LIGHTS OUT ELECTRONICS ASSEMBLY

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ABSTRACT

Lights out electronic assembly is the ability to run printed circuit board (PCB) assembly lines without operators for an extended period of time. The advantages include: increased productivity, reduced costs (labor and energy), improved quality, and increased customer satisfaction by delivering products on time. Current equipment does not support the Smart Factory concept. This paper describes the challenges in achieving lights out electronics assembly, discusses the use of different state of the art technologies to reach that goal, and proposes an electronics assembly line design that can run without operators.

Key words: Lights out electronics assembly, Smart Factory, Industry 4.0.

BACKGROUND

After two decades of talks about how lean manufacturing is going to save the world, we are now few years into two decades of Factory 4.0 and Smart Factory hype. Consultants and manufacturers of tape that is used to mark equipment location on the floor, benefitted the most from lean manufacturing. Who will benefit the most from Industry 4.0?

The labor cost has been the main reason for moving electronics manufacturing plants from high labor cost to low cost countries. Automation, including robotics, was never a primary reason for loss of electronics manufacturing jobs, as often promoted. That is about to change. Although loss of jobs is completely avoided in all Industry 4.0 panels and discussions, it will happen. Western, high cost countries, will promote total automation to be able to keep manufacturing plants at home and solve quality labor issues. The technological advancements cannot be stopped by not talking about them. Envisioning the future will prepare us for the future. New generations need to be trained to program robots, use artificial intelligence to solve problems, program mobile applications, and gain skills to work at the new high tech companies. There will be less and less well paid industrial jobs in electronics manufacturing.

This paper proposes the design of electronics assembly lines that could run without operators and controlled by just a small number of skilled workers from a Control Room.

Printed circuit board assembly (PCBA) is a complex process that involves operators, machines, materials and processes. Current software, information systems, and equipment are not designed to run a plant without operators. New solutions are necessary. The use of the following modern technologies is discussed in this paper and proposed to support lights out electronics assembly:

- ❖ Programmable logic controllers that support embedded applications and Internet of Things
- ❖ Artificial Intelligence
- ❖ New electronics assembly equipment designs
- ❖ M2M communication standards
- ❖ Robots and Automated Guided Vehicles
- ❖ Sensors
- ❖ RF Technology

We will not consider cloud computing as a viable technology for lights out electronics assembly. No serious manufacturing company will use cloud computing until its shortcomings are solved: security and cost. In words of an Industry 4.0 manager in a large automotive electronics company, "With cloud computing, we still have to have DB administrators and IT personnel, plus all security risks. No, we will not be using it anytime soon."

We will also not discuss 3D printing, often included as an emerging technology in Industry 4.0 discussions. While 3D printing will reduce cost and production downtime by providing cheaper and easily available parts and devices, its contribution to lights out electronics assembly is negligible.

A smart factory consists of smart subsystems of automation that communicate with other subsystems using a standard communication protocol. Intelligent subsystems must be able to perform their function unattended, while collecting all data needed to support business decisions. To achieve lights out electronics assembly, the following concepts must be integrated into a smart factory design:

- ❖ Intelligent and real-time production control
- ❖ Smart and reliable equipment
- ❖ Smart products
- ❖ Smart interfaces
- ❖ Mobile solutions

❖ Intelligent predictive equipment maintenance
❖ Manufacturing intelligence

In the following sections, the application of these technologies to electronics assembly is discussed. And finally, their integration in lights out electronics assembly lines is proposed.

INTELLIGENT PRODUCTION CONTROL

An interesting ongoing discussion in the Factory 4.0 community is about the future role of ERP and MES systems. Smart machines and smart products will make MES systems obsolete. On the other hand, ERP systems are actually a much bigger obstacle to the success of smart factories and the overall Industry 4.0 idea. Companies that sell ERP systems are able to sell a big database, outdated algorithms, and lousy interfaces for millions of dollars. ERP systems lure companies into believing they have everything in control just by implementing an ERP system. That is far from the truth.

Lights out electronics assembly plants will be based on real customer demand. They will build quality products at a fast production rate. There is no place in smart factories for forecasting and central, but often wrong, job progress tracking of today's ERP system. In addition, lights out electronics assembly plants will be able to produce batch sizes of 1 without production delays.

If we eliminate ERP and MES systems, how will some of the most important production decision be made, including: when to reorder components, to what line to send the next job, when to send AGVs to bring bare boards, when to switch programs on machines, when to send AGVs to bring material replenishment, etc?

The future is in smart assembly equipment and smart products interacting for real time production scheduling, or may we call it: assembly line self-scheduling. The smart lines will know how many products have been completed of the current work order and will request next job as well as advise what kind of products the line can do. Smart products will compete for assembly line time based on their priority (due date or urgent delivery need), material availability, and technological constraints. The assembly line self-scheduling process will be monitored using the production scheduling dashboards in the Control Room.

The traditional MES function, WIP tracking, will be performed by smart products. The products will carry information about process operations and WIP status. Machines will talk to each other to change program, change conveyor width, and other setup actions.

A central database will be used to store machine programs, released work orders data, inventory counts, and other plant wide data. Components will be reordered based on an actual demand and electronic KANBAN signals sent to the supplier. A supplier maintained inventory system will be used.

SMART EQUIPMENT

The current electronics assembly equipment is not designed for smart factories. However, there are already equipment manufacturers that are accepting the challenge and designing equipment that will support lights out electronics assembly. Some of them will be discussed in this paper in the following sections.

The concept of smart equipment goes further than just simple changing machine design. The autonomous and smart machines and assembly lines are independent intelligent subsystems of automation that can talk to other equipment and smart products to control production as well as to report and request their own maintenance needs. There are two stages in achieving smart equipment to support lights out electronics assembly:

❖ Attach a "machine brain" to an existing machine (short term)
❖ Embed a machine brain into new equipment designs (long term)

Figure 1 shows new Rockwell Automation's Compact Logix controller with embedded Windows 10 IoT that can be used to provide manufacturing intelligence to electronics assembly equipment.

Figure 1. Rockwell Automation's Compact Logix 5480 Controller with Embedded Windows 10 IoT

An intelligent machine controller, such as one show in Figure 1, will enable embedded applications that will perform the following tasks:

❖ Communicate with smart jobs
❖ Communicate with other smart machines
❖ Switch recipes based on smart product data, adjusting conveyor, and other setup actions
❖ Traceability data collection
❖ Collect performance data
❖ Send alerts
❖ Monitor vibration and temperature sensors and report limits being exceeded
❖ Make predictive maintenance decisions
❖ Track job progress

- Issue material replenishment requests
- Request next job
- Communicate with robots
- Prevent machine from running if necessary

Each machine will track job progress and communicate set up changeover requirements to the next machine in the line.

SMART PRODUCTS

Think about smart products as behaving similarly to persons in a store trying to pick the cashier that will process his purchases the fastest. The person cannot go to "Under 10 items" cashier if he purchased more than 10 items, so he has to pick from remaining cashiers.

Smart electronics products will schedule themselves in communication with smart machines. The following data must be stored on each product to make them smart:

- Product ID and Job ID
- Routing operations and routing history
- Program and setup requirements for each machine in the routing
- Component, process, and quality traceability data
- Defect data, if detected by a test machine

An obvious media to store this information on are RFID tags. Since, in some cases, tags cannot be placed on small printed circuit boards, RFID chips should be used.

Smart products will communicate to machines responsible for completing their operations and collecting traceability data at each operation. There is no need for routing enforcement and other MES checks since the process will be completely automated and an operation cannot be skipped or product cannot be processed in next operation if a defect was found in the previous operation. All smart products will go through "debriefing" in a shipping station where the data will be read and stored in the central database.

SMART INTERFACES

Equipment manufacturers and the electronics assembly community have failed to create a standard communication protocol that will support smart factory. Two efforts worth mentioning here are:

- IPC Factory Connectivity Standard
- Siemens/Mentor's Open Manufacturing Language

Both of these efforts are targeting a standard way of communicating with equipment from an MES system point of view. They assume there will be a central MES system that will collect job progress and traceability data using one of these standards. Since we disregard MES systems, none of these approaches is of interest.

An interesting development happened in April of 2017 when 17 equipment manufacturers met and decided to develop the Hermes Protocol for M2M communication. The Hermes Protocol is an open standard that uses XML and TCP/IP for M2M communication. We advocate smart machines and smart products talking to each other, and this effort is in the right direction. We are very skeptical this will actually bring results. The effort is again led by a strong equipment manufacturer (ASM/Siplace) and no other pick and place manufacturers are part of the initiative at this point. In addition, we have already heard from some of 17 participants that they are proceeding with development of their proprietary communication protocols to offer to other vendors a way of extracting data from their machine. It does not sound like they believe in this effort either, unfortunately. "Too many cooks spoil the broth" will most likely apply in this case and the effort is likely to fail.

For such an effort to succeed, the initiative must be led by a neutral trade organization, such as IPC, and the pressure must come from customers, not machine vendors. Until that is in place, we will not have a standard M2M communication protocol. For now, we will have to live with dealing with proprietary protocols for each machine.

MOBILE SOLUTIONS

There will be no PCs on the floor of a lights out electronics assembly plant. Even in traditional electronics assembly plants, customers are now asking for mobile solutions, without PCs. In a lights out electronics assembly plant, mobile solutions, used by support personnel and management, will include the following capabilities:

- Real time production dashboards
- Materials dashboards and alerts
- Sensor alerts dashboard
- Real time equipment performance monitoring
- Live OEE calculation for machine, line, and plant
- Equipment maintenance reports
- Historical production reports
- Quality Dashboards

Figure 2 illustrates real time production monitoring in a multi-line electronics assembly plant on a mobile device.

Figure 2. Real Time Production Monitoring

The progress of each job, cycle times, and estimated completion times are monitored in real time.

The Control Room must have complete and real time insight into production and equipment operation and the data from the floor is constantly streaming into the global database. Figure 3 illustrates how such a process is put in place for ASM/Siplace machines to provide big data collection and complete insight into machine operation on mobile devices. The control room is able to monitor machine performance, component consumption and scrap, current setup, and even lock machine if necessary.

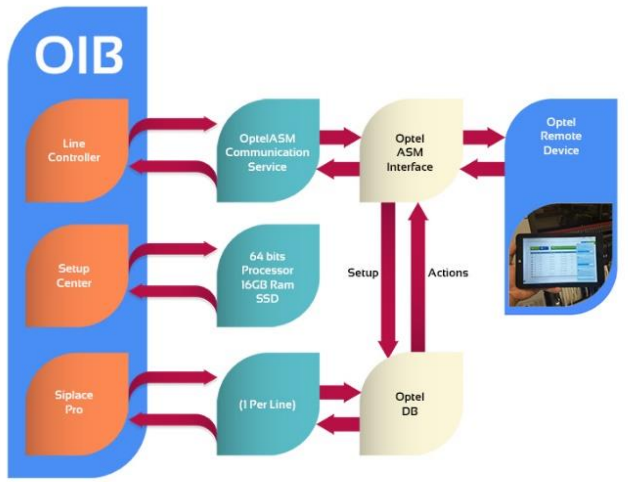

Figure 3. ASM/Siplace Mobile Machine Control

Mobile solutions allow the plant management to have instant access to manufacturing intelligence anytime from anywhere.

INTELLIGENT PREDICTIVE MAINTENANCE

Lights out electronics assembly can only work if we have reliable equipment using an effective predictive maintenance program where each machine is responsible for its own maintenance. Machine controllers will provide the following capabilities:

- ❖ Embedded Artificial Intelligence based programs that will monitor machine status and send alerts
- ❖ Wireless communication with sensors (vibration and temperature)
- ❖ Alarms

Predictive maintenance helps reduce machine downtime, increase mean time between failures (MTBF), and reduce maintenance costs. Maintenance decisions can be made based on the historical and real-time data from the machine itself. For example, wireless vibration and temperature sensors can detect signs of misaligned, loose or worn parts on a machine (Figure 4). The wireless sensors then transmit that information to the machine controller that makes data available immediately (via text or email alerts), and for long term analysis using artificial intelligence.

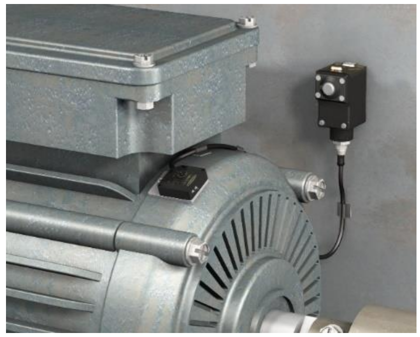

Figure 4. Banner Wireless Vibration Sensor

Artificial Intelligence has been around for 3-4 decades, but just recently becoming a very popular subject, often overhyped and misunderstood. Artificial Neural Networks (ANNs) have been widely used in engineering. In electronics assembly, neural networks have been already applied for prediction of fine pitch stencil printing quality [1] and solder join inspection [2]. The author used another artificial intelligence technique, genetic algorithms that mimic human evolutionary processes, to optimize electronics manufacturing processes. Those AI algorithms are in use today at some of the largest companies in the world.

A predictive maintenance system based on artificial neural networks and IoT will be able to predict when the equipment will fail, prescribe maintenance actions, as well as perform failure detection and diagnosis, at the part and machine level.

ANNs are particularly well suited in diagnostic systems where there are large sets of test data. That makes them a strong candidate to be used in intelligent systems for data-driven predictive maintenance of electronics assembly equipment.

By monitoring machine components in real-time, for increases in vibration and temperature, problems can be detected and resolved before they become too severe and cause unplanned downtime. The historical data creates a valuable machine performance log that can be used to make more informed predictive maintenance decisions.

Visibility into the operational status of machine components (both historically and in real-time) allows plant supervisors to remotely monitor and diagnose systems quickly as well as identify and resolve problems before the impact on machine availability and productivity compounds.
For example, tower lights with wireless communication allow supervisors in the Control Room to remotely monitor machine performance without lengthy and expensive cable runs. The lights indicate machine status visually while updates are also transmitted over a secure wireless network

to a remote device, triggering an action or prompting a response from a supervisor in the Control Room.

MANUFACTURING INTELLIGENCE

Big Data and Digitization are terms often used to explain Industry 4.0. In electronics assembly, big data and digitization include real time collection of all production data, material data, equipment performance, as well as component, process, and quality traceability data. Although distributed data collection and storage is advocated here, we still need a central database where the data relevant to real time production monitoring and reporting is collected and presented to personnel that supervises the lights out electronics assembly from the Control Room.

Manufacturing intelligence dashboards and reports in the Control Room include:

- Materials dashboards
- Status of each released work order
- Historical work order completion report
- Historical plant production report
- Live OEE calculation per machine, line, plant
- Quality dashboards

SMART FACTORY DESIGN PROPOSAL

In this section, we propose a lights out electronics assembly line that can assemble printed circuit boards without operators. We will also describe how specific equipment is suited for this goal and why they are included in this proposal.

The proposed electronics assembly line consists of the following processes and equipment:

- Material Supply Equipment
- Board Loader
- Laser Marking Machine
- Soldering Machine
- Solder Paste Inspection Machine
- Pick and Place Machines
- Reflow Oven
- AOI Test Machine
- Functional Test

Material Supply

One of the biggest problems in electronics assembly is the inability to prepare materials for the next job as well as deliver replenishment materials on time. Often, the line is down because operators are waiting for the next setup to arrive, or replenishment reels to be delivered. Those problems will be eliminated in lights out electronics assembly by implementing the following process:

- Machine controller sends signal for bare board, component, and other setup materials delivery for the next setup with enough time for AGVs to deliver them on time to the line.
- Electronics replenishment signals, IoT signals sent to AGVs, are sent based on accurate component consumed and scrap quantities collected in real time.

An AGV goes to the stockroom and picks up bare boards and delivers them to the line (Figure 5). The boards must be first labeled and then inserted into the board loader, an input buffer for the laser marking machine. After marking is completed, the boards moves to the paste printing machine.

Figure 5. Automated Material Delivery in an Automotive Electronics Manufacturing Plant

Paste Printing

Traditionally, paste printing is performed by screen printers that use stencils, created for specific PCB designs, to dispense leaded or lead free solder paste on the pads. Stencil changeover requires operators; a better solution is required for lights out soldering. Jet printing has emerged as an alternative to screen printing and the process can be automated since jet printers are completely software driven. Jet printers have been used mostly in NPI and prototype shops due to slow cycle time. Recently, the jet printing speed has increased dramatically. For example, Mycronic's MY500 had a speed of 27500 cph. Their most recent MY700 version has two jet heads, two conveyers and can achieve dispense speed of 98000 cph. This might soon result in wider acceptance of jet printing solutions in different segments of industry.

Jet printers also provide 2D inspection and automatic repair to dispense missing dots identified by the 2D inspection. It cannot however detect insufficient solder paste problems. In addition, 2D inspection adds to the operation cycle time and is prohibitive in medium to high volume productions.

Lights out soldering solution is as follows:

- An RFID reader reads incoming board data and triggers machine software to load the right program and set the conveyor width automatically.
- A robot is used to perform solder paste changeover from lead free to leaded, or tube replenishment when a sensor indicates the solder paste tube is empty.

- After a sensor is activated, the machine stops and sends message to the robot to perform a solder paste changeover task including what type of solder paste or glue to install.
- Machine will use the Hermes protocol to send a message to the robot, or a proprietary protocol if needed.
- Robot confirms and executes the task: opens the machine cover, removes old tube, picks up new correct tube and installs the tube inside machine.
- After the robot completes the changeover task, the robot sends "task completed" message (possible using the Hermes Protocol) to the machine.
- Machine verifies the empty tube solder sensor is off.
- Machine resumes production.
- Machine dispenses solder paste and performs 2D inspection. If a dot is missing, the board is automatically repaired.

One of the challenges in this area, again, is lack of a standard M2M protocol for communication between machines and robots and between robots. For our lights out electronics assembly design, we are here proposing an all in one jet printing machine: The "Jet Printer of the Future" will have several jet heads dispensing solder in a sequence. The head workload will be balanced to get best cycle time and will dramatically reduce cycle time. After dispensing solder by jet heads, 3D inspection is performed. If any problem is found, the program is modified automatically. The last stage of the machine is reserved for the "repair jet head" that will repair the board, if possible. If not possible, the board is removed from output conveyor by a robot.

Solder Paste Inspection

Solder paste inspection machines use 3D optical inspection to detect soldering problems that cannot be detected using 2D inspection on current jet printers. 3D solder paste inspection is necessary for lights out electronics assembly. Koh-Young is one of the solder paste inspection equipment vendors that is making a significant effort to support smart factories. The role of SPI in a lights out electronics assembly is as follows:

- SPI program and conveyor width are automatically changed over based on the PCB data scan, or based on message from the jet printer directly to the SPI machine. Both Mycronic and Koh-Young are members of the group of 17 machine vendors that agreed to implement the Hermes Protocol for M2M communication.
- If a soldering problem is detected, the Koh-Young SPI machine sends message to the Mycronic jet printer, which modifies the program to eliminate the problem.
- The defect PCB is rejected and stopped between the SPI and the first pick and place machine, and then picked up by a robot and placed into a rework bin.
- In case of multi circuit panels, the SPI machine sends a message to the pick and place machines instructing them not to place parts on the defect PCBs.

The machine status, production line yield, and real time defect information from all Koh Young SPI and AOI machines in multiple production lines are part of the manufacturing intelligence in the Control Room. Factory supervisors can track root causes of defect issues and apply changes to inspection programs in real time.

A self-corrective automatic soldering and solder inspection system is essential for lights out electronics assembly. The system must provide the following capabilities:

- Software driven soldering that supports processing a batch of 1 without production delays.
- Solder paste inspection machines that provides feedback to soldering machines and feedforward to pick and place machines.
- Ability to monitor the process remotely, modify soldering parameters and handle defect issues without stopping production.

SMT Pick and Place

Current Pick and place equipment is not designed to work without being attended by operators. Operators perform setup changeovers, material replenishment, and attend the machine in case of production stops due to machine malfunctions, feeder problems, or other reasons. The following enhancements are necessary to support lights out electronics assembly:

- Make machines intelligent as described in the previous section
- Modify machine design to eliminate the need for operators
- Provide mobile and remote machine control and performance monitoring

Robert Rowland identified component packaging and its associated feeders as the weak link in a placement machine [3]. Current tape feeders do not support operator-free production. Replenishment is either done by splicing or changing reels and currently an operator is required to set up the machine or perform material replenishment.

An obvious solution to eliminate the need for operators to perform replenishment is to eliminate replenishments. That can be done, in some cases, by using multiple feeders for the same part number. In that case, feeders will be set up off line in a separate area on feeder cart, and automated guided vehicles would be employed to bring feeder carts to the machine and insert them into the machine. The machine controller will use sensors and RFID readers to guild AGV to insert feeder carts in the correct location on the machine. That approach still requires operators in the off line area.

New and innovative solutions are needed. One such solutions is the new bulk feeder by ASM for their Siplace machines, as shown in Figure 6.

Figure 6. ASM BulkFeeder X

Components come in bulk, in special 32-mm blister pockets, with each holding up to 250,000 units (01005), for up to 1.5 million components per fill-up. Components are poured on a glass pick up plate by a vibration mechanism. A camera takes picture of components analyzed for position and alignment and then picked up and placed by the placement head.

The issues with ASM's bulk feeders is they can currently handle only 01005, 0201, and 0402 components, and they cannot do polarized components (i.e. caps and LEDs) and the inspection equipment (AOI) will fail for resistors that are upside down. Eventually, the bulk feeders must be replenished with new cartridges, so a robotic replenishment system must be implemented.

Soldering

Reflow ovens are often responsible for long setup times, especially when long cooling or heating times are required. A new Pyramax ZeroTurn dual chamber reflow oven by BTU solves that problem by eliminating process changeover time. This oven also allows advanced process control features. In addition to SECS-GEM, this oven provides a REST interface and MQTT message broker support. The oven recipe is automatically loaded using one of the following approaches:

- ❖ An RFID reader reads data from the incoming board and oven controller loads correct recipe, if not loaded already.
- ❖ Last pick-and-place machine in the line, or AOI machine, sends a message to the reflow oven to verify the setup is ready for the PCB exiting the pick-and-place machine. The oven controller then sets the conveyor width and loads the recipe.

The reflow oven process is monitored from the Control Room. The process traceability data is collected and assigned to each PCB serial number, such as recipe name, belt speed, zone temperatures, and static pressure. A mobile application controls each oven and ensures the oven is set up for the current job, or the board is prevented from entering the oven. Temperature and static pressure values are monitored in real time from the Control Room.

Testing

A pre-reflow test is used to identify placement errors, while a post-reflow test is used to identify placement and soldering defects. Missing components, misalignments and upside down components are some of the critical defects that can be identified by an AOI machine. A self-correcting process requires a closed-loop feedback from the AOI machine to the pick-and-place machine that is responsible for the defect.

For our lights out electronics assembly lines, we propose the following process:

- ❖ AOI machine performs the tests
- ❖ Defects found are analyzed by the machine controller that runs an embedded artificial neural networks application to classify defects as correct or false calls.
- ❖ In case of correct calls, a feedback is sent to the pick-and-place machine with a corrective action. The board is also removed from the line by a robot after a command is sent from the AOI controller.
- ❖ In case of false calls, the board is cleared to proceed to the next operation.

Automated Optical Inspection is an image processing classification problem and is suitable for the application of artificial neural networks [4]. As a matter of fact, Koh-Young opened an Artificial Intelligence center in San Diego in the summer of 2016. The idea is to apply artificial intelligence to develop smarter, faster, and cheaper AOI algorithms with better closed-loop feedback.

Functional testing is the final test and verification that the product works properly. The process can be completely automated and robots are used to move boards in and out of the functional test unit (Figure 7).

Figure 7. Robot Automated Functional Testing

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Control Room

The plant personnel is responsible for performing the top level production functions, including:

- ❖ Work order release based on customer demands/orders
- ❖ Production monitoring to meet productivity goals
- ❖ Monitoring machine performance and maintenance alerts and scheduling maintenance actions
- ❖ Monitoring quality dashboards and addressing excess defects, scrap, and downtimes
- ❖ Monitoring materials inventories and making sure components are ordered on time, i.e. reorder Kanban signals are working

The Control Room is set of dashboards, reports, and alerts monitored by skilled supervisors ready to address any problem that may appear in production.

CONCLUSION

Electronics assembly plants that can run without operators for an extended period of time will become the reality in the near future. The technology solutions are mostly already available. The most important missing parts are:

- ❖ Changes in equipment design to eliminate need for operators
- ❖ An M2M communication protocol that will be supported by all major equipment suppliers.

Modern technologies that will be used to achieve lights out electronics assembly were reviewed and a design of such assembly lines proposed. Social implications of running large manufacturing plants with a small group of supervisors and loss of jobs was out of scope of this paper, but will have to be addressed.

REFERENCES

[1] Ko, K.W. and H.S. Cho, "Solder joints inspection using a neural network and fuzzy rule-based classification method," IEEE Transactions on Electronics Packing Manufacturing, Vol. 23, No. 2, pp. 93-103, 2000.

[2] Barajas, L.G., M.B. Egerstedt, E.W. Kamen, and A. Goldstein, "Stencil Printing Process Modeling and Control Using Statistical Neural Networks," IEEE Transactions on Electronics Packaging Manufacturing, Vol. 31, No. 1, 2008.

[3] Roland, R. "Rapid Setup and Changeover." http://pcb.iconnect007.com.

[4] Lera, M. and A. Montisci, "Neural Networks Based AOI Systems for Electronic Device Diagnosis," Proceedings of SPIE, 2003.