21st Century PCB FAB Factory Design Which Eliminates Regional Cost Advantages

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Over fifteen years has passed since North America and Europe ceased being the center of worldwide PCB fabrication, and were supplanted by a Far East market with low cost labor, more relaxed environmental requirements, and strong government support. In just a few short years, the superior cost advantages of this new dynamic put volume PCB production in the West out of business, aside for the military and specialty technology applications contained in the few shops that continue to exist today.

Recently, however, the conditions which created the current equilibrium appear to be shifting again. In this new dynamic, automation, innovative green wastewater technologies, and next generation process equipment innovations have combined to make new factories capable of achieving rapid ROI for PCB fabrication almost anywhere. This paper means to illustrate this new dynamic, and provide case study examples from the new greenfield installation at the company captive facility in New Hampshire.

Automation

The number of equipment offerings in the PCB Fabrication automation business has increased by a factor of 10 in the past five years. At the 2015 HKPCA show, automation could be found on almost every piece of process equipment being shown. Automation of many serially interconnected processes, can also offer far greater labor efficiency gains than simple load/unload automation on an individual piece of equipment, especially when in-line QC/fault management, and automated production control are included in these fully engineered process segments. The fully automated line contains 38 integrated pieces of equipment in a single piece flow digital process.

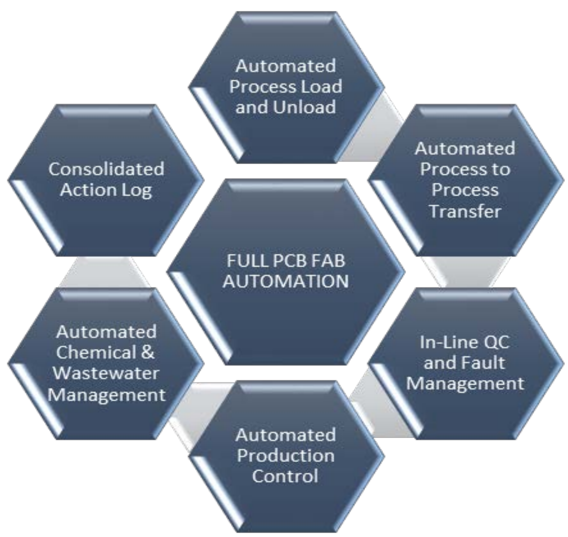


FIGURE 1 – Requirements for Full PCB Fab

Automation

TABLE 1 –COMPANY PROCESS FLOW (50 Panels/Hr OL & 18 Panels/Hr Multilayer)

PROCESS SEQUENCE		**LABOR REQUIREMENT**	
1	Loader		
2	Deburr		
3	In Line Load/Unload		
4	Conductive Polymer/Horizontal Cu Plate		
5	In Line Load/Unload		
6	Pre-clean		
7	30 Panel Smart Buffer (First In/Any Out)		
8	Inkjet Primary Image		
9	In Line Load/Unload		
10	30 Panel Smart Buffer (First In/Any Out)	**TECH #1**	
11	Tin Plate		
12	FIFO Buffer		
13	Resist Strip (Plate & Etch)		
14	90 Degree Turn		
15	Etch		
16	Resist Strip (Print & Etch)		
17	In Line Load/Unload		
18	Tin Strip		
19	In Line Load/Unload		
20	Oxide/Mask Pre-clean		**TECH #3 (Back-Up)**
21	In Line Load/Unload		
22	Oxide Post-Dip		
23	In Line Load/Unload		
24	Solder Mask Screen Coat		
25	Solder Mask Tack Oven		
26	In Line Load/Unload		
27	LDI with Robot		
28	In Line Load/Unload		
29	Legend Printers x 2 with Robot	**TECH #2**	
30	In Line Load/Unload		
31	Final Cure		
32	In Line Load/Unload		
33	90 Degree Turn		
34	HASL Pre-clean		
35	HASL		
36	HASL Post-clean		
37	90 Degree Turn		
38	Unload		

OFF-LINE PROCESSES		
I	Drill/Rout/Score	**TECH #4**
II	ET/Final Inspect/Shipping	**TECH #5**
III	Layup/Press/Plasma	**TECH #6**
IV	Maintenance	**TECH #7**

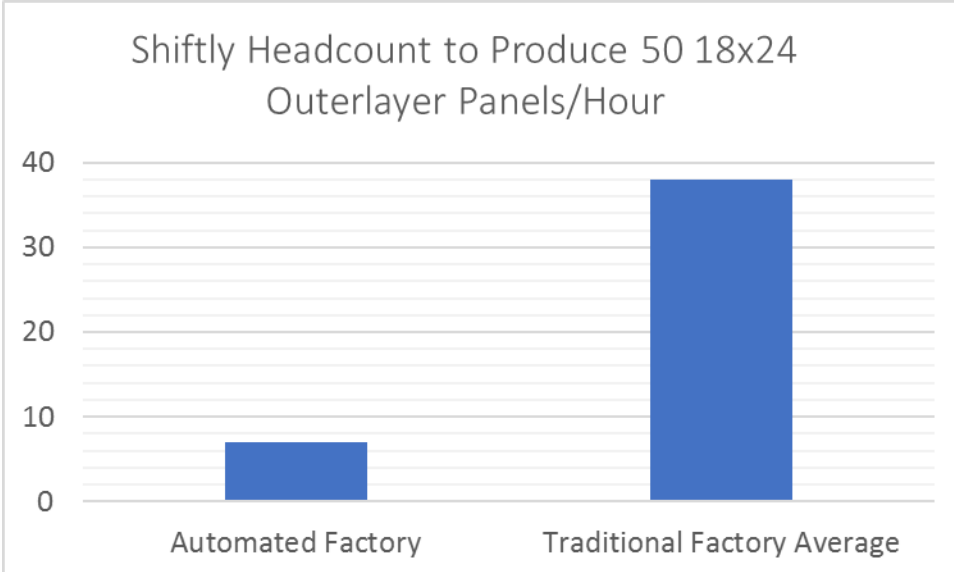


FIGURE 2

Process-to-process transfers are most economically accomplished when the process steps are laid out in a continuous in-line fashion, although autonomous transport systems can also be utilized where the luxury of an open floor plan does not exist. With an in-line configuration, the cost of automation equipment and associated floor space for said equipment can be reduced by 35%+ since there is no longer a need for separate loaders/unloaders. In-line QC inspection (AOI) and even ET can also be integrated using tools on the market today. At this facility, an in-line AOI scanner was incorporated directly into the primary image process, which proved to have few enough defect escapes to qualify as the only necessary solution for the entire circuit patterning process.

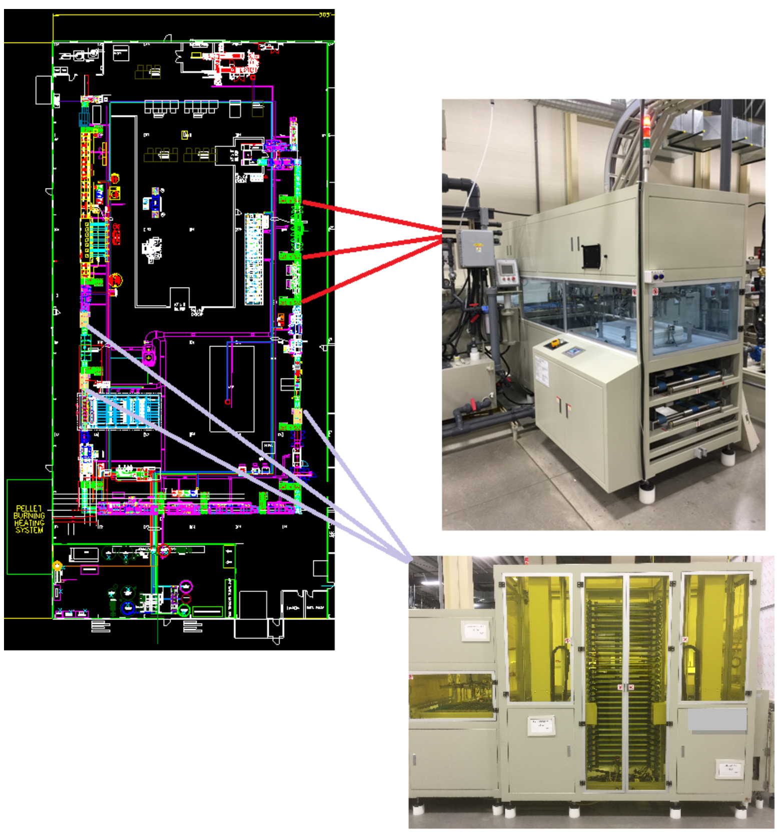


FIGURE 3 – In Line Loader/Unloader example for serial transfer between processes.

As cycle time decreases due to process efficiency gains, the cost of production control also decreases. The short cycle times of in-line processes limits production control to only two decisions, which can then be highly automated:

1) Deciding the priority order to feed jobs through, with no concern for in-process priority changes.
2) Determining if remakes are necessary based upon quality feedback/issue management.

Inclusion of dozens of cheap, redundant fiber optic sensors in the process line allows real time tracking of jobs as they progress. This information can be easily appended live to an SQL database. For the annual cost of two seats of a production cloud enabled database platform, a shop can purchase 12 annual seats of easy-to-use visual software from an online store for integrated cloud web applications that also integrates with the SQL backend, which can then be integrated with ERP, QMS, and Mediawiki systems. Self-training to integrate can be completed using an online education company for $30/month (it took the project manager 3 months of on-again/off- again training to complete this at the company site).

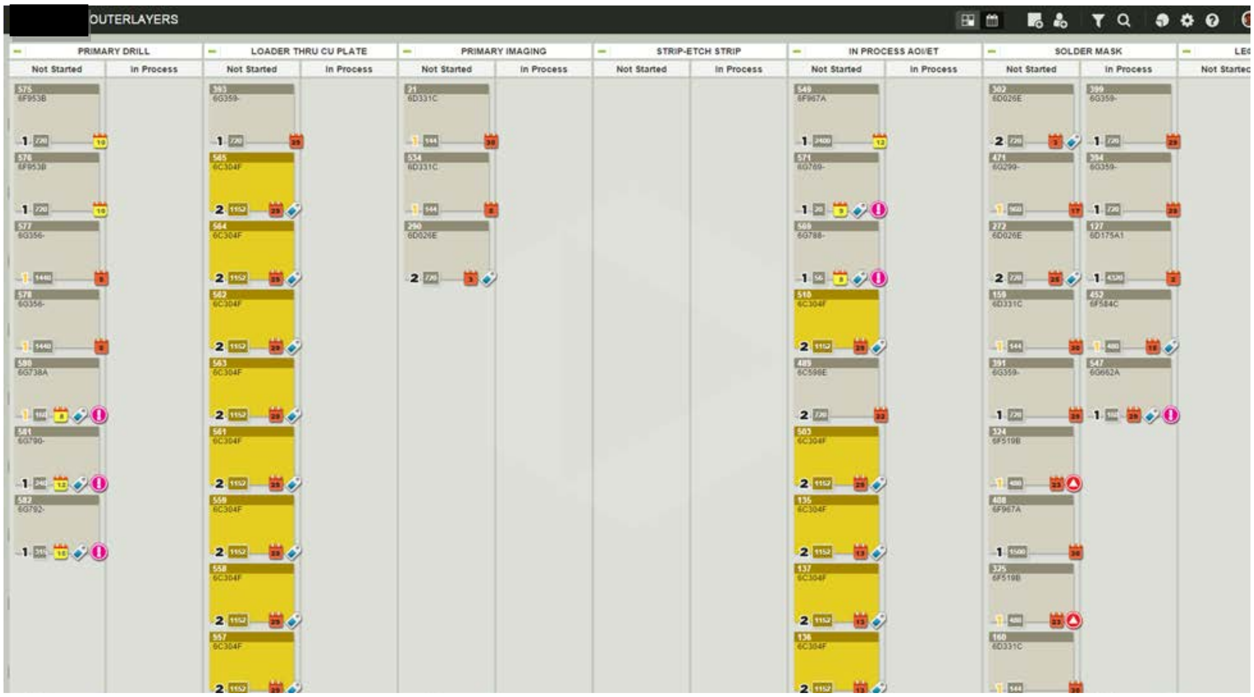
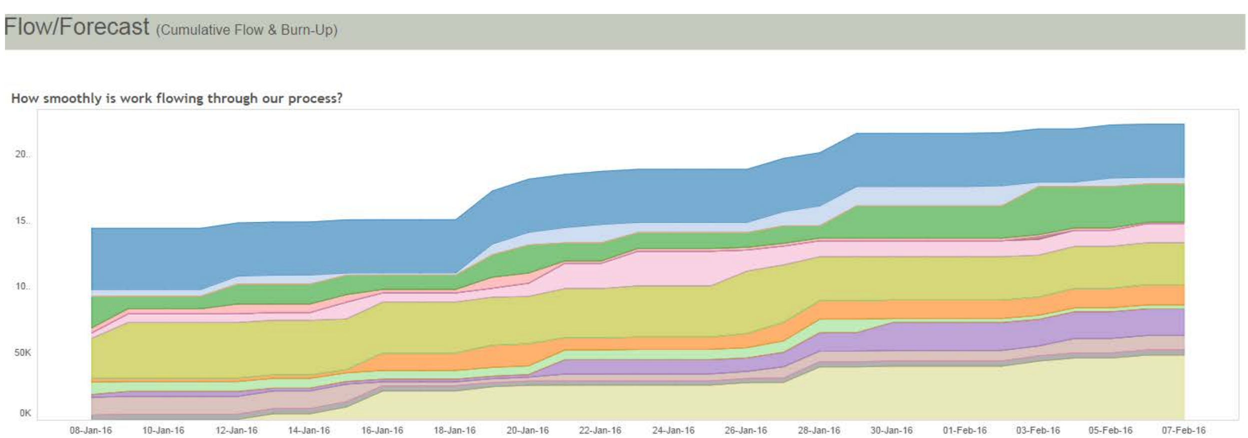
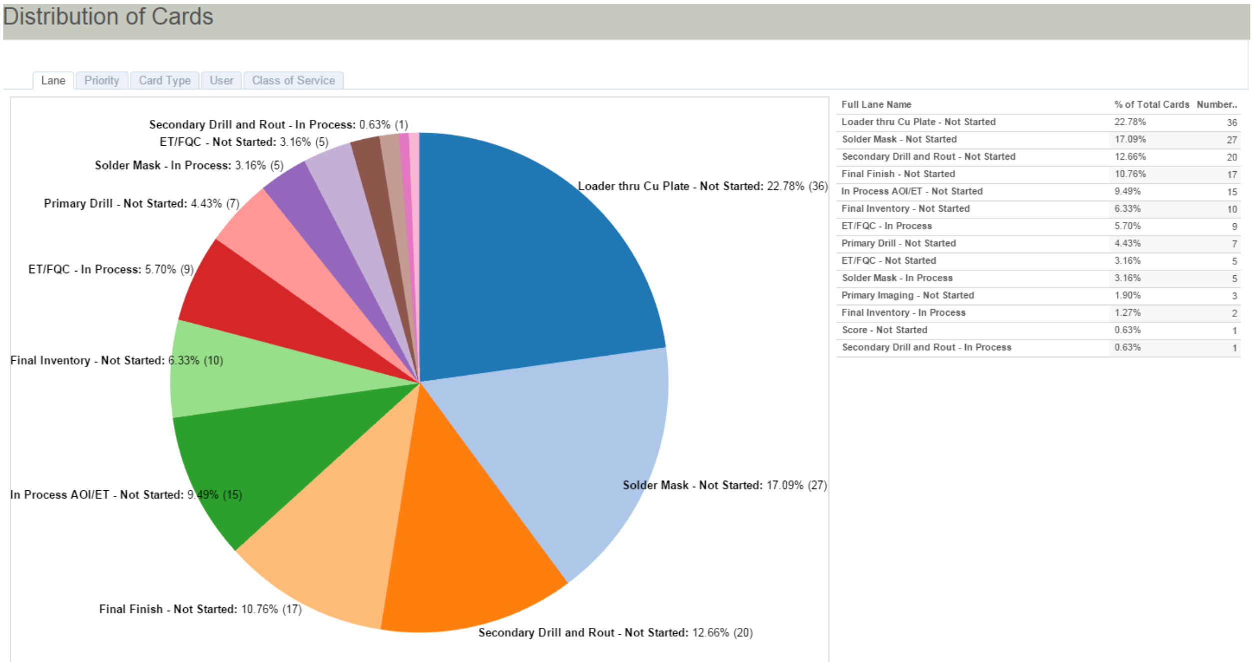


FIGURE 4 - Examples of visual job movement and analytics, (Courtesy: Google)[1]





Full Lane Name	% of Total Cards	Number..
Loader thru Cu Plate - Not Started	22.78%	36
Solder Mask - Not Started	17.09%	27
Secondary Drill and Rout - Not Started	12.66%	20
Final Finish - Not Started	10.76%	17
In Process AOI/ET - Not Started	9.49%	15
Final Inventory - Not Started	6.33%	10
ET/FQC - In Process	5.70%	9
Primary Drill - Not Started	4.43%	7
ET/FQC - Not Started	3.16%	5
Solder Mask - In Process	3.16%	5
Primary Imaging - Not Started	1.90%	3
Final Inventory - In Process	1.27%	2
Score - Not Started	0.63%	1
Secondary Drill and Rout - In Process	0.63%	1

Automation of chemical dosing, cleaning cycles, and wastewater management are quite inexpensive to execute and pay for themselves quickly by reduction in errors and provision for programmable alerts. By having daytanks sized to the packages being purchased, and integrated with continuous sensors, a live chemical inventory of the factory can be made available on a web page. It has been proven now that a factory using these techniques will typically need only 20 hours/week of lab analysis.

FIGURE 5 – Examples of automated chemical dosing systems.

Once all of the programming logic has been scripted for the factory automation, a consolidated live list of issues should then be developed for driving tactical corrective actions for escalated issues as well as continuous improvement of the systems. A modified version of the open source web-based general-purpose bugtracker and testing software tool [2] (also with a connected SQL backend) can be used to manage this. The software auto-escalates when issues are not closed in a timely fashion and is used to facilitate periodic management review. Software setup takes just a few days and is free.

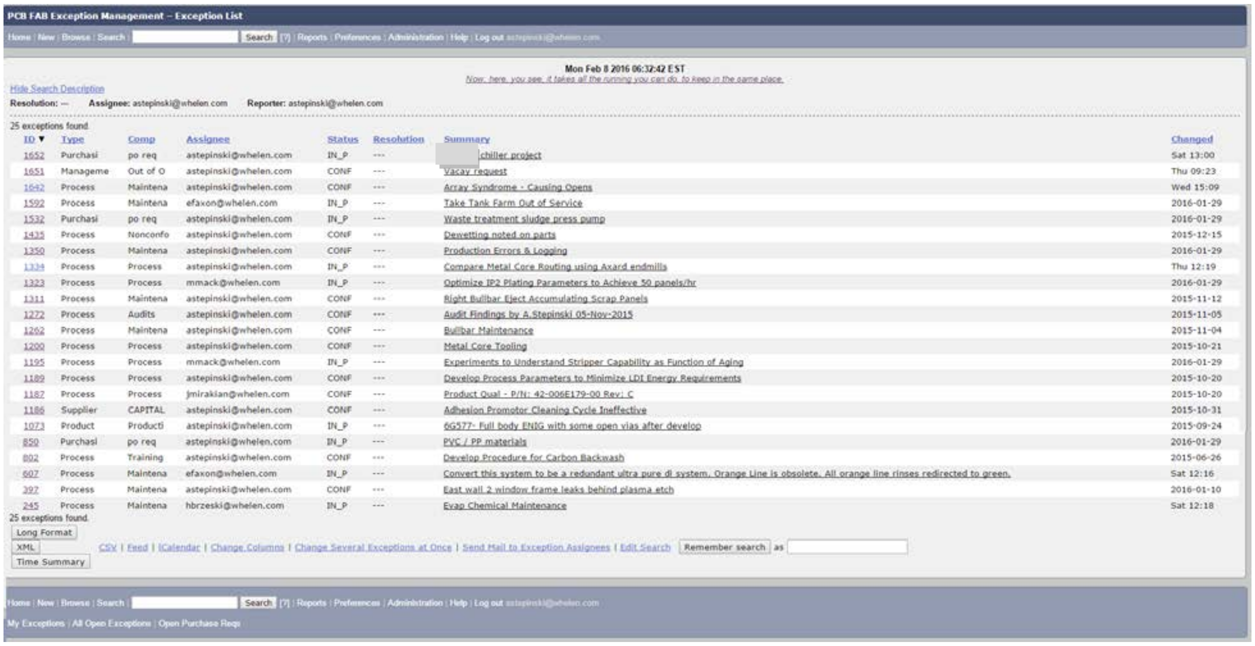


FIGURE 6 – Example of consolidated live web list of action items.

In general, the control afforded by a fully automated factory has enormous consequences for cost reduction. An in-line process flow allows for the removal of the cleaners, microetches, and antitarnish baths found in most PCB shops, since the need to compensate for handling/hold times with these chemistries is mitigated by handling and hold time reduction/elimination. This yields a direct savings in process chemical purchase cost as well as waste treatment. Additionally, chemical dosing and process set-points can be reduced due to the low process variability, so that there is near zero economic loss due to excessively biased mean target values which are required to compensate for highly variable processes in most PCB shops.

Green Process Technologies

The opportunities for designing out toxic chemicals and implementing chemical and water recycling are tremendous in the PCB industry, yet few factories realize these solutions. Most recycling systems max out at around 75% recycling due to increasing costs/diminishing returns. The reason for this upper limit is that the conventional technologies (membrane systems and ion exchange) also produce large quantities of brine either continuously or through regeneration, and this by-product can be quite expensive to treat.

TABLE 2 – Typical top PCB Fab high environmental impact waste streams

Typical Top PCB FAB High Impact Waste Streams	Example Countermeasure
Wastewater Effluent	Recycle Wastewater
Spent Etchant	Closed Loop Etch Recycling
F006 Sludge	Implement F006 Precursor Point Source Systems
Ammonia Gas	Closed Loop Etch Recycling
Solvent Emissions	Design out Toxic Solvents

The key to achieving an economical zero liquid discharge PCB Fab plant is to properly research each waste stream, adjust its attributes if necessary, and segregate streams to achieve the most efficient overall solution. Control of the waste stream at the point of generation is the key to achieving high efficiency. Additionally, chemical suppliers invariably sell chemicals that will become “spent” and need to be replaced by fresh chemicals. They in fact research how to make them optimally which then become spent . Without this, they cannot make money. With a little bit of research, making modified formulations that can last forever, or using the superior control of an automated factory to reduce consumption, can yield tremendous savings in regulatory and process costs.

WASTE WATER TREATMENT SYSTEM

NORMAL PRODUCTION										MAINTENANCE				
Process	Waste Stream from Normal Operations	pH Range	Destination	Working Volume (Liters)	Hourly Waste Volume (Liters)	Hours/Week Production	Weekly Volume	TDS (mg/L) as CaCO3	TDS (kg/week)	Waste Stream from Maintenance Operations	Waste Volume	pH Range	Destination	TDS (mg/L) as CaCO3
Deburr	Water	5-9	Green Line	360	300	50	15,000	130	1.95	Dump of Process Bath	360	5-9	Green Line	130
Horizontal Plater	Monopersulfate Cleaner	1-2	Blue Line	155	1.2	45	54	33,000	1.782	Dump of Process Bath	155	1-2	Blue Line	33,000
Horizontal Plater	Monopersulfate Cleaner Concentrate Rinse	1-4	Blue Line	103	0	45	0	2,000	0	Dump of Concentrate Rinse	103	1-4	Blue Line	2,000
Horizontal Plater	Monopersulfate Cleaner Cascade Rinse	4-7	Green Line	310	40	45	1,800	500	0.9	Dump of Cascade Rinse	310	4-7	Green Line	500
Horizontal Plater	Conditioner	8-10	Blue Line	207	0.2	45	9	42,000	0.378	Dump of Process Bath	207	8-10	Blue Line	42,000
Horizontal Plater	Conditioner Cleaner Concentrate Rinse	7-9	Blue Line	103	0	45	0	2,000	0	Dump of Concentrate Rinse	103	7-9	Blue Line	2,000
Horizontal Plater	Conditioner Cleaner Cascade Rinse	7-9	Green Line	310	40	45	1,800	500	0.9	Dump of Cascade Rinse	310	7-9	Green Line	500
Horizontal Plater	Adhesion Promotor Pre-Rinse	5-8	Green Line	103	0	45	0	2,000	0	Dump of Concentrate Rinse	103	5-8	Green Line	2,000
Horizontal Plater	Adhesion Promotor	5-8	Blue Line	415	0.3	45	14	112,000	1.512	Clean-Out with Peroxysulfuric Solution	415	1-2	Blue Line	139,000
Horizontal Plater	Adhesion Promotor Concentrate Rinse	5-8	Blue Line	103	0	45	0	2,000	0	Dump of Concentrate Rinse	103	5-8	Blue Line	2,000
Horizontal Plater	Adhesion Promotor Cascade Rinse	5-7	Green Line	310	40	45	1,800	500	0.9	Dump of Cascade Rinse	310	5-7	Green Line	500
Horizontal Plater	Conductive Polymer	1-2	Red Line	150	0.2	45	9	28,000	0.252	Dump of Process Bath	150	1-2	Red Line	28,000
Horizontal Plater	Conductive Polymer Concentrate Rinse	2-7	Red Line	103	0	45	0	2,000	0	Dump of Concentrate Rinse	103	2-7	Red Line	2,000
Horizontal Plater	Conductive Polymer Cascade Rinse	4-7	Green Line	310	40	45	1,800	500	0.9	Dump of Cascade Rinse	310	4-7	Green Line	500
Horizontal Plater	Sulfuric Acid Predip	0-2	Blue Line	103	0	45	0	150,000	0	Dump of Process Bath	103	0-2	Blue Line	150,000
Horizontal Plater	Copper Plate	0-2	Blue Line	5000	0	45	0	388,000	0	Dump of Process Bath	5000	0-2	Blue Line	388,000
Horizontal Plater	Copper Plate Concentrate Rinse	1-4	Blue Line	103	0	45	0	3,000	0	Dump of Concentrate Rinse	103	1-4	Blue Line	3,000
Horizontal Plater	Copper Plate Cascade Rinse	4-7	Green Line	310	40	45	1,800	500	0.9	Dump of Cascade Rinse	310	4-7	Green Line	500
Ink Preclean	Monopersulfate Cleaner	1-2	Blue Line	190	1	50	50	33,000	1.65	Dump of Process Bath	190	1-2	Blue Line	33,000
Ink Preclean	Monopersulfate Cleaner Concentrate Rinse	1-4	Blue Line	115	0	50	0	2,000	0	Dump of Concentrate Rinse	115	1-4	Blue Line	2,000
Ink Preclean	Monopersulfate Cleaner Cascade Rinse	4-7	Green Line	190	6	50	300	500	0.15	Dump of Cascade Rinse	190	4-7	Green Line	500
Tin Plate	Tin Plate Predip	0-2	Blue Line	965	0	45	0	150,000	0	Dump of Process Bath	965	0-2	Blue Line	0
Tin Plate	Tin Plate Tank 1	0-2	Blue Line	2840	0	45	0	392,000	0	Dump of Process Bath	2840	0-2	Blue Line	392,000
Tin Plate	Tin Plate Tank 2	0-2	Blue Line	2840	0	45	0	392,000	0	Dump of Process Bath	2840	0-2	Blue Line	392,000
Tin Plate	Tin Plate Drag-out Rinse	1-4	Blue Line	965	0	45	0	10,000	0	Dump of Concentrate Rinse	965	1-4	Blue Line	10,000
Tin Plate	Tin Plate Vertical Flowing Rinse	3-7	Green Line	965	480	45	0	800	0	Dump of Flowing Rinse	965	3-7	Green Line	800
Tin Plate	Tin Plate Horizontal Spray Rinse	2-7	Green Line	0	480	45	0	500	0	-				
Tin Plate	Tin Plate Rack Strip	0-1	Blue Line	245	0	45	0	431,000	0	Dump of Process Bath	245	0-1	Drum up for pH Adjust	0
Resist Strip I	Resist Stripper I	10-11	Red Line	570	12	45	42	214,000	8.988	Dump of Process Bath	570	10-11	Red Line	0
Resist Strip I	Resist Stripper I Polish	10-11	Red Line	190	0	45	0	187,000	0	Dump of Process Bath	190	10-11	Red Line	0
Resist Strip I	Resist Stripper I Concentrate Rinse	7-11	Red Line	114	0	45	0	5,000	0	Dump of Concentrate Rinse	114	7-11	Red Line	5,000
Resist Strip I	Resist Stripper I Cascade Rinse	7-10	Orange Line	341	480	45	21,600	150	3.24	Dump of Cascade Rinse	341	7-10	Orange Line	150
Etch	Etcher	8-9	Oxidize+Electrowin	3200	0	50	0	185,000	0	-				
Etch	Triple Cascade Rinse	7-8	Electrodialysis	341	0	50	0	500	0	-				
Resist Strip II	Resist Stripper II	10-11	Red Line	570	12	5	5	214,000	1.07	Dump of Process Bath	570	10-11	Red Line	0
Resist Strip II	Resist Stripper II Polish	10-11	Red Line	190	0	5	0	187,000	0	Dump of Process Bath	190	10-11	Red Line	0

FIGURE 7 – Example waste stream characteristic catalogue.

For under $1M in capital expenditure, a zero discharge treatment system can be implemented from a combination of ion exchange, membranes, distillation, crystallization, and etch recycling that is capable of supporting a 10,000 panel per week outer layer operation. This represents a capital cost savings when compared to the current “industry best practice” solutions.

FIGURE 8 – Example of zero liquid discharge system.

TABLE 3 - Zero Liquid Discharge Chemical Waste Management Costs versus Industry “Best Practice”

Zero Liquid Discharge w/ Etch Recycling		Equivalent Standard 75% Recycling System
Water	$8	$3,099
Power	$798	$714
Propane	$2,092	$0
Waste Treat Chemicals	$511	$1,354
Maintenance	$812	$680
Sludge Hauling	$1,521	$462
Permit Cost & Regulatory Analysis	$0	$2,200
Labor	$3,200	$9,600
Copper Recovery	-$6,758	$6,100
Monthly Total	**$2,184**	**$24,209**

Annualized Savings from Green Solution versus "Industry Best Practice"	**$264,305**

Action	Impact
Convert all first rinses to static drag-outs & increase flow rate of cascade rinses to compensate for less cascade	Decreased IX Regenerations by 70%, while increasing concentrate waste dumps by 25%. Net reduction in total concentrate waste volume of 30%.
Develop a losed Loop Cu Recycling System	Eliminated chemical costs for etching and yielded a positive cash flow from recovered 99.99% pure copper. Also, stabilized etch rate to +/-2%, eliminated venting of ammonia to scrubber, and recovered etch rinse dragout back to etcher.
Eliminate cleaners, microetches, predips, anti-tarnishes	Decreased wastewater system and chemical costs.
Increase temperature of process baths if possible, and replenish evaporative loss from dragouts.	Decreased Concentrate waste volume by 25%.
Develop a closed loop resist strip process	>$20,000 in annual savings from chemical usage and treatment
Develop a closed loop F006 precursor rinse recovery process	Reduced F006 hazardous waste by 95%
Conductive Polymer Metallization	Eliminated formaldehyde from electroless copper
Utilize inkjet for primary image	Eliminated preclean, developer, tin plate cleaner/microetch/predip, and strip chemicals.
Horizontal copper pulse plating w/ insoluble anodes	Huge waste reduction and improved thickness tolerancing. Control of roughness allowed elimination of microetching for adhesion as well.
Zero liquid discharge waste treatment	Eliminated permit, saved water.
Rotary oxygen plasma etch	Eliminated need for chemical desmear with solvents and/or plasma with toxic gases.

FIGURE 9- Key Company “Green” Decisions

It should also be noted that in a well-engineered zero liquid discharge environment, water conservation is unnecessary. Instead, the focus is TDS (total dissolved solids) budgeting throughout the plant, along with analysis of specific critical contaminants. Water supply is only limited by the size of the pumps. For instance, in order to maximize absorption in the fume scrubber, 10 gallons/minute of DI water can be fed continuously into and out of the scrubber system reservoir. Additionally, rinses can be operated at 3-5 gallons/minute whether they need it or not. With a closed loop system, there is no sacrificing of rinse quality to save water. Lift stations integrated with conductivity sensors can automatically identify an out-of-control waste stream as it happens, allowing for quick corrections by maintenance. Also, fresh rinse-water conductivity is always DI quality.

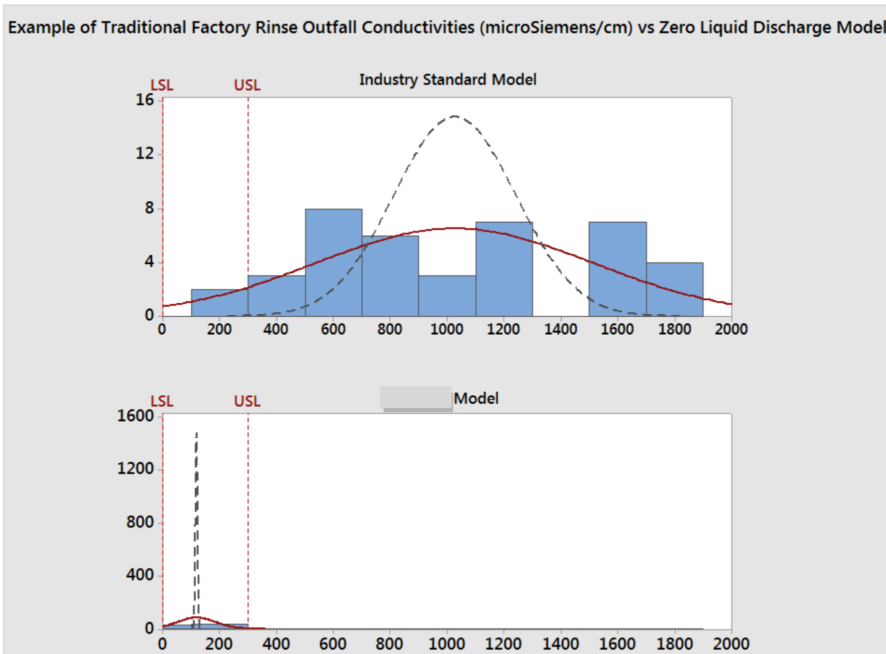


FIGURE 10- Comparison of spent rinse-water conductivity.

New Equipment Technology

In the past decade great developments have occurred in horizontal plating technologies along with direct imaging, inkjet, and CNC equipment. Only some of these have been realized in North American and European factories.

Horizontal copper plating is an especially rare technology in the U.S. market. The current state-of-the-art horizontal plater is capable of conformal panel plating 30 microns (1.2 mils) of copper at 100% throwing power in just 18 minutes at 50 panels/hour for most designs--at a fraction of the cost and thickness variation of standard vertical plating. These platers can also fill blind vias, through-holes and even trenches for embedded transmission lines, realizing 1- and 2-mil feature resolution. Yet, there are only two of these units in the USA--and hundreds in Asia. At this captive facility, the total surface copper thickness variation achieved from this process is only 3%. Additionally, the ability to control the pulse profile (and hence surface roughness) on each individual insoluble anode segment has successfully eliminated the need for subtractive etching of the copper surface for resist adhesion.

FIGURE 11 - Horizontal conductive polymer metallization.

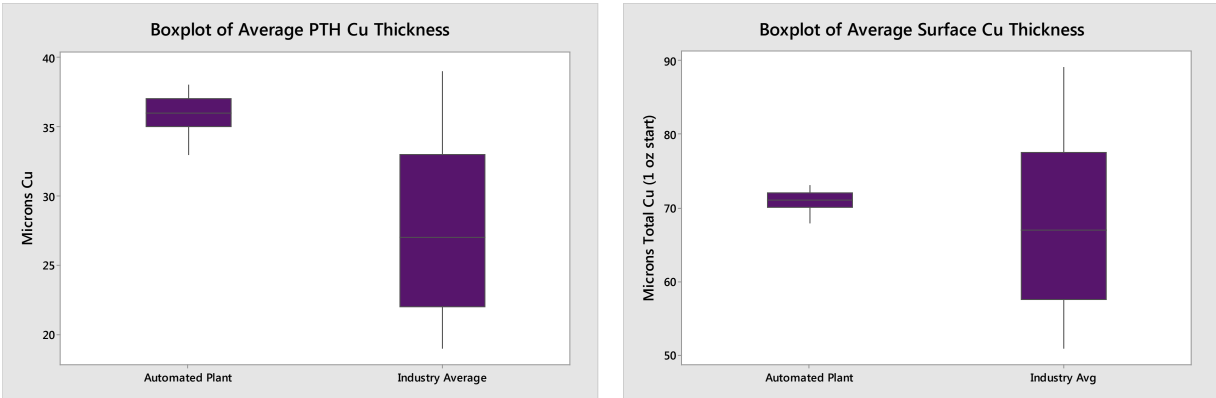


Figure 12 - Copper pulse plate and Cu thickness results.

Direct imaging has been on the market for quite some time now, and is used as a mass production tool. At the 2015 productronica show in Munich, new LDI and MDI solutions with lower operating costs than traditional UV laser systems could be found everywhere. Also emerging now are inkjet processes, with some even containing integrated AOI solutions.

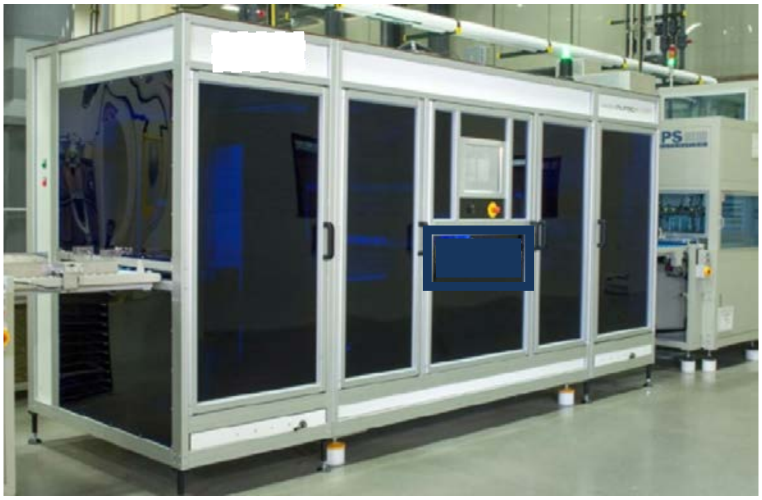


FIGURE 13 - Etch resist inkjet machine with integrated AOI.

Economical, new single station CNC systems with capability to drill/rout with the same spindles along with auto-load/unload and integrated cameras provide great flexibility and can facilitate substantial savings in a high mix environment.

FIGURE 14 – Multi-purpose drill/rout single-station systems with cameras and loaders/unloaders.

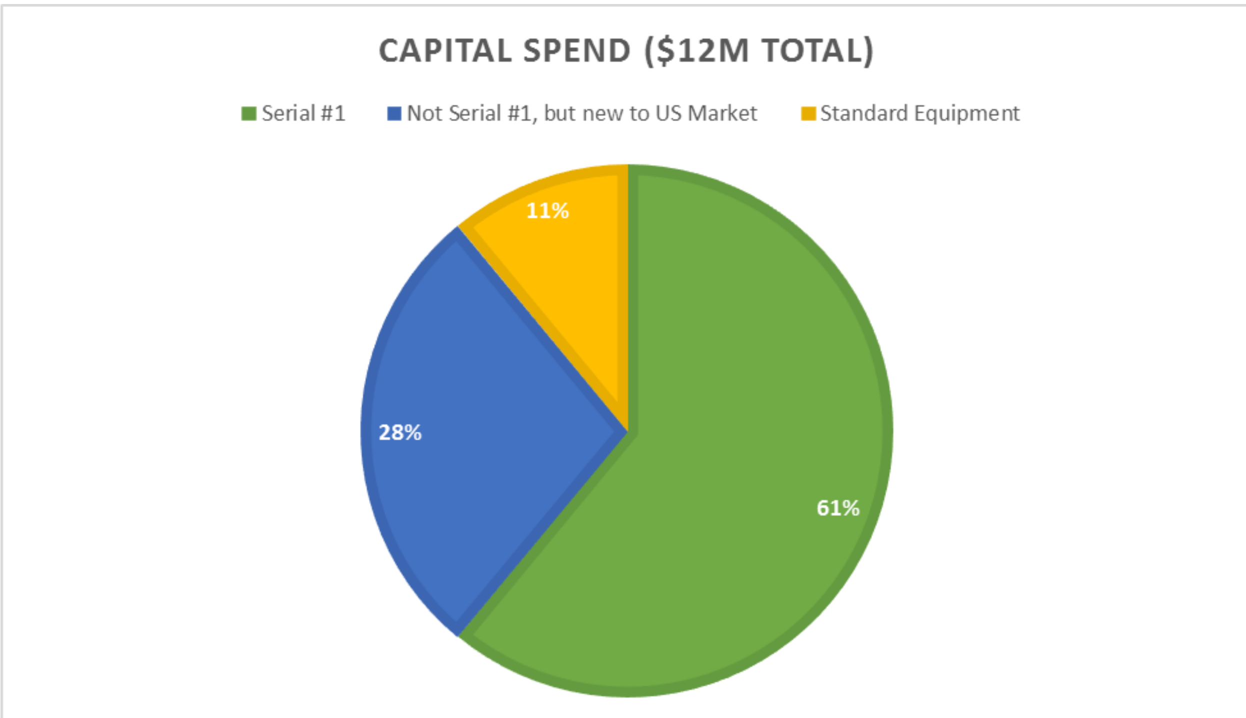


FIGURE 15–Company capital spend.

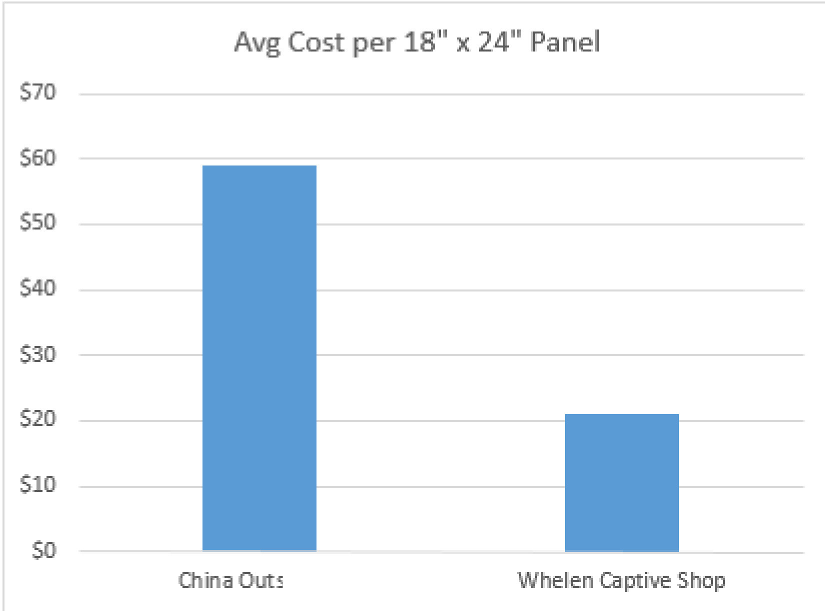


FIGURE 16 – Automated factory differentiating performance metrics.

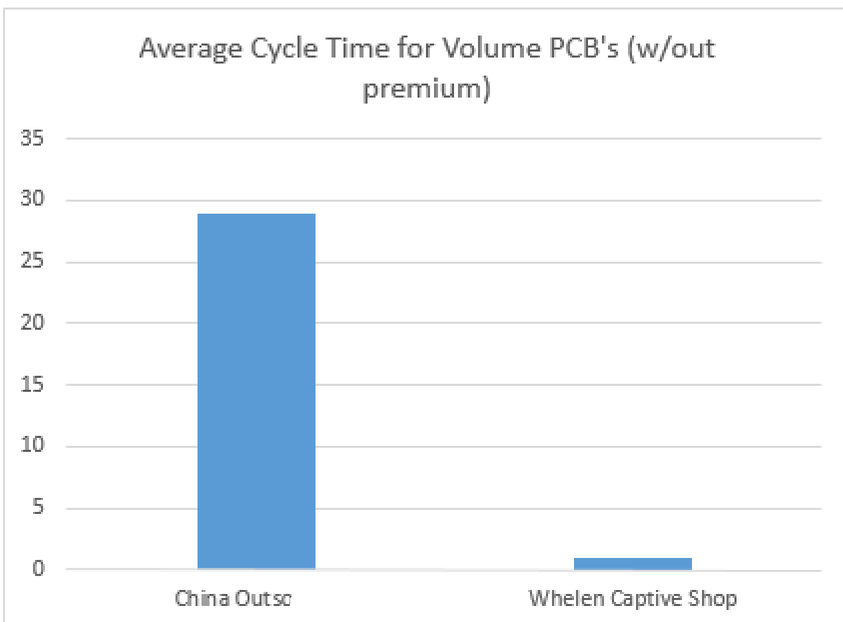


Figure 17: Average Cycle Time for Volume PCBs (without premium)

Conclusions and Summary:

The net effect of integrating all of the various automation, wastewater, and new equipment technologies presented can result in tremendous savings in PCB cost. With the factory in New Hampshire in North America only 35% utilized, a greater than 50% operating cost savings has been achieved over the previous Far East suppliers, and an ROI of three years has been achieved. A more fully utilized factory could achieve ROI even faster. The company had to assume substantial risk and invest 89% of the factory budget into new and emerging technologies in order to accomplish the PCB Fab project, however, future and existing factories in North America and Europe could now stand to benefit from this R&D effort.

References

1. Google Marketplace LEANKIT SOFTWARE with SQL Integration (usable via PC, Tablet, and Smartphone)
2. Bugzilla software.