
P1140	1	Bottom	540	32,311	60	238	13,976	61	65	No
P1126	1	Bottom	1,200	32,311	134	384	13,976	99	138	No

Figure 6. Line Model Computations

Product impact analysis (outputs):
1. Line Constraint Cycle Time (LCCT) is the constraint machine cycle time. If the constraint machine on the line is a placement machine the typical panel transfer time is added as the machine is not producing product when the panel is transferring. (Many SMT machines have the option to pre-pick components to reduce the impact of panel transfer time. The Line Model is configured assuming this feature is not enabled.)

2. Net CPH Loss by SMT Machine (NCLM) when running that product. This represents the CPH potential lost when running a product based upon the amount of time that machine is not picking and placing components due to another constraint on the line and panel transfer time.

$$NCLM = (PCT - LCCT) * PCPH - (MaxCPH - PCPH)$$

NCLM = Net CPH Loss per Machine
PCT = Product Cycle Time for a machine
LCCT = Line Constraint Cycle Time
MaxCPH = Max CPH of that machine
PCPH = Product CPH for that machine

3. Product Running Line CPH (PRLCPH). This represents the CPH potential of that product on that SMT line configuration when the line is running.

$$PRLCPH = LineCPH + \sum NCLM$$

PRLCPH = Product Running Line CPH
LineCPH = Line CPH
NCLM = Net CPH Loss per Machine

4. Percentage of Line CPH Capability (%LCC). This represents the percentage of Line CPH capacity a product utilizes on that line configuration.

$$\%LCC = \frac{PRLCPH}{LineCPH}$$

%LCC = Line CPH Capability Percentage
PRLCPH = Product Running Line CPH
LineCPH = Line CPH

5. Panel Volume Percentage (PV%). This is percentage of panel volume that product represents relative to the Total Panel Volume (TPV) in that plant.

$$PV\% = PPV/TPV$$

PV% = Panel Volume Percentage
PPV = Product Panel Volume
TPV = Total Panel Volume

6. CPH Category (CPHC). This is a weight assigned to a product based upon the %LCC that it utilizes when running.

    a. If %LCC < 25% CPHC = 10
    b. If 25% < %LCC < 50% CPHC = 7
    c. If 50% < %LCC < 75% CPHC = 3
    d. If %LCC > 75% CPHC = 1

    %LCC = Line CPH Capability Percentage
    CPHC = CPH Category

7. Volume Category (VC). This is a weight assigned to a product based upon the percentage of panel volume that it represents. The Total Panel Volume (TPV) is split into three segments, product panel volumes that represent the top 40%, middle 40% and bottom 20% of the total panel volume for that plant.

    a. Top 40% VC = 10
    b. Middle 40% VC = 4
    c. Bottom 20% VC = 1

    VC = Volume Category

8. (CPHC x VC) product. A product weight ranging from 1 to 100 that represents the volume and CPH utilization to rank the products on that line. This is a prioritization factor, larger the number the more potential impact relative to improving CPH utilization based on line configuration and its panel volume.

9. Product Cycle Time Ratio (PCTR). A ratio of the observed cycle time (POCT) to the calculated line constraint cycle time (LCCT) for a product. A PCTR greater than 1.0 represents a product running slower than its calculated potential. Ideally this value would fall between 0.8 and 1.2 which represents the typical error in the model.

$$PCTR = POCT/LCCT$$

PCTR = Product Cycle Time Ratio
POCT = Product Observed Cycle Time
LCCT = Line Constraint Cycle Time

			Product Impact Analysis								
						Line CPH 46,287	Total Panels (TPV) 220,233	10 = Low CPH	10 = High Volume		
Product	Line	Side	Net M1 CPH Loss (NCLM1)	Net M2 CPH Loss (NCLM2)	Product Running Line CPH (PRLCPH)	% of LineCPH Capability (%LCC)	Panel Volume % (PV%)	CPH Category (CPHC)	Volume Category (VC)	Product (CPHC x PV)	ObsCT/ ConstraintCT (PCTR)
P841	1	Top	-20,071	-8,696	17,520	38%	3.09%	7	10	70	1.2
P1134	1	Bottom	-15,580	-607	30,100	65%	4.09%	3	10	30	0.8
P1146	1	Bottom	-15,192	-3,737	27,358	59%	3.09%	3	10	30	0.8
P862	1	Bottom	-25,249	-6,084	14,954	32%	0.59%	7	4	28	1.4
P1124	1	Bottom	-1,616	-1,284	43,387	94%	3.15%	1	10	10	1.2
P1151	1	Bottom	-6,780	-3,034	36,473	79%	3.86%	1	10	10	0.9
P797	1	Top	-28,506	-6,367	11,414	25%	0.03%	10	1	10	1.1
P798	1	Top	-22,231	-11,456	12,600	27%	0.04%	7	1	7	1.1
P1152	1	Top	-3,070	-8,333	34,884	75%	1.98%	1	4	4	1.6
P1142	1	Bottom	-1,425	-4,925	39,937	86%	0.41%	1	4	4	1.0
P1129	1	Top	-695	-8,862	36,730	79%	0.48%	1	4	4	0.9
P783	1	Bottom	-3,223	-13,437	29,627	64%	0.01%	3	1	3	1.3
P1148	1	Top	-811	-463	45,013	97%	0.02%	1	1	1	0.7
P1140	1	Bottom	-2,543	-856	42,888	93%	0.29%	1	1	1	1.1
P1126	1	Bottom	-939	-3,937	41,412	89%	0.25%	1	1	1	1.5

Figure 7. Line Model Impact Analysis

RESULTS & CONCLUSIONS

1. The machine and line models can be used to quickly evaluate the throughput and CPH utilization for an entire line in order to select the best machine. With additional tabulations, estimates can reflect the return on investment of replacing a machine. When replacing two SMT machines on an existing line, the Line Model estimated product run time would be reduced by 44 hours per month (32% reduction).

2. Using (CPHC x VC) and the Product Cycle Time Ratio (PCTR), an engineer can evaluate an entire Plant by line to identify products with greatest improvement opportunity. When used to evaluate a SMT line, eight products with a large Product Cycle Time Ratio (PCTR) where identified and optimized, saving 136 hours of product run time per month (30% reduction).

3. By evaluating the (CPHC x VC) and brainstorming alternative line configurations, an engineer can perform "what if" analysis to ensure a product is being built on the best line configuration to maximize capacity utilization and throughput.

Products "placements per panel" and "forecasted panel volume" are important factors to consider when choosing what capacity SMT machine to purchase.

With information equipment manufacturers have today, they can calculate the CPH equations for their equipment to share with customers to supplement the "IPC-9850" and "Manufacturer Maximum CPH" figures. Together the supplier and customer can understand the impact of different machines for all their products on an SMT line.

REFERENCES

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[3] IPC-9850, Surface Mount Placement Equipment Characterization, 2002, Form 9850-F1 Performance