Closed-Loop Process Control in the Solder Paste Printing Process

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Abstract
Over the last several years there has been a great deal of advancement in post-print inspection technology. The capability to inspect printed solder paste deposits immediately after the printing process and immediately before the component placement process has become more accurate, more repeatable and much faster. Post print solder paste inspection systems which are an integral feature of the printing machine itself or a standalone automated optical inspection (AOI) system are now able to provide much more reliable inspection capability at or near the speed of the product cycle times.

However, regardless of how sophisticated, no post print inspection system can actually correct the defects it detects. The existing post print inspection systems can certainly identify the defects and notify the operator or process engineer of a problem. The identified defect can be fixed before it becomes a more costly defect than if it were discovered later in the manufacturing process. A process engineer or technician must evaluate the solder paste printing performance data generated by the post print inspection and/or statistical process control (SPC) systems to determine the "root cause" of the defect and what action is required to actually eliminate or minimize the problem from reoccurring. No post print inspection system has ever eliminated any defect from reoccurring without a process engineer implementing permanent corrective action.

The concept of a closed-loop process control solder paste printing process involves a system that not only detects the defects but also has the intelligence to make adjustment to the process (primarily adjustments to the printing equipment's operating parameters) to prevent them from reoccurring. This paper will discuss various concepts of closed-loop process control involving the solder paste printing process. The discussion includes the current status of our research in this field, benefits, limitations, the technology required for implementation and future innovations.

Introduction
Closed-loop process controls have permeated SMT manufacturing processes, as board assembly manufacturers are demanding better yields for their assembly lines. Presently, these process controllers are primarily seen in component placement and reflow soldering. One area where process control can be implemented with significant impact to board assembly manufacturers is the stencil printing process. Printed circuit board assembly manufacturers are always interested in detecting print defects. Assemblers are starting to have genuine interest in a defect prevention capability rather than just defect detection features. This can only be achieved with proven and robust closed-loop process controls.

What is "Closed-loop Process Control"?
"Closed-loop Process Control" is a method to continually monitor and adjust a process to maintain a particular target value of an output or outputs. There are a number of ways to consider what closed-loop process control is. There are certainly many systems that monitor and control functions internal to a particular process. For example; a transducer will read a pressure and call for an increase or decrease in that pressure per the process requirements. This is closed-loop process control internal to that particular process.

This paper will focus on closed-loop process control that measures the output or result of a particular process and then adjusts a particular operating parameter or parameters of that process to maintain the target value of the output. For a closed-loop process control system to function we must know what to measure (called the output) and what factors influence the fluctuations of that output. The critical output or outputs (height, weight, volume, shape, temperature, voltage, etc.) of a particular process must first be identified and quantified through the use of formal statistical tools such as Design of Experiments (DOE). The operating parameter or parameters (for example: temperature, speed, pressure, etc.) that will influence the performance of the selected output also must be identified and quantified using formal statistical tools.

Once we identify and quantify the critical operating method to measure these outputs, they must then be identified and qualified. The qualification of the measurement method must include statistically valid testing such as Gauge Repeatability and Reproducibility Studies (Gauge R&R Studies) to ensure the measurement system is both accurate and repeatable. Once the identified output is measured, the closed-loop system must then understand which operating parameter or operating parameters must be adjusted to bring the output measurement back to the target value. A sophisticated electronic manufacturing operation will always have two strategies to produce the highest possible first pass product yield. First pass yield is defined as a product that works the first time it is tested without any touch up or repair. The first strategy is to prevent defects from occurring and the second is to find the defects that do occur as early in the process as possible. Along with good sound process development and process control work, closed-loop process control is an ideal tool for supporting the "preventing defects from occurring" strategy.

A closed-loop process results in the absolute maximum time the process is in an ideal state and in theory producing the absolute minimum amount of defects that this particular process can produce. A process that produces the minimum possible number of defects will produce the maximum amount of profits.

Business impact of Closed-loop Process Control

The business impact of closed-loop process control is reducing manufacturing defects to the absolute minimum that any particular process is capable of. A total closed-loop process that is self-monitoring and self-correcting can provide significant cost savings in the form of:

- Reduced rework
- Reduced repair
- Eliminating damage caused by rework and repair (ESD, handling, etc.)
- Reduced scrap
- Reduced inspection and test equipment and resources
- Reduced returns
- Lower warranty costs
- Preventing delayed deliveries
- Increased customer satisfaction

There are a number of factors that are accelerating the emphasis first, on preventing defects and second, on finding defects as early in the process as possible. Electronics components are continually becoming more complex (large area and perimeter BGA's, Column Grid Arrays, etc.), smaller (0201, 01005, CSP, micro BGA, etc.) and more expensive. The smaller and more complex components make the defects more difficult to find and are difficult to repair. Any component that is damaged by the rework process results in scrap. Preventing defects is always the primary goal. Even defects that are found very early in the process will have a repair cost. Obviously defects that do not occur have zero cost of repair. If we examine several studies on the cost of a defect in an electronics manufacturing process, we learn that defects that escape into the field and are discovered at the customer's site cost many times more than defects that are discovered at various stages of the manufacturing process (see Table 1 and Table 2 for the cost of a defect). A closed-loop process provides an even greater cost savings by preventing defects from ever occurring.

Table 1 - Cost of Defect (USA Based Modem Manufacturer)

Defect Discover Process Step	**Cost of Defect**
Prior to reflow soldering	$0.44
After reflow and prior to ICT	$1.65
In circuit test (ICT)	$2.33
Final product assembly	$49.73
In the field (after shipment)	$550.00

(1,250 times more costly than prior to reflow soldering)

Table 2 - Cost of Defect (Major AOI Equipment Supplier)

Defect Discover Process Step	**Cost of Defect**
Prior to reflow soldering	$0.50
After reflow and prior to ICT	$5.00
In circuit test (ICT	$35.00
In the field (after shipment)	$350.00

(700 times more costly than after reflow soldering)

The "rule of thumb" for the cost of a defect is called the "Order of Magnitude Rule". This rule states that finding a defect at any stage in the manufacturing process will cost 10 times or more than finding the same defect at the previous stage in the manufacturing process.

Consider the following example:

- Placing 4000 BGAs per day either on 1,000 boards (4 BGAs per board) or on 4,000 boards (1 BGA per board)

- The manufacturing process runs 365 days per year
- The defect rate is 100ppm
- The BGAs cost $100 each
- The BGAs have 250 pins each
- The BGA rework cost is $100 per BGA

In this example, the result would be 36,500 BGA pin defects per year or 100 BGA pin defects per day. Let's assume the defects occur on ten boards a day. The resulting rework and parts scrap costs would be $2,000/day or $730,000/year! If closed-loop process control can prevent even a portion of these defects, significant cost savings can be realized.

Table 3 - Benefits of Closed-loop Process Control

% BGA defects prevented with Closed-Loop Process Control	$ Savings/ Year
100%	$730K
90%	$657K
80%	$584K
70%	$511K
60%	$438K
50%	$365K
40%	$292K
30%	$219K
20%	$146K
10%	$73K
0%	$0

Where are the defects?

The vast majority of electronic assembly operations will calculate the number of "Opportunities for a Defect" by counting the total number of component leads and then adding one defect opportunity for the component itself. The actual number of defects is then compared to the total opportunities for a defect and the defect rate is calculated and usually expressed in defects per million defect opportunities (PPMO). Using this method of calculating opportunities for a defect, in excess of 75% of all defect opportunities are controlled by the solder paste printing and soldering processes (reflow and wave soldering).

One high-volume manufacturer's six-month study indicates the average percentage of defect opportunities from the screen-printing reflow process, and wave soldering process was 84.08%. Even a marginal improvement in defect reduction in the solder paste printing process will provide a significant improvement in the overall process quality and first pass product yield (see table 4). A closed-loop solder paste printing process would provide significant benefit in the process that controls the vast majority of opportunities for a defect.

Table 4 - Effects of Solder Joint DPMO on Assembly Level Yields on a Printed Circuit Assembly with 3,000 Solder Joints

Solder Joint DPMO	Printed Circuit Assembly Yield
5	98.5%
10	97%
25	92.5
50	85%
100	70%

Closed-loop control for the Stencil Printing Process

This section of the paper discusses the application of closed-loop control to the stencil printing process. The closed-loop systems discussed below are currently available in a stencil printer or between a stencil printer and an external AOI system.

A) X-Y-Theta print position control within the Stencil Printer

The most common closed-loop control system applied to a solder paste printer deals with accurately placing solder deposit on top of PCB pads. Although most circuit board printers have automated systems that perform the alignment of the stencil to the PCB, misplaced solder paste deposits are not uncommon. These print errors can be produced either by board-to-board variations, stencil stretch, inaccuracies in the alignment system or other sources. A closed-loop controller that corrects for deposit positional inaccuracies will typically measure the offset of the printed deposit with respect to the pads on the boards and correct the relative position of the stencil to the PCB. All corrections are done in the plane of the stencil or board. If a stencil is not adequately matched to a board, algorithms that minimize the distance between deposits and their respective pads can be implemented. In general, the position of the deposits relative to the pads is measured within the printer if the impact on cycle time is acceptable. Alternately, if minimizing cycle time is critical, inspection of the circuit board can be exported outside the printer and performed in parallel to the print operation.

B) X-Y-Theta print position control by Stencil Printer from AOI Measurements

Speedline Technologies and Agilent Technologies are currently working on a closed-loop control system to compensate for X, Y and theta print offsets during a PCB print operation. After a board is printed in the stencil printer, it is passed onto an AOI system which measures the solder deposits and provides an X, Y and theta print offsets. These offsets are relayed back to the stencil printer and the stencil printer compensates for these offsets during the next print stroke. This process is repeated until the print offsets reach the customer specified print offset tolerances. When the process falls within the tolerance, then a SPC control is used to monitor the print offsets on the AOI. The graphs below show the X, Y and theta print offset correction in the stencil printer from AOI measurements.

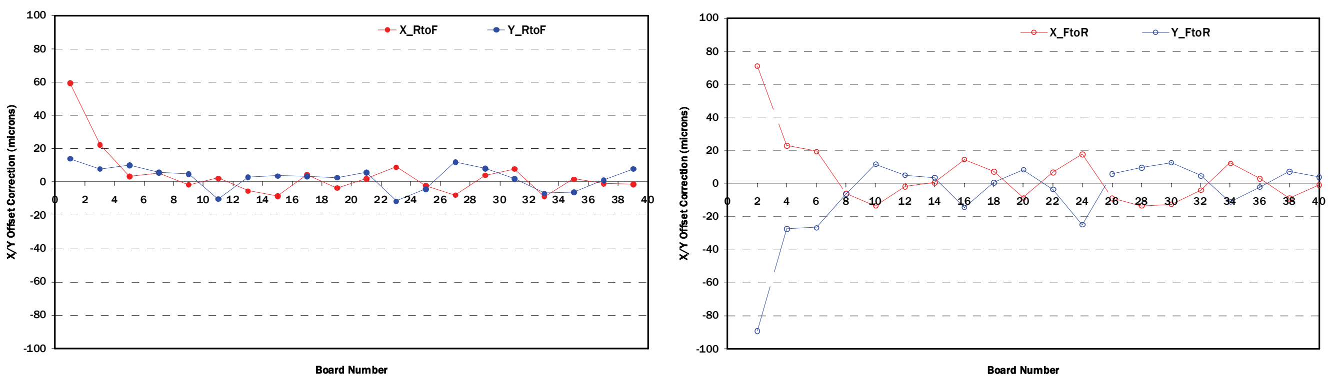

Figure 1 - X and Y Print Offset Correction Results for RtoF stroke (Left) and for FtoR Stroke (Right)

C) Bridge vision and stencil inspection and wipe

The detection of solder paste that is erroneously deposited between pads is critical to circuit board manufacturers since such print errors may result in the formation of electrical shorts during the reflow stage. Such print defects are commonly called bridges and need to be minimized if not eradicated. Solder paste bridges can be caused by stencil misalignment, excess print pressure, inadequate gasketing between the stencil and the pads or a stencil carrying solder paste contamination. Most printer and AOI manufacturers have devised techniques that detect solder paste bridges on circuit boards. These techniques are usually qualitative in nature and lend themselves to interpretation. The Bridge Vision product offered on some MPM printers goes one step beyond by measuring various attributes of bridges and bridge like features. In particular, the amount of paste found between two pads can be reported and compared to a user-defined threshold. Similarly, the span of bridges between two pads (the distance a bridge protrudes inside a gap) can also be compared to user specified limits. When either quantity reaches some predefined limit, a wipe of the stencil may be triggered to reduce the probability of the stencil being responsible for producing bridge-like defects.

Another defect control option consists of inspecting the stencil for bridges (e.g. paste located between apertures) and paste remaining inside the stencil apertures due to incomplete paste transfer at the time of the stencil/PCB separation. When the stencil begins to carry relatively large amount of contaminants, it can be shown that defects on the boards are more frequent. Figure 2 shows plots of the maximum amount paste found between apertures of a particular device on a stencil and the maximum span of bridge-like features for the corresponding device located on the PCB. Both curves are plotted as a function of number of boards printed. One must note that as the paste contamination measured on the stencil increases, the size of bridges on the PBC increases as well to the point where a 100% bridge is created.

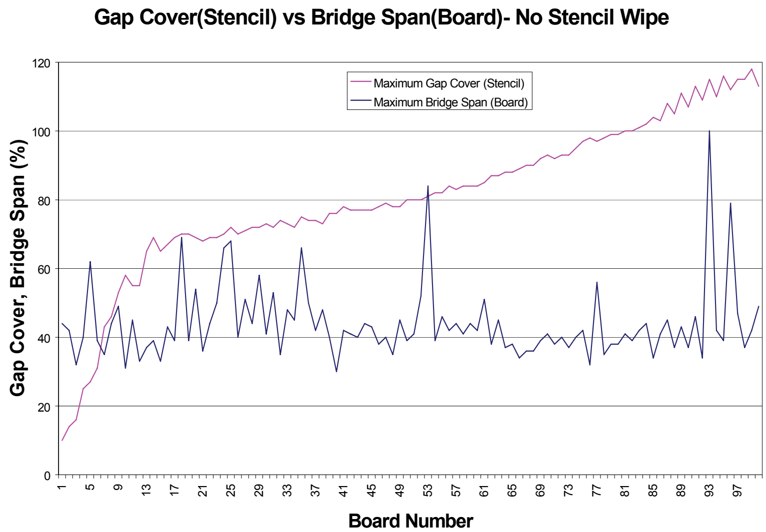

Figure 2 - Maximum Gap Cover on the Stencil (pink) and Maximum Bridge Span on Board (dark blue). No stencil wipe

Figure 3 shows the same quantities plotted. In this case, however, a stencil wipe is triggered each time the amount of paste on the stencil reaches a user-defined limit. It can clearly be seen from the plots that the size of the bridges on the PCB stay controlled and never grow beyond 60% of a gap length. These measurements demonstrate that by monitoring solder paste on the stencil, a closed-loop control that prevents bridges from occurring can be implemented with relative ease. In this particular test, the same vision probe used for aligning the stencil to the PCB was used to perform the inspection tasks.

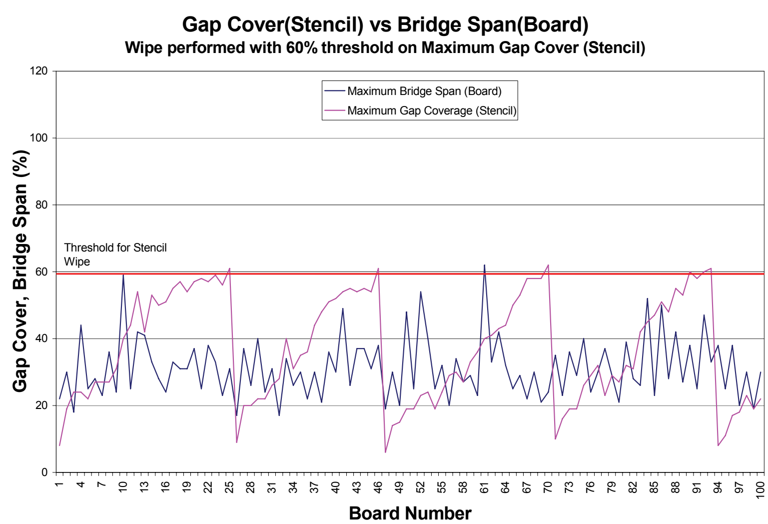

Figure 3 - Maximum Gap Cover on Stencil (pink) and Maximum Bridge Span on Board (dark blue). Stencil wipe triggered when paste between aperture of the stencil reaches 60%

D) 3D Closed-loop Process Control of the Solder Paste Printing Process

Stencil printing is a critical first step in surface mount assembly. It is often cited that about 70% or more of the defects found in the assembly of PCBs are attributed to stencil printing. To improve the performance of the solder paste printing process, a closed-loop system was proposed to monitor the process and make changes when required. The closed-loop system that is being developed by Speedline Technologies in partnership with Georgia Tech utilizes the 3D paste measurements to control the print parameters.

The closed-loop controller was developed to compensate for:

- Discrepancies associated with different print directions;
- Recovers from faulty initial settings;
- Provide robustness by maintaining the performance of the process in the presence of environmental variations or unscheduled process interrupts.

The closed-loop control is based on an algorithm, which generates a sequence of iterative values that converge to an optimum set of machine parameters for a desired solder paste volume. The merit of the control is that it minimizes the variance and the steady state error of the weighted sample mean versus the desired target (e.g. volume, height and area), which improves the quality of the process. The proposed control scheme is based on a weak-search algorithm that can be used in the presence of large amounts of noise as well as when only a limited amount of information is known about the process. The control law is given by a modified version of a constrained conjugated-gradient method, transitioned into a windowed-smoothed block-form of the least-squares affine estimator. In addition, it considers print direction and different component types independently.

Though many parameters affect the stencil printing process, print speed and print pressure are the two critical parameters affecting the performance of the solder paste printing process. Currently many studies have been conducted which show that print speed and print pressure are the two parameters to control to improve the paste printing performance. When the board is printed, a 3D AOI is used to measure the solder brick area and height. These measurements are transferred to a control system, which compares the current values to the preset/target value. Based on the algorithm, the controller predicts a change in the print speed or print pressure to compensate for the difference in the measurements.

Tests were performed to evaluate the response of the closed-loop control algorithm when changes in the temperature and humidity are applied to the printing process. The tests were carried out for 100 boards using a Type IV paste. The target height for the BGA36 component was set at 5.2 mils. The controller was set to run at a constant pressure of 1.5 lbs/inch and speeds as the control variable. The initial speeds for the boards were set at 2.0, 2.5 and 3.0 in/sec. Additionally, the temperature was increased every 10 boards by 4^{o} F. This test simulates the temperature change that takes in a production factory, where the temperature is around 75 ^{o} F at the start of the shift and as the day progresses the temperature increases. To compare the performance of the controller, the height measurements from the prints with controller is compared to the height measurements of the prints without controller for the BGA36 component. Also Cp and Cpk analysis is done to compare the print performance for the prints with and without control.

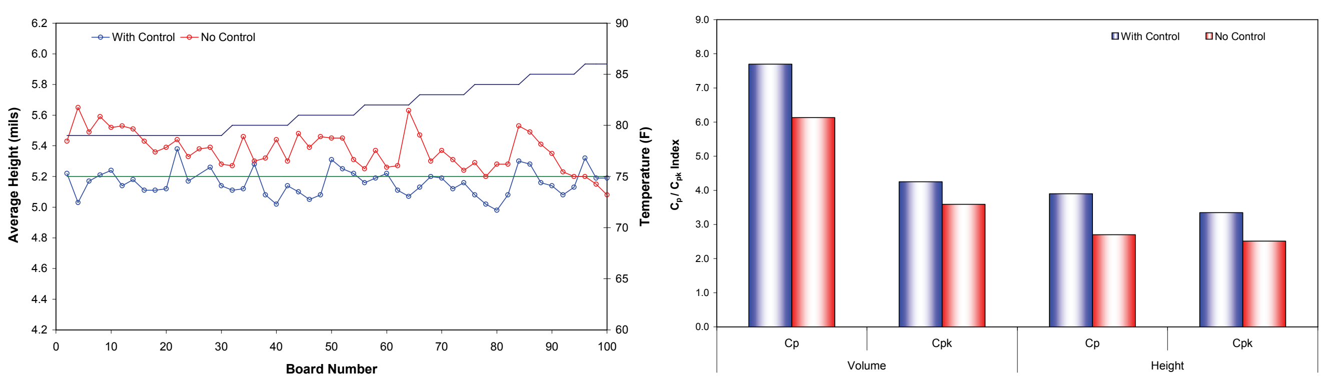

Figure 4 - Results for Temperature Response Tests

The above graphs for average height show that as the temperature increases, the height measurements for the print without control start to fluctuate. The height measurements for the print with controller show that the closed-loop control algorithm was able to maintain the print process closer to the target height. The Cp and Cpk analysis on volume and height measurements show that print with control have better print process compared to the prints without control.

Though the tests showed promising results, the controller was effective only with few Type IV pastes.

Future Innovations

The primary impetus behind closed-loop is the prevention of defects by monitoring and changing process variables. Therefore, it would be safe to say that closed-loop process control can take many forms and be implemented in various fashions. This could include direct feedback to the printer as discussed earlier in this publication, or it could include automated root cause analysis techniques and responses which present the user likely fixes to a detected process issue. Paste printing is a process incorporating many variables, and sometimes, inspection data can point to several potential issues, which require user intervention. The key is to eliminate as many potential variables as possible, and make the process correction more efficient.

Unfortunately, no printing process is perfect, and the process is subject to the design constraints and technology used on the PCB. Concessions are made in order to balance the printing needs of certain devices, and the resulting performance will be less that optimal for more sensitive aperture sizes. In order to conduct any type of measurement for automated root cause analysis, the system must understand what the process is capable of, and the resulting stability and steady state performance. This is also known as process characterization. This requirement also provides an opportunity for using AOI to test different machine setups to determine which yield the best printing performance. By automating the process of conducting a small DOE to determine optimal printing speed and pressure, the process can then be characterized about its true potential.

After conducting the process characterization steps to determine the best potential performance, traditional SPC methods can be used to identify process issues when they arise. However, secondary analysis must be completed in order to establish root cause or provide corrective feedback. By isolating certain printing conditions, such as whether error conditions are dependent upon stroke direction, the automated root cause analysis is simplified due to a reduction in the number of common faults. For instance, if SPC tools determine that there is a trend of a reduction of paste volume, then there needs to be action taken on the printer to regain the expected volume. However, this could be attributed to several conditions such as aperture buildup, low paste on the screen, or poor paste condition (temperature). By considering variables such as y-offset biased aperture fills and print direction, the number of root causes is decreased, because different causes will have resulting measurable affects in the resulting print. The data simply has to be analyzed to present the user with these differences.

Another opportunity for automated root cause analysis stems from the fact that certain printer faults will manifest themselves in regional fashions on the board's layout. For instance, stencil blade damage will only appear in a single print direction, and typically along a single line, suggesting a low variance in the horizontal position of the defects or average change in height and volume. Another example would be when there is significant buildup on the underside of a screen, otherwise known as "coining". In this scenario, the increase in volume and height will be tied to a certain location on the board, and will be independent of print direction.

Therefore, it is understood that the printing process is filled with many variables affecting the printing performance, making it difficult to offer confident and direct feedback. However, through careful analysis of the measurements conducted by 3D AOI tied together with print stroke and history, conclusions can be drawn using automated data analysis techniques, and the number of likely causes can be dramatically reduced. These techniques rely on characterization and SPC as a baseline, but require intelligent analysis to eliminate variables and have the potential to present the user a minimal list of corrective actions to take. This structured approach to closed-loop and defect prevention allows manufacturers to identify and solve issues in an efficient manner before sacrificing quality, promoting a lower sustaining cost and higher yields.

Conclusions

Closed-loop controls have been implemented at many stages along circuit board manufacturing lines. They have successfully been implemented within reflow ovens and at the components placement stage. There are many incarnations of closed-loop control for the solder paste printer going from the simple viscosity-sensing squeegee to the sophisticated solder paste volume controller using laser triangulation for measurements.

As electronics manufacturers demand the capability to produce circuit boards with higher yields and at a lower cost, it is clear that closed-loop-process controls will slowly but surely permeate assembly lines in the not too distant future. Closed-loop controllers, when implemented correctly, present the advantages of keeping complex processes within control limits even when small external perturbations affect the product line, ultimately preventing end-of-line defects. In addition, process controllers minimize operator intervention and have self-tuning properties. Closed-loop controllers will tend to migrate toward the front of the line where defects are less expensive to correct. In that regard, controlling the solder paste printing process presents significant advantages and will certainly be very attractive for board assembly manufacturers for high production yields, which are critical to the health of their highly competitive business.