The semiconductor and photovoltaics industries have a lot of similarities throughout the manufacturing processes. Acting under guidance from the advisory board, *Photovoltaics International* will feature articles from semiconductor companies presenting best-practice knowledge garnered from the semiconductor industry.

A realistic approach to achieving zero equipment failures

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ABSTRACT

In most complex manufacturing environments, equipment failures dominate. These failures are commonly referred to as 'fires' because of the chaos and damage they inflict on factory operations. This paper recommends taking specific non-disruptive steps to establish 'fire prevention' and induce a culture change to set the organization on a path to achieve zero production disruptions.

Fire-fighting culture

Consider this common scenario. A key piece of equipment fails, creating a blockage in the production line. One or more personnel are quickly dispatched to fix the problem. The situation is dire, threatening to slow daily product starts and slip output goals. Those working the problem know this failure is being discussed at the highest levels and they feel the heat. They know if they can just get the machine working well enough, everyone will be satisfied and the stress will be lifted. Their logic leads them to suspect a specific component. They replace it, hold their breath, test the machine, then celebrate when they realize the problem is gone. The machine is now processing and those involved in 'getting it running again' receive praise from management before being quickly directed to the next fire. So was the problem resolved? Those that were directly involved might answer in the affirmative because of a common tendency to associate 'problem' with a source of pressure or stress. Once the pressure is lifted, so too is the perceived problem. But in truth, the problem was clearly *not* resolved. This failure will occur again, at any time and with an unpredictable severity because the *reason* for the failure was not determined. Did the part simply reach its expected lifetime, or did it fail for some other reason? Perhaps the part had a manufacturing defect, or something else in the machine is causing it to fail prematurely; without this knowledge, the abundance of work applied to this problem will produce only temporary relief, not sustained improvement. This is the fire-fighting culture, which only values efforts that quickly 'get it running again'. Inevitably, these fires return, because the real cause was either not found, or not properly addressed to prevent reoccurrence.

Factories with a pure fire-fighting culture ultimately cannot survive. If sources of failure are not identified and eliminated, they will accumulate with equipment age, eventually becoming too costly for the company to sustain (see Fig.1).

So why are robust equipment-focused continuous improvement programs absent in many organizations, especially since equipment performance clearly impacts nearly all factory performance metrics? Sustained improvement in equipment performance, availability and stability will increase factory capacity, improve cycle time, improve predictability of product out (planning), improve safety, prevent customer disruptions, improve morale and transform cost into company profit. Emergency repair work can cost an organization three times more than the same repair when pre-planned, which can amount to an annual cost of multiple millions of dollars for a semiconductor fab [1].

Zero Unscheduled Maintenance (ZUM) is an equipment-focused continuous improvement program developed at Texas Instruments that mandates fire prevention and provides the tools needed to achieve continuous and cumulative equipment downtime reduction. ZUM contains aspects of Total Productive Maintenance (TPM) that enable comprehensive analyses, closed-loop problem solving, and effective equipment knowledge management. It also embraces the fundamental TPM principle that zero equipment failures can be achieved. *Unlike* TPM, ZUM can bring about an equipment-centric culture change with minimal disruption to existing operations.

The right mindset for culture change

Maintenance is not glamorous. It lacks intuitive appeal. For many, the thought of 'maintenance' conjures up images of mechanics in auto shops replacing oil. Maintenance is neither considered at the heart of what most hi-tech companies do, nor considered essential to what factories do, i.e. developing new processes that enable more advanced products or more profit. Maintenance is often just tolerated. Here are three reasons why this mindset must change.

1) *Managing equipment performance in complex manufacturing environments is incredibly complicated*. Typical semiconductor fabs have 500 to 1000 individual processing machines, each built with combinations of the most advanced technologies available today, using a wide range of exotic energies, chemicals, gases and materials, all managed with a very lean workforce. In some factories, each of these machines might fail as often as once every week.

2) *The skills required to master equipment performance are significant.* Maintenance is the pursuit of perfection; perfect understanding of and control over equipment behaviour. To accomplish this, one must seek an understanding of how thousands of components within a single machine interconnect and interact; of how degradation of one aspect of a single component can affect other components causing chain reactions and complex problems. A skilled person attempting a repair on such a machine may seem distant and disengaged, because their mind is completely occupied sorting through the associations and hierarchies of this vast complexity. They may develop a 'feel' for the system is basically the recognition of patterns in this vast complexity that indicate a potential for certain outcomes. These are practical, curious and tenacious perfectionists who often make the equipment achieve more than the OEM designers would have thought possible.

3) *Equipment performance has an overwhelming impact on profit, quality and nearly every aspect of product creation.* For this reason alone, it must be given a top priority.

Although the challenge is significant, there is no magic required. Even the most complex machine functions entirely in accordance with the laws of science and reason, and therefore every problem has a root cause that can be found and addressed. Before an organization can take on this challenge, it must believe they can prevent *all* failures from reoccurring, and be committed to the continuous development and fine-tuning of advanced, comprehensive and concise maintenance.

There is a mountain of work required to achieve zero failures, so the ascent requires patience, and choosing the correct path is crucial. ZUM provides the tools to identify this path. Without these tools, a fab manager may expend energy following many different available trails, only to find years later that they are right back where they started.

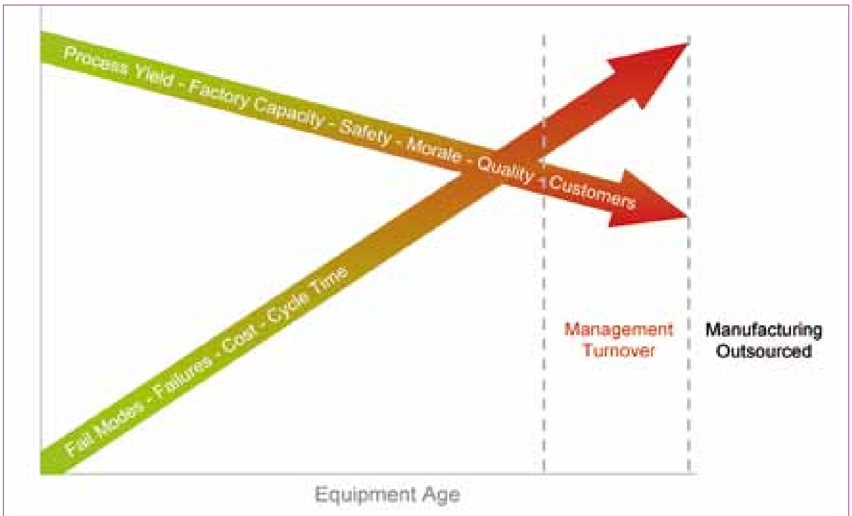

Figure 1. Without fire prevention, failure modes and therefore fails will accumulate with equipment age.

Developing a program that fits into 'what we already do'

It is important that the program resonate within the organization to enable the culture change. There are three well-known key elements for creating change: 1) make it available; 2) make it simple; and 3) make it mandatory. Expanding on the 'simple' element, the program should be practical, feasible and (ideally) non-disruptive meaning the required work must fit into 'what we already do'. Those that have been directly involved with full-blown TPM implementations or Reliability Centered Maintenance (RCM) programs know they require a significant redirection and realignment of resources and overtime, resulting in frustration, resentment, resistance and likely failure. Sources cite success rates of 5 to 30% for TPM, RCM and large-scale changes [2,3]. The required work is often viewed as being in addition to 'what we already do'.

The limited resources of a lean workforce in the semiconductor industry require us to instead take a reactive 'forward-looking' approach. This means that instead of sporadic, lengthy, resource-intensive sessions that take deep dives into the often murky waters of equipment history, we can instead establish a smooth continuous process of analysis and actions based on a 30-day performance. Rather than create a thousand actions to address all known failure modes for a machine, we will address the most significant equipment losses *as they occur*, and map and resolve each failure *as they occur*. Think of it as choosing to disintegrate a boulder either by occasionally hefting an unbalanced 100lb sledgehammer, or by chipping at it continuously, knowing that each tap will produce a chip that will take you closer to your goal. This approach may rankle some purist academic viewpoints, but it is necessary to minimize disruption and achieve the desired culture change.

Clean data, accurate metrics, and the ability to breakdown losses

An organization must achieve two fundamental objectives concerning data and reporting:

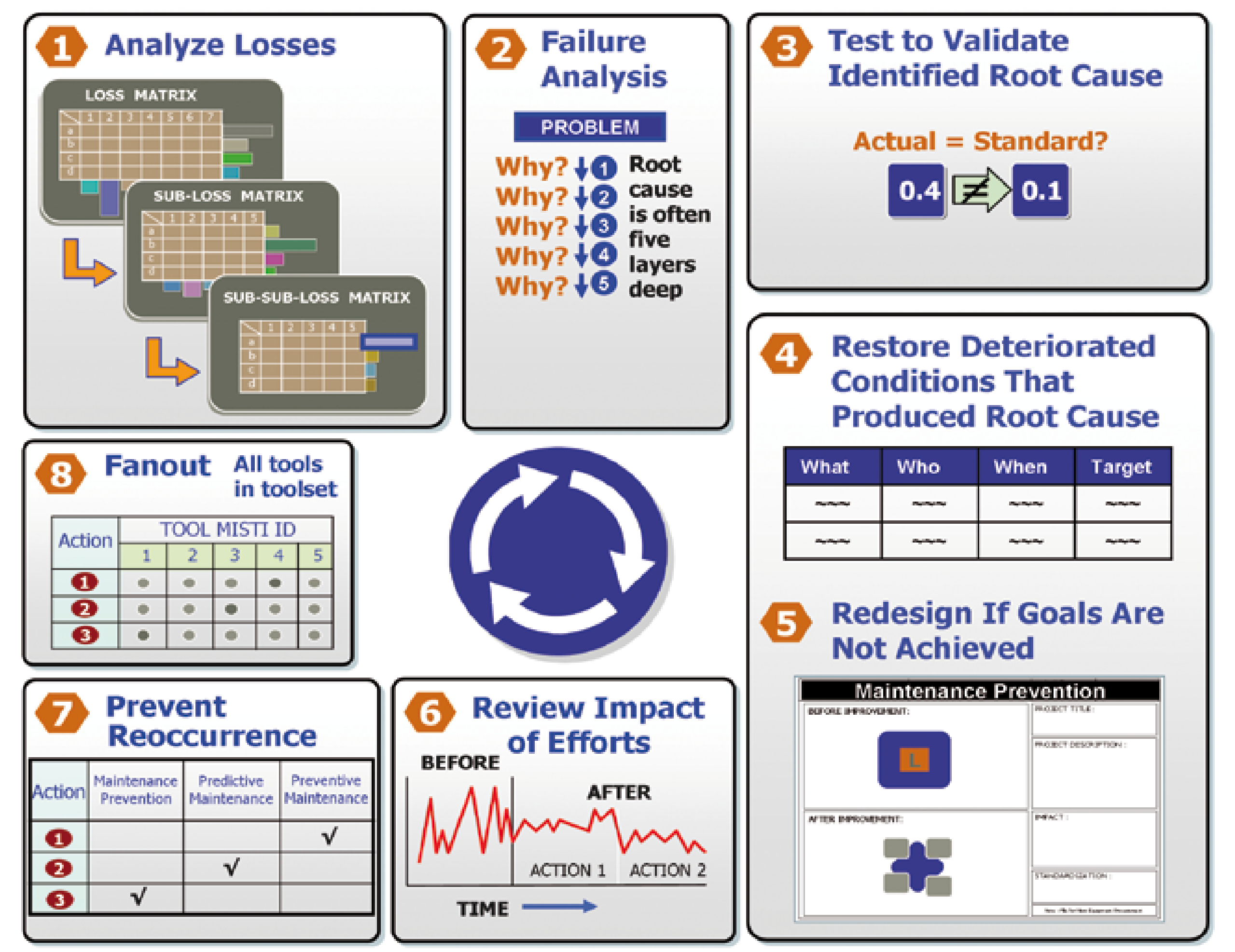

Figure 2. ZUM Methodology: all steps must be completed to ensure elimination of failure modes.

1) *Full transparency of equipment condition and performance.* Human nature dictates that if the capability to manipulate performance metrics exists, some will choose to do it. If the accuracy of your performance metrics is questionable, it will result in perpetual argument and conflict over whether a perceived problem truly exists. The likely result is frustration and mistrust, and what is being concealed will inevitably be revealed in an important customer audit causing embarrassment for the company to the detriment of customer relations. Only full transparency will ensure the organization devotes its time on solutions, and not debate over whether or not a problem exists.

2) *Full access to comprehensive data and tools that will enable anyone in the organization to analyze individual machine losses.* An organization must develop data, systems and clear analytical techniques that enable anyone in the company to confidently quantify equipment performance and quickly break down equipment losses to identify the few issues causing the most disruption to manufacturing. This will ensure that time is preserved for the crucial work of determining root cause and preventive action.

Accomplishing these two objectives will eliminate some potentially gross inefficiencies and sharpen the focus of the organization.

Setting performance goals at the factory and equipment levels

The primary metric used in the ZUM program is equipment availability, or the percentage of time that equipment is available to process production. Goals should be set for the overall factory and each equipment type within the factory. Some will say that working to maintain excellent equipment performance for all equipment types is an ineffective use of resources, because only bottleneck machine performance determines the pace of factory output. However, in fab environments, bottlenecks appear and disappear throughout each day in an unpredictable manner. Therefore applying a proactive maintenance approach to a handful of machines and a reactive fire-fighting approach to the others is not a realistic strategy. In fab environments, all machines are potential bottlenecks, so all require goals that, at a minimum, should represent performance required to meet planned factory output. If a machine or equipment-type does not achieve its goal, it is a potential bottleneck that requires analysis and actions. Working to maintain these goals proactively prevents bottlenecks from occurring.

The overall factory goal is also necessary for measuring overall success and progress for the program, and to ensure performance does not dip too far. As factory equipment performance drops, at some level a 'critical' state emerges. This is a state of particular fragility for the factory, when unpredictability is amplified. At this level, the entire factory is 'sick' and any individual machine failure can cause considerable cycle time delays as alternative routes commonly available are blocked by poorly-performing equipment. A factory that is falling below its known critical performance level should be on high alert due to an exponentially increasing probability of customer disruptions, high costs, safety incidents and cycle time excursions.

The closed-loop equipment problem-solving methodology

Closed-loop problem-solving methodologies are nothing new to complex manufacturing organizations, so it should not seem out of place to apply them to equipment maintenance. Because the challenge of achieving world-class equipment performance is

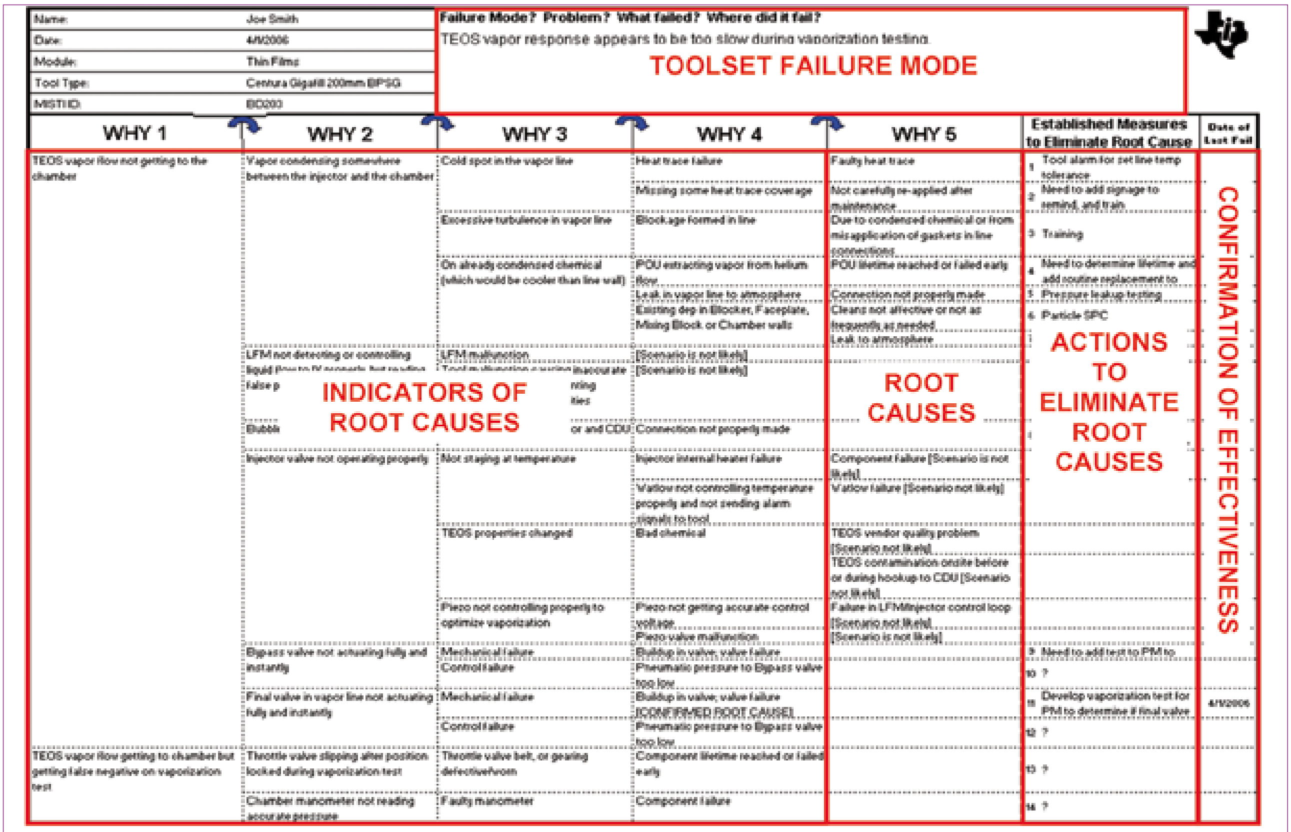

Figure 3. Multi-level 5 Why Failure Analysis is used to capture knowledge, break the cycle of re-learning, quicken troubleshooting and repair, assist root cause analysis and strengthen FMEAs.

so great, the approach to maintenance and problem solving must always be concise and thorough. A closed-loop methodology can communicate these needs and expectations, ensuring everyone's understanding of and commitment to the system. Any skipped step represents wasted efforts and resources, so total compliance is important and should be confirmed.

Pay special attention to Step 7 of the schematic depicted in Fig. 2 which calls for action to prevent reoccurrence. This *Maintenance Decision* represents the difference between simply changing out a failed component and taking action to ensure it does not fail again through redesign, routine replacement, or failure detection. Remember that the overall intent of this program is achieving *Zero Unscheduled Maintenance*, so the Maintenance Decision should be a visible and scrutinized choice.

Defeating chronic problems by mapping failure modes

Chronic problems occur every day in complex manufacturing environments. Due to the complexity of the equipment, it is not uncommon for a failure mode to have 100 or more root causes involving 1000 or more components. The fire fighter assigned to a chronic problem will typically jump in, guess the cause, replace a part, then repeat the process after discovering the guess was incorrect. Such a process could repeat for days, consuming considerable human resource and cost while creating a disruptive bottleneck situation in the factory.

This is not necessarily the fault of the person assigned to the repair. It is simply impossible for someone to retain in their memory all of the hierarchies, interconnections and potential interactions between the thousands of components in these complex machines. Someone in the midst of this type of repair would hear people say things like "I just remembered that the last time this happened we tried…" as the trial and error process stimulates the resurfacing of memories of past repair attempts and findings long forgotten. These machines will fail over and over again for the exact same reason because true component-level root cause was either not sought or not properly documented to break this re-learning cycle.

Resolution of this problem starts with the person attempting the repair seeking component-level root cause. Many are aware of the '5 Whys'; the process that requires the user to ask 'Why?' five times to get to the root cause. Here is a simple example for determining why a room is dark:

Q1: Why is the room dark?
A: No light

Q2: Why is there no light?
A: Light bulb won't turn on

Q3: Why won't the light bulb turn on?
A: Light bulb is defective

Q4: Why is the light bulb defective?
A: Light bulb filament is broken

Q5: Why is the filament broken?
A: Expected life of the filament was exceeded

The root cause for why the room is dark is not a defective light bulb; it is the filament component of the light bulb that had exceeded its expected lifetime. Someone attempting a repair must seek this level of root cause. If they do not, they are willingly sustaining the problem for someone else to resolve.

Expanding on the 5 Why concept, allowing multiple answers to each "Why?" results in something very similar to a Fault Tree Diagram with many branches, each ending with a root cause. This is the "Multi-Level 5 Why". Actions to prevent reoccurrence are mapped alongside each root cause so users are aware of those that have been addressed and those they may encounter in the future (see Fig. 3).

Some may say this type of mapping is the same as what is required by RCM and Fail Mode Effects Analysis (FMEA), but it clearly is not. The first difference is that the Multi-Level 5 Why is simple whereas RCM and FMEA entries are relatively complex. Entries for these simple maps can be done quickly and easily, encouraging collaborative development involving everyone that works with the machines, not just equipment owners or engineers. The second difference is that unlike RCM and FMEA, these maps can be built as root causes are revealed day-to-day, so that the process is not disruptive to the organization. An RCM

PHASE 1		PHASE 2		PHASE 3		PHASE 4	
Establish Basic Conditions		**Correct Weaknesses**		**Periodically Restore Deterioration**		**Predict Equipment Life**	
Establish your ***foundation***, correct gross abnormalities and ensure the basics of Preventive Maintenance are in place.		Optimize ***Corrective Maintenance*** (maintenance after failure) with failure analysis, loss analysis, mistake-proofing, maintenance prevention and skills training.		Optimize ***Preventive Maintenance*** by ensuring concise documentation, execution and effectiveness tracking.		Optimize ***Predictive Maintenance*** by implementing it in a prioritized manner; advanced analyses and increased awareness of R&D opportunities.	
Criteria #1	√	Criteria #1		Criteria #1	√	Criteria #1	
Criteria #2	√	Criteria #2	√	Criteria #2		Criteria #2	
Criteria #3	√	Criteria #3		Criteria #3		Criteria #3	
Criteria #4	√	Criteria #4	√	Criteria #4	√	Criteria #4	
Criteria #5		Criteria #5	√	Criteria #5	√	Criteria #5	
Criteria #6	√	Criteria #6		Criteria #6		Criteria #6	
Criteria #7	√	Criteria #7		Criteria #7		Criteria #7	√
Criteria #8		Criteria #8	√	Criteria #8		Criteria #8	

Figure 4. The 4 Phases Gap Assessment is a structured roadmap that guides users through the process of building the optimal maintenance system for their equipment.

or FMEA is not typically utilized on a daily basis by those working to resolve existing equipment problems.

After a couple of years, a Multi-Level 5 Why should contain a majority of the root causes for that chronic failure mode and, if preventive actions have been applied, the failure mode should no longer be chronic. There are many benefits of using these simple maps: capturing knowledge, breaking the cycle of re-learning, speeding up the troubleshooting and repair processes, assisting root cause analysis and strengthening FMEAs.

Building the maintenance system to improve and reinforce performance

Exactly what is required to achieve perfect maintenance? It is easy for an organization to say that they have not achieved it, but what is "it"? Those asked will likely provide different answers and none would have the complete answer. The result is a factory with no shared vision of what they want to achieve and how to do it. The criteria for this shared vision should be comprehensive and created with input from all departments associated with the equipment. In TPM, this list is called "The 4 Phases", which divides the criteria in four distinct families: Autonomous Maintenance, Failure Maintenance, Preventive Maintenance, and Predictive Maintenance (see Fig. 4). Using this framework, the criteria become two things to the user: a gap assessment that enables the user to understand what it is they are pursuing and where their weaknesses are, and a 'structured roadmap' that guides the user through the process of building an ideal maintenance system for their equipment, starting with their gaps in the first phase and working towards achieving the ideal predictive capabilities in the fourth.

This gap assessment is a very simple tool that will enable the organization to first understand how they can achieve perfect maintenance, determine existing gaps, and then drive them to closure, one machine at a time.

The future of Predictive Maintenance

It has unfortunately proven to be expensive for factories to develop predictive maintenance systems independent of OEMs. This will surely change in the future as OEMs build new capabilities into their tools that will take warning/interdiction modelling and SPC to the component level. Imagine the future when parts are able to communicate condition and degradation levels, and machines have the capability to detect degradation and defects at the component level. Future machines will understand how component degradation and failure will impact other components and subsystems and assess failure probabilities throughout. These advances will take us another level closer to zero equipment failures.

Summary of required steps to implement a ZUM program

Here are the steps that should be taken in order to implement a ZUM program:

1. Achieve the right mindset for your culture change
2. Develop the program to fit into 'what we already do'
3. Achieve clean data, accurate metrics, ability to break down losses
4. Set performance goals at the factory and equipment levels
5. Establish a closed-loop equipment problem-solving methodology
6. Utilize Multi-Level 5 Whys to collaboratively defeat chronic failure modes
7. Utilize 4 Phases Gap Assessments to build your maintenance system.

References

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[3] Bloom, N. 2005, *RCM – Implementation Made Simple*, McGraw-Hill.

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