Improving c-Si factory productivity and efficiency via an effective automation software strategy

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ABSTRACT

This paper presents a strategy for improving c-Si factory productivity and efficiency via software, focusing on software systems that improve yield and reduce cost. Specifically, the role of automation software systems and example areas where they can provide impact will be discussed. Key requirements of these software systems will then be identified that guarantee reusability, reconfigurability and extensibility, and thus high and continuing ROI. Case studies will then be presented illustrating how Advanced Process Control (APC) software has been successfully applied in the semiconductor and Flat Panel Display (FPD) industries to improve productivity and efficiency. The paper concludes with a roadmap for automation software implementation to support PV factory productivity and efficiency improvements.

Introduction

The c-Si industry has probably had more pressure for technology ramp-up than any other semiconductor-related industry. In addition, the technology ramp-up is taking place in an environment where economic conditions force a major focus on cost savings and rapid ROI. Luckily, the c-Si industry has many similarities to the more mature LCD flat panel display and integrated circuit industries to the extent that we can leverage productivity and efficiency capabilities along with best practices quickly into the c-Si industry. Key among these capabilities are automation software systems; automation software systems represent a largely untapped source of competitive advantage in c-Si manufacturing. The success of these systems hinges on the individual automation tools collectively providing systems that are reusable, reconfigurable, and extensible, so that the accompanying business application model can provide high and rapid ROI.

In this paper, an overview of critical automation software capabilities that can be employed collectively in c-Si manufacturing to improve productivity and yield and reduce cost is presented. Case studies will illustrate how an effective c-Si automation software strategy will allow the leveraging of these capabilities into the c-Si industry. The roadmap for automation software implementation includes a summary of the next steps that can be taken to achieve immediate ROI [1].

The role of automation software systems

Automation software systems are a key differentiator in c-Si manufacturing. As shown in Fig. 1, these software systems go hand-in-hand with lifecycle and automation and service infrastructure to deliver factory productivity and efficiency improvements while minimizing waste. An automation software system can be subdivided into three categories based on the capabilities they provide:

Manufacturing Execution Systems (MES) provide capabilities for execution of Enterprise Resource Planning production orders including scheduling, dispatch, tracking and traceability, and maintenance management.

Advanced Process Control (APC) provides capabilities for individual and overall factory process control and optimization, equipment and process diagnostics, and statistical process control.

Yield Management Systems (YMS) provide capabilities for yield performance management, and optimization, yield excursion identification and investigation, and links to design for manufacturability (DFM) systems.

Automation software systems provide benefits at the pre-ramp, ramp, production and optimization stages of manufacturing. Specifically at pre-ramp they help define manufacturing platforms and operational strategies. At the ramp stage they provide capacity plans, layout designs, supply chain management strategies and staffing plans, leveraging simulation and modelling, tracking and execution. At the production stage they provide more advanced MES, APC and YMS capabilities, as shown in Fig. 1, thereby providing a mechanism for optimization and continuous improvement of manufacturing systems.

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Focusing on cell efficiency improvement during production is vital to profitability, as illustrated in Fig. 2. Experience in implementation of automation software systems in semiconductor and display

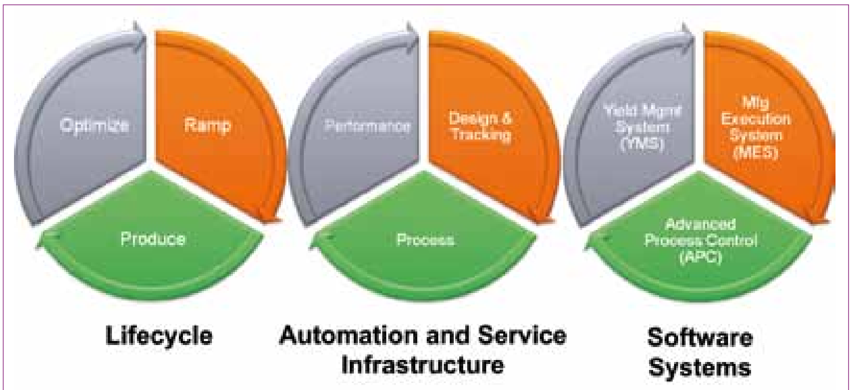

Figure 1. Factory productivity and efficiency contributors.

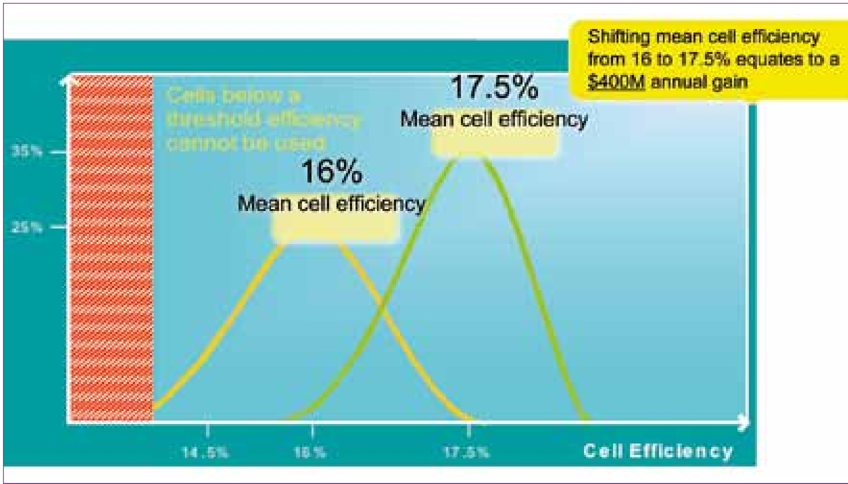

Figure 2. Utilizing APC and yield management to improve cell efficiency.

industries tells us that automation systems can be the key to maximizing this cell efficiency as well as throughput, especially as improvements resulting from hardware and automation begin to plateau. In other words, automation software systems represent an under-utilized resource that can provide c-Si manufacturers with immediate and continuing competitive advantage.

For example, c-Si factories today employ open-loop process control where cells are tested at the end of the line and then batched based on performance and colour. This end-of-line correction scheme can result in lost throughput, scrap, and, most importantly, reduced mean cell efficiency. Automation software systems (notably APC in this case) can address this problem by providing closed loop control targeting improved cell efficiency at each process.

Requirements for effective automation software systems

Achieving high and continuous ROI with MES, APC and YMS automation software systems necessitates that a number of requirements be met. Meeting these requirements should be considered as a critical part of the c-Si manufacturing roadmap [2]. Fortunately, as similar challenges have been faced previously in the semiconductor and display industries, automation software systems developed for these industries can be leveraged effectively into the c-Si industry.

The requirements focus on providing for ease of integration, flexibility, re-usability and extensibility [3]. First and foremost among them is that the *automation software solution be modular, integrated and easily reconfigurable*, allowing for rapid ramp-up of systems, but also rapid tailoring and expansion of these systems to meet the dynamics of manufacturability. As an example, Fig. 3 illustrates two approaches to software integration. In Fig. 3a, software capabilities are integrated in a point-to-point fashion, usually based

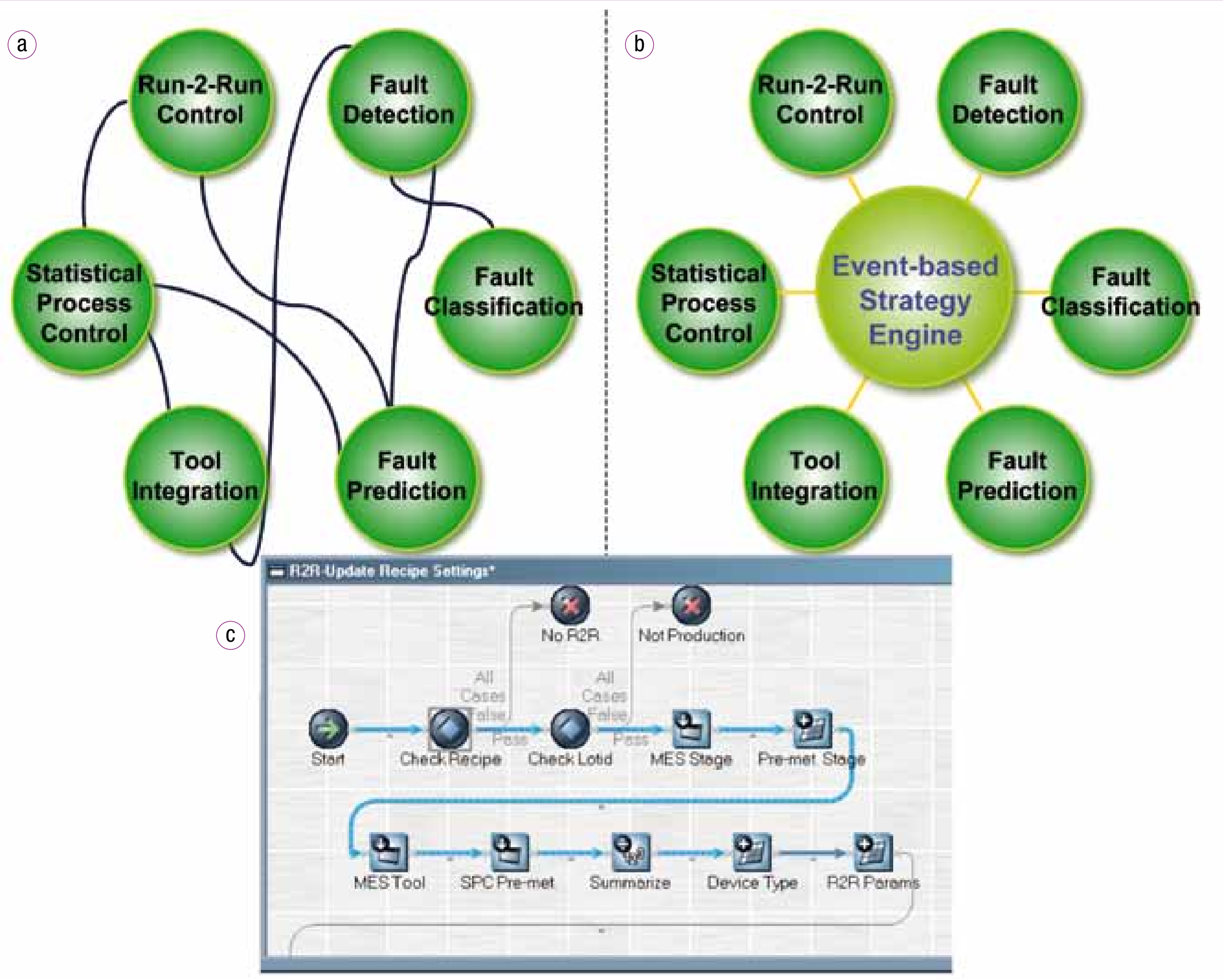

Figure 3. Approaches to software integration. Schematic 3a (top left) represents a traditional 'point-to-point' approach, while 3b (top right) represents a more flexible and coordinated approach where event-based strategies such as presented in 3c (bottom) are used to govern the interaction of software capabilities.

on requirements identified in the initial stages of production. This solution is difficult to diagnose and modify, requiring cycles of integration software development and quality assurance each time a change is needed. Fig. 3b represents a solution to this problem. Software capabilities communicate in a common publish-subscribe environment via well-defined and consistent interfaces, and event-based 'strategies' define the collaborative interaction of these capabilities to provide manufacturing services are developed and maintained graphically (Fig. 3c), requiring no software programming during re-configuration.

Consolidation of data, objects, naming conventions, etc., among the software capabilities further simplifies the automation software development and maintenance process. The 'event-based strategy' also provides a streamlined knowledge-base system for capturing learning so that knowledge gained can be quickly incorporated as best practices; specifically, the software strategies serve as a graphical tool for conveying and implementing these best practices throughout the manufacturing employment structure. Note that this approach to manufacturing software has been proven effective in both semiconductor and display industries [4, 5].

A second key requirement for automation software solution effectiveness is *adherence to a standardized environment for software-to-hardware and software-to-software integration*. For example, adherence to the SEMI SECS/GEM (SEMI Equipment Communication Standard/Generic Equipment Model) E30 communication standard for all manufacturing equipment will simplify the equipment integration and automation process, reducing unnecessary duplication of effort, and enhancing capabilities for re-usability and diagnosability. Adherence to the Process Control System (PCS) E133 standard for APC software integration allows APC systems to more readily share information and leverage each other's capabilities. SEMI has dedicated significant resources to leveraging the semiconductor manufacturing standardization approach and results into the solar manufacturing industries. Many semiconductor equipment automation standards are being considered for adoption in the solar manufacturing industries with some such as E30 already being adopted [2, 6].

A third requirement is the *utilization of sensors and metrology*. A key to automation software system effectiveness is its ability to view and understand its environment. Metrology systems enable a key process control capability that can be directly linked to improved process capability and improved yield, while maximum utilization of equipment sensory information ensures an optimal capability for equipment and process diagnostics so that scrap and equipment downtime can be minimized. Note that both hardware 'real' and 'soft' (i.e., 'virtual') sensor and metrology systems should be considered [4].

Other important automation software requirements include: 1) integration and consolidation of data management; 2) integration and consolidation of data visualization – often termed 'dashboard'; and 3) proven track record of application in similar industries [3]. Delivering on these requirements will result in an extensible automation software framework upon which key software capabilities can be integrated.

At the software management level there is an additional requirement that a *software services capability* be maintained. As the advantages of software systems are realized, they will become an increasingly large portion of the total manufacturing solution, and will be the source of a large percentage of manufacturing innovations that lead to competitive advantage. The deployment, growth, and tight integration of software systems into the manufacturing process needs to be managed so that costs are minimized, focus on a consistent and extensible architecture is maintained, and individual software efforts necessarily roll up to a consistent enterprise-wide software strategy.

Key automation software capabilities

Fig. 4 provides a summary of automation software capabilities that should be leveraged into c-Si manufacturing production. At the data generation level, standards can be utilized to maximize re-usability in tool and metrology integration. Metrology can be in-line or off-line, real or virtual (as noted earlier). Data collection should be of a sufficient rate so as to be able to capture excursions that result in downtime, scrap and lost yield.

At the process monitoring level, APC capabilities should be leveraged to provide for process monitoring and optimization [3, 6], and include:

Statistical Process Control: a capability that utilizes a set of rules applied to data

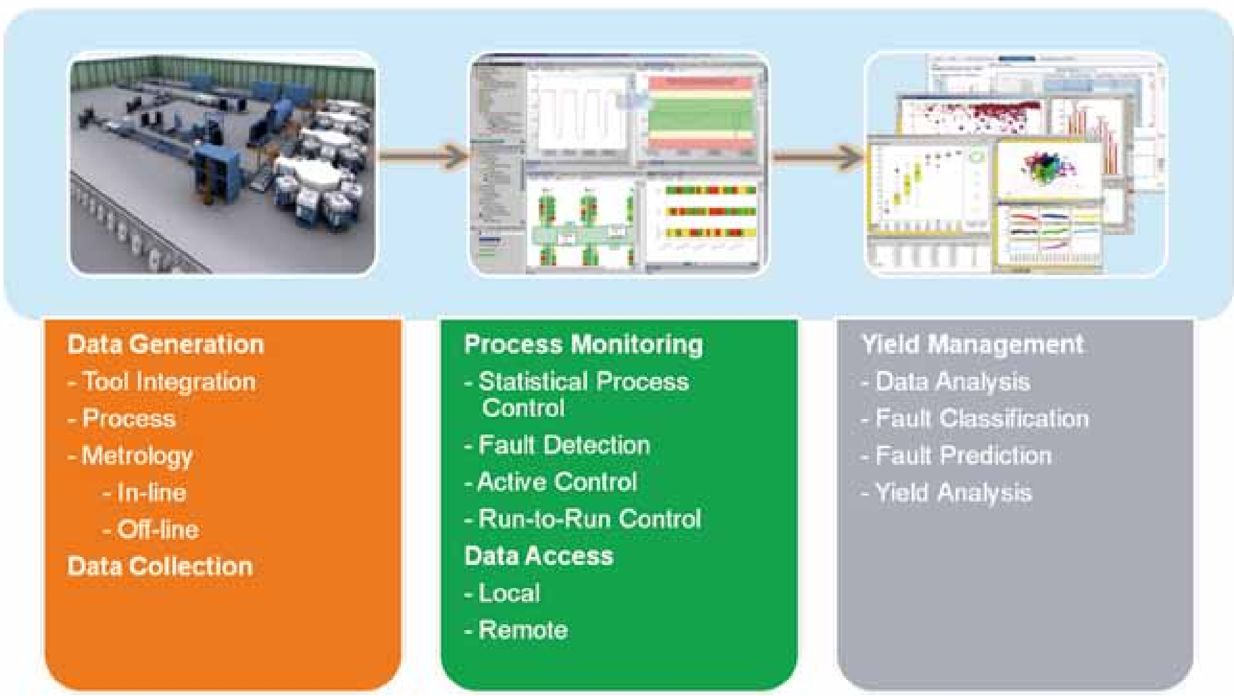

Figure 4. Software capabilities that should be leveraged into c-Si production to support factory productivity and yield improvement.

sets to detect statistical anomalies. These anomalies can then be related to specific equipment or process problems to be addressed.

Fault Detection: an automated equipment and process heath monitoring capability that utilizes equipment data collected during run-time along with a number of analysis techniques to determine the health of the equipment and/or product. It can provide alarming information as necessary to avoid scrap and unnecessary equipment downtime, and convert unscheduled downtime to scheduled downtime.

Run-to-run Control: a model-based control capability that provides for continuous process tuning via run-to-run process recipe adjustment to optimize the process to productivity goals.

APC capabilities developed, customized for, and proven in both the semiconductor and display industries can and should be directly leveraged into c-Si manufacturing facilities.

At the yield management level, Fault Classification allows for fault detection indications, realized at the process monitoring level, to be linked to specific causes or classifications so that appropriate maintenance activities can be readily scheduled, thereby reducing mean time to resolve (MTTR) and the incidence of low yield production.

Fault Prediction additionally allows the utilization of Fault Detection and Classification information to support proactive or preventative maintenance, further reducing MTTR. Finally, Yield Analysis allows for the identification of and investigation into yield issues.

All of these automation software systems contribute to improving c-Si factory productivity and efficiency; however, their effectiveness is significantly enhanced if these systems work together collectively towards factory productivity objectives. Provision of the flexible integration environment along with software services to guide this integration is thus key to obtaining maximum ROI from these automation software systems.

Automation case studies

In this section, select case studies of software implementation in the display industry focusing on the utilization of APC software capabilities are highlighted. As noted earlier, c-Si manufacturing should leverage automation software capabilities in both the semiconductor and display industries as these industries have or have had very similar productivity and/or efficiency issues as part of their maturation process. Reviewing case studies in these industries is an important part of the software evaluation process for c-Si. The particular case studies presented here focus on first illustrating success in the semiconductor industry, and then applying capabilities proven in the semiconductor industry to the display industry. In a similar fashion, all of these automation capabilities could be applied to the c-Si manufacturing industry. In implementing each of these solutions, the Applied E3 equipment automation and APC software solution was leveraged. This software meets the requirements of integration, flexibility, re-usability and extensibility, and thus the cost side of the ROI equation is minimized.

Fault detection and R2R control in semiconductor manufacturing

In these case studies, typical applications of APC capabilities are presented for semiconductor manufacturing [5]. The fault detection capability is often used to detect problems that lead to lost product. In the case study presented in Fig. 5a, a phenomenon called 'etch arcing,' which can be very destructive to product, is detected. Direct detection of etch arcing is very difficult because extremely high sampling rates are needed to catch the DC bias arcing spikes. In this example, the arcing is detected indirectly by monitoring Optical Emissions Spectroscopy (OES) of the etch chamber plasma. The OES intensity profile at a particular wavelength is different if arcing has occurred, indicating that the photo-resist by-product has been created. A windowing tool of the FDC system allows for high-resolution zeroing-in on this feature so that an arcing fault can be clearly determined.

Fig. 5b summarizes a case study of a common application of run-to-run control that generates high ROI via improved process capability. In this case, a Cpk improvement of over 50% is achieved by applying run-to-run control to a lithography process to reduce process variability and better centre processing to recipe targets.

Fault detection in display manufacturing

In this case study, a display manufacturer that makes 42" and 47" TFT-LCDs, flat TVs and monitors, had an issue with glass centre strain and particulates. Working with APC software, they determined that the root cause was a leak: specifically, a cooling block caused a break in ceramic due to temperature differences, which in turn caused a ring type of strain on the glass. The E3 software was configured by setting up the automation component to automatically collect data from the equipment during processing. A Fault Detection software strategy was configured (graphically) to analyze equipment data, detect conditions related to the fault, and provide alarm notification to engineers when the fault conditions first appeared. The engineers were then instructed to shut down, repair and requalify the equipment.

As a result of implementation of the E3 APC system in this case, the incidence of scrapped glass was reduced from 22 substrates per every four lots (approximately 25%), to less than one substrate, which signifies a scrap reduction of over 95%. Considering that the raw glass costs US$1500 and the finished glass costs US$3000 per unit, and that the manufacturer makes about 90,000 panels per month, monthly savings from scrap reduction alone ranged from US$3.2 to US$6.4 million. Additional ROI is achieved from increased productivity by detecting and eliminating scrap, and reduced downtime as a result of identifying specific maintenance issues and instructing maintenance engineers appropriately, thus reducing MTTR.

Run-to-run control in display manufacturing

This case study saw a display manufacturer employ E3 automated run-to-run

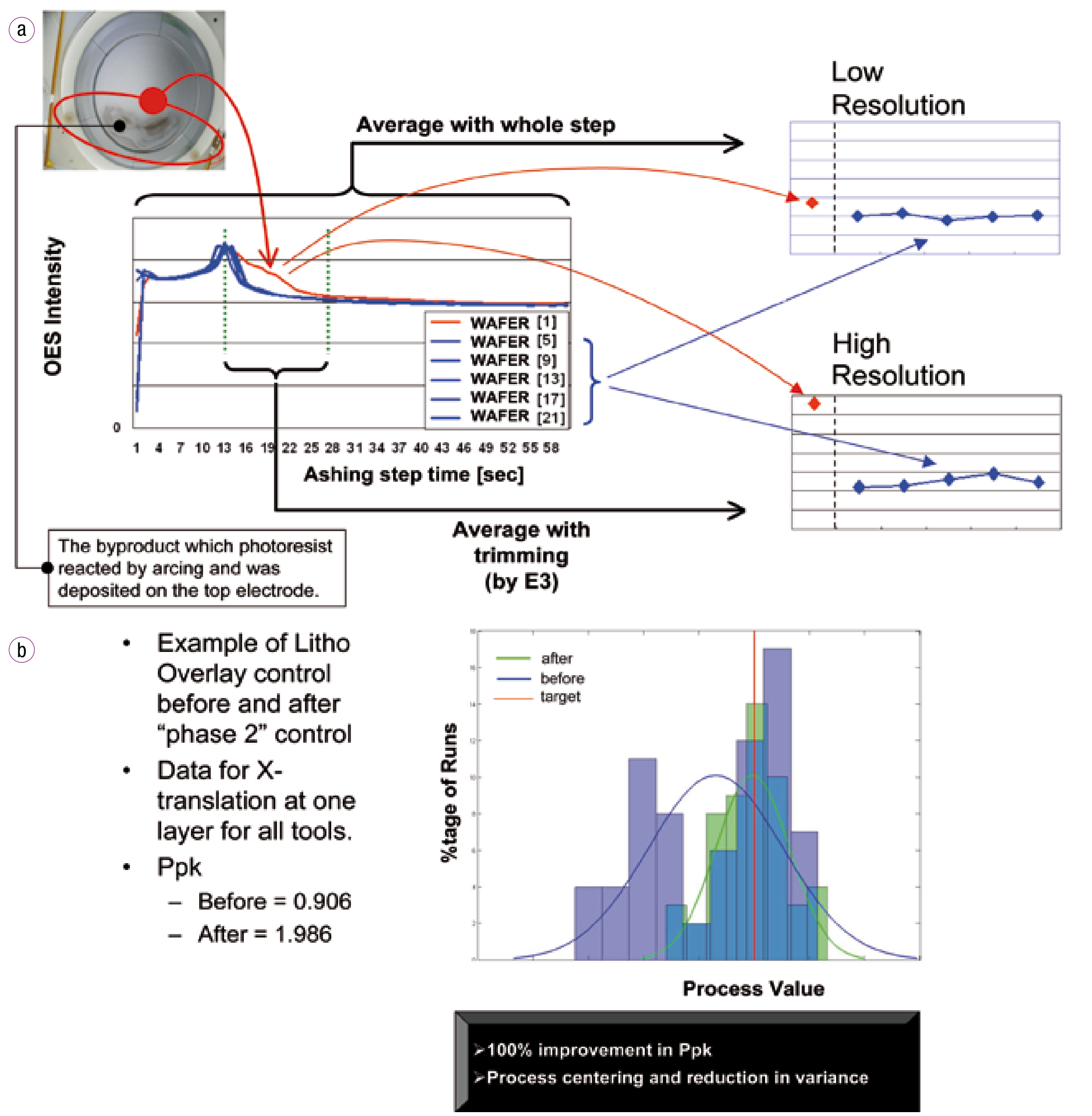

Figure 5. Illustration of application of APC capabilities to semiconductor processing. In 5a (top), etch arcing is detected using fault detection resulting in reduced wafer scrap (of future wafers). The graph in 5b (bottom) shows results of run-to-run control being applied to a lithography process resulting in over 50% improvement in process capability (Cpk).

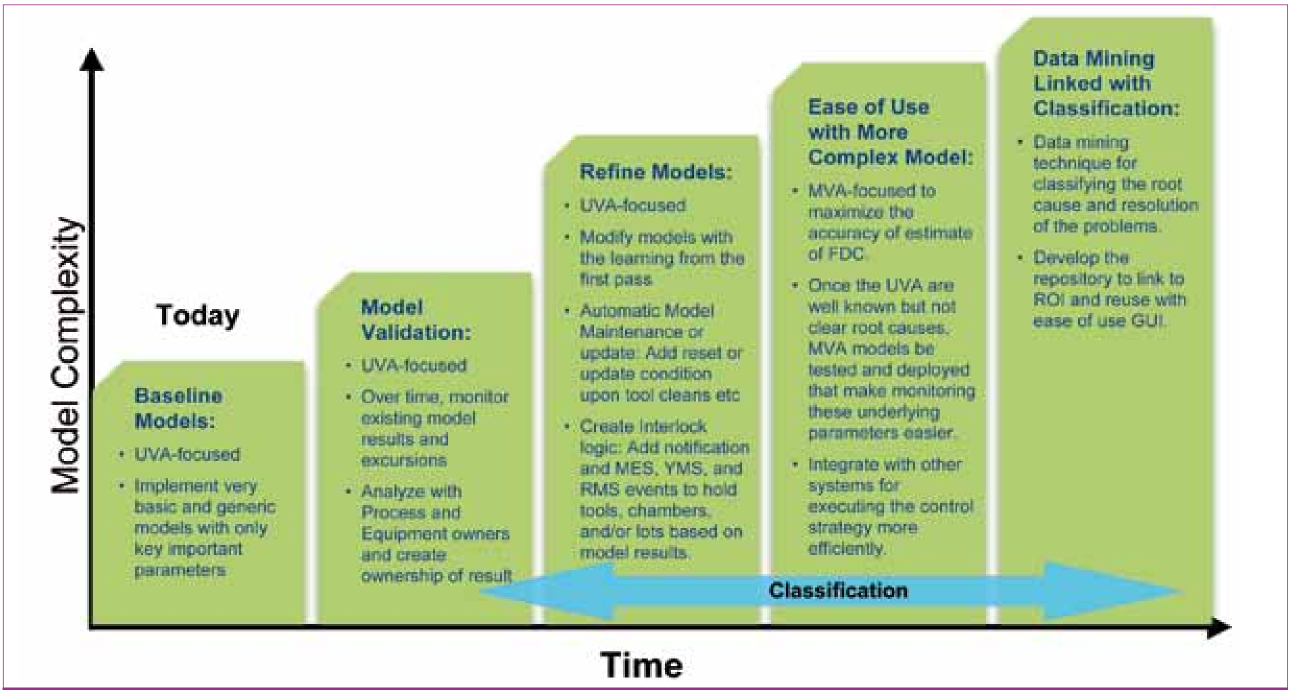

Figure 6. Automation software system implementation strategy and roadmap.

process control on a photolithography process. Prior to application of this control, tool operation was achieved by manual adjustment of equipment recipes, which resulted in lost productivity due to time taken to make equipment recipe adjustments, and which required an operator resource to implement the recipe adjustments. With the implementation of automated run-to-run process control, idle time due to recipe adjustment was virtually eliminated as was the need for operator time to support recipe adjustment. The resulting monthly cost savings are approximately US$2900 (due to savings in personnel) + US$36,300 (due to increase in throughput) = US$39K savings per month per equipment. Additional ROI is achieved from increased process capability and reduced variability of the process achieved from application of process control.

Moving forward: a roadmap for PV factory productivity and efficiency improvement

Automation software systems implementation in c-Si manufacturing represents a potential continuing ROI opportunity for many years to come. As with any software implementation strategy, basic requirements (as presented earlier) should be adhered to so as to allow the automation software solutions to evolve as manufacturing practices mature, and software services should be utilized to guarantee adherence to these requirements on a common extensible framework.

It is also important to start with simple implementations on this framework so that immediate ROI can be achieved. Fig. 6 illustrates a sample automation software system strategy, showing gradual implementation of more complex capabilities after baseline capabilities are implemented and proven. Today's systems should be aligned with these baseline capabilities. These include simple univariate (UVA, one input to one output relationship) models, fault detection only, and focus on basic diagnostic and control models. Such models should be validated to verify approaches and best practices and to establish a baseline from which models can be refined and more complex models such as multivariate (MVA, multiple input to multiple output relationships) can be developed. Fault detection schemes can also be linked to fault classifications and maintenance events, and ultimately solutions can move from reactive fault detection to more proactive fault prediction and predictive maintenance.

The key is identifying a strategy for long-term cost of ownership that continually leverages an extensible automation software system for the collaborative integration of new capabilities as the manufacturing environment matures. In this way, COO is minimized and the full ROI of each automation software capability can be realized as it is incorporated into the factory.

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