Developing Overall Equipment Effectiveness Metrics for Prototype Precision Manufacturing

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January 2011

Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Engineer Degree is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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(Michael O'Neill)

Acknowledgements

While we were ultimately not able to complete the project, I would like to thank the operators, technicians and engineers of Company-X who provided the needed feedback to develop a pragmatic process and an effective interface. I would also thank Dr. Paul Young for his academic steering, and my wife Marcy O'Neill for helping to make my work intelligible.

Abstract

Overall Equipment Effectiveness (OEE) is a powerful metric of manufacturing performance incorporating measures of the utilisation, yield and efficiency of a given process, machine or manufacturing line. When associated with the reasons for performance loss, OEE provides the means to compare and prioritise improvement efforts. This research assesses the current systems used in the high-volume production lines of Company-X, a precision manufacturer of computer components. This assessment led to the design of a singular methodology that functions in a high-volume production environment, in the rapid prototyping production, and the program qualification production divisions of Company-X. The methodology defined indicators (Utilisation, Efficiency and Yield), and factors that must be recorded on an individual piece of equipment within a manufacturing line to determine its OEE. These equipment-level records were captured utilising the equipment's computer-controller, supplemented by minimal user input, to minimise the non-value added activities associated with data-entry. The methodology also determined the means to aggregate the records to prioritize improvement activities (Weighted OEE Pareto) and calculate the manufacturing lines overall performance (Overall Line Effectiveness).

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1 Introduction

Overall Equipment Effectiveness, or OEE for short, is a productivity and performance metric that is widely discussed in the manufacturing industry. While the theoretical merits of the metrics are understood and accepted, the application is a challenge to any manufacturing organisation.

One challenge of OEE is the adaptation of a metric primarily used for capacity planning and improvement of high-volume manufacturing performance to a manufacturing environment that performs low-volume prototype builds mixed with extensive product/process development and testing. How can a single system for tracking OEE be deployed in an environment that facilitates prototype manufacturing, product/process development and high-volume manufacturing?

This was the challenge facing Company-X. Despite various systems deployed to track the OEE of its high-volume manufacturing lines, these same systems proved to be confusing and were ultimately rejected when deployed on the prototyping and development lines.

Unless a single system can be designed and developed to track the OEE of all equipment and manufacturing lines regardless of the focus (prototype; development; volume of lines) it cannot be installed and used to improve performance of the overall manufacturing system utilised by the company. This is due to:

1. Company-X personnel whom support prototype, development and high-volume lines will not easily accept three different systems and metrics
2. Company-X will not have a metric that predicts how well a prototype or development product will perform at development or high-volume respectively.
3. Company-X will not be able to create performance goals or baselines for prototype or development line's performance that correlated to high-volume performance.

1.1 Background of Company-X

Company-X is a precision manufacturing company which specializes in components for the hard-drive industry. The company has a practice of developing new iterations of the same or similar products for its customers to win contracts for new programs (future products or product lines). This development process results in the program life-cycle having three phases:

- Prototype Manufacturing (PTM)
- Program-development Manufacturing (PDM)
- High-volume Manufacturing (HVM)

The first is initial prototyping where units (individual pieces of product) are fabricated on stand-alone equipment and standard tooling in batch volume. These units are used by the customer to evaluate the viability of the components in their assemblies. In this phase, the goal of Company-X is to have the shortest lead time from placing a build order to shipping the product. These prototyping build occur at the Company-X's prototype manufacturing (PTM) lines.

Based on this evaluation, the customer will request units, but with an eye to sourcing a high-volume supplier. At this point, Company-X will move from the stand-alone equipment to a coupled line with dedicated tooling which are optimized to meet the product specifications. Low volume manufacturing orders of these units are purchased by the customer to develop and qualify a particular hard-drive design. The goal for Company-X is to provide these units on time, at superior quality and at a lower cost compared to Company-X's competitors who are also trying to qualify their design with the customer. This allows the customer to see Company-X as a viable supplier for the program as well as qualify Company-X and the product design for high volume production. These activities occur on Company-X's program-development manufacturing (PDM) lines.

Upon being qualified as a high-volume supplier, Company-X will establish one or more high-volume manufacturing (HVM) lines to meet the demands of the customer. More often than not this warrants high-volume 24/7 production. Company-X specifically "pulses" the PTM line to evaluate the line's throughput and yield. "Pulsing" is the practice of running the manufacturing-line at maximum capacity and taking the quickest action to restart and stoppages without investigating or resolving root-cause during the build. The pulse is to simulate the line under HVM conditions. Staff would also diligently record the condition which caused the stoppage and any yield loss. The transfer of tooling and equipment from the PDM-focused line to one of the HVM-focused lines was contingent on passing a set of criteria which indicated the line's reliability in producing units at a rate and quality to maintain good profit margins. Should these criteria not be met, engineering would address the issues recorded during the pulse and correct them before the next pulse.

Due to increased and evolving market pressures, the opportunity to prove the line's reliability and to progressively ramp-up to high-volume have been diminished. Customers' expect a qualified program to immediately yield between 50% and 75% units per week per line compared to full high-volume capacity. This market pressure decreased the pulsing and reliability testing activities as Company-X's focus has been on keeping the customer satisfied by meeting the volume rates and commit dates. Failure to meet the volume rates and commitment dates can lead to Company-X not being the preferred supplier on this or future programs.

Engineers within Company-X know and understand Overall Equipment Effectiveness (OEE) as the most reliable measure of equipment productivity. Unfortunately, the company's primary focus is on "Delivery to Commit" and "Customer Incident Reduction". "Delivery to Commit" means ensuring that all manufacturing orders are filled regardless of yield rates manual sorting and over-time. "Customer Incident Reduction" means ensuring the customer does not detect and report an issue with the quality of the shipped units.

The problem with these metrics is that they are captured and recorded at the end of the manufacturing process. While a drop in these metrics will indicate a significant error that the company should respond to, the damage will already have been done with respect to the customer. Their ordered shipment will either be recommitted, with a future ship date determined, cancelled, or contain less than perfect or unacceptable product. None of these outcomes is favourable to the company's long-term relationship with the customer.

Understanding this, the industrial and manufacturing engineers at the company have worked piece-meal over time to establish more predictive metrics. They have established defect tracking systems and down-time tracking systems. In addition, they have established a means of calculating the OEE for each manufacturing line.

To date, the culture at Company-X has not embraced the OEE metric and therefore management has established neither baselines nor goals. There are two keys reasons for this, each of which will be examined in this thesis:

1. Lack of confidence in the accuracy of the metric
2. Lack of use of these metrics in the PTM & PDM phases

The existing methods are not flawless and their shortcomings can quickly be seen by anyone required to interact with these systems: those responsible for capturing the data and those using it. This lack of confidence has a ‘downward-spiral’ effect. With the quality of the metric data output in question, it does not get used. When those at the front-end of the system know that those at the back-end of the system are not using the data, the care and effort they invest the system degrades. This degradation further impacts the quality of the output metrics and the cycle starts over again.

Specifically in the PDM plant, these metrics are viewed as only being important for those programs at the HVM plants. In PDM, builds are low and changes are plentiful. In HVM, volumes are high and the program is qualified and therefore not subject to frequent change. The perception is that it is easier and more valuable to capture, develop trends and address issues with yield, down-time and cycle-time in the HVM line as it is more “stable”. While a “stable” system is undoubtedly easier to characterise than an “unstable” system there is a significant reason as to why this perception exists at Company-X.

To a certain degree, Company-X treats every program as if it was a brand-new product that was not previously manufactured when in reality most programs are following on from previous programs, e.g. the customer used to retail a 10 GB laptop drive and is phasing out that product for a 50 GB drive. Many of the product’s design requirements and components are the same or have some minor evolution. The point being that understanding the manufacturing productivity of the 10 GB program will result in a reasonable baseline of the productivity the 50 GB should achieve.

This understanding needs to be developed for each of the three stages of the lifetime of the program: the concept prototyping (PTM), the low-volume supplier qualification (PDM), and the high-volume manufacturing (HVM). A baseline of all three phases will serve as a means to monitor the new program at all phases. Similarly, understanding the relationship between PTM productivity and the later phases will serve as a predictor of future problems and opportunities before the program does mature to the later phases.

Company-X's existing systems were developed for the HVM plants and then later deployed to the PTM & PDM plant. One key flaw to this is the reliance of the systems to exist in a manufacturing line of continuous, coupled equipment. PTM lines have decoupled equipment and require more manual operation (e.g. the loading and unloading of units to and from equipment) from the personnel. Lack of the systems available in coupled lines resulted in only throughput quantities being manually tracked on PTM to ensure the ordered quantity was achieved.

A compounding issue is that there was no specific focus on making the systems lean; lean referring to the principles of *Lean Manufacturing*[1]. For example, let us assume the yield-tracking system takes 5 minutes of user-time to classify and log a detected defect on a unit. As the productivity of the program should improve over the program lifecycle, the occurrence of these defects should be rare enough that the 5 minutes is a negligible impact on productivity by the time it reaches the HVM phase. In the PTM phase where defects and down-time events are expected and numerous, 5 minutes per occurrence is too significant of an impact to productivity to be ignored. The lack of an efficient system means the volume of work to capture this data is high and therefore not available in an environment where lead-time for shipping is critical.

1.2 Genesis of the project at Company-X

Company-X's systems are not uniform amongst all the equipment and plants, indeed within a single line there are three different methods of recording defects. While this lack of uniformity needs to be progressively removed, it provides the opportunity to compare and contrast the different methods and propose the best alternative. Additionally, the issues with these systems are well documented and understood.

These issues were not previously resolved due lack of a department with the resources and remit to prioritise and address them. Engineering groups either had a customer (product specific) focus or an equipment specific focus. The creation of an engineering role responsible for improving the transition of a program through the three phases became the genesis of an effort to define metrics for determining the productivity of the manufacturing. The department was named 'Operations Manufacturing Engineering' or OME for short.

The author was hired by Company-X as an Operations Manufacturing Engineer to find that no metrics and baseline existed to correlate performance of a PTM or PDM line with a HVM line. The first action of the author in this role was to develop these metrics. The author proposed the development of lean systems that would capture data needed to compile OEE for each individual piece of equipment. These systems would:

- Function in the PTM environment
- Function in the PDM environment
- Function in the HVM environment
- Be accepted and properly used by all personnel due to their ease of use
- Be accepted as an accurate productivity metric by management
- Allow for baselines to be created and OEE goals to be set
- Provide a threshold to trigger preventative and proactive measures to ensure delivery dates and customer satisfaction
- Allow the data from all manufacturing builds to be collected
- Eliminate the need for pulsing by providing pulse-like data for every manufacturing order

It was determined that Equipment-Z, which performs several critical value-added operations, would be used to develop the proposed OEE system. It would serve as the proof-of-concept and ultimately would be used to justify work to expand the system to all of Company-X's equipment.

1.3 Research Methodology

As the Operations Manufacturing Engineer for Equipment-Z, this work was undertaken by the author and is represented in this thesis. While the input and approval of many individuals was required for the testing and refinement of this system, the author performed as system designer and software programmer. The system was then developed, tested and improved in the following manner:

1. Investigate existing methods, both internal to Company-X and in the broader industry, and in academic papers.

2. Devise new approach, one that break the *Information Paradox* as much as possible, and an implementation plan.
3. Review new approach and implementation direct end-users and technical support of end-users before developing code
4. Develop code and implement pilot on specific instances of Equipment-Z for a define period of time.
5. Review and evaluate approach and code the same personnel in step 3:
    a. Make revisions as necessary and repeat steps 3 to 5.
    b. Once final version was agreed upon, proceed to step 6.
6. Review and evaluate performance with Management & Engineering; once approved, changes would be implemented in all instances of Equipment-Z, and plans to develop and implement for all other devices would be executed.

1.4 Chapter Summary

This project will develop a new singular, OEE metric implementation suitable for prototype, program-development and high-volume manufacturing lines.

2 Literature Survey

If a goal is to be achieved it must be measurable. This is particularly true in manufacturing where profit is dependant on the productivity of its people and equipment [2]. As de Ron and Rooda state [3]:

> *[H]undreds of performance measures are being used. Managers want to have one clear metric and dislike the plurality of information.*

As no one traditional metric, such as yield or utilisation, depicts the whole picture. Worse still is improvement on one metric can come at the cost of another [4]. Some aggregate of existing measures is needed. From here forward the term *metric* will be reserved for the aggregated measure while *indicator* will be used for the measures that comprise this metric. It is important that these measures be accurately and reliably captured to ensure any completed activities will lead to improved productivity [5].

2.1 Overall Equipment Effectiveness

There are many potential goals and indicators that can be used. Poorly set goals will lead to inter-departmental conflict [6]. Three commonly used for manufacturing performance [5] & [7]:

- Availability or Availability Efficiency
- Performance Rate or Performance Efficiency
- Quality Rate or Quality Efficiency

While these naming conventions were codified by SEMI, companies such as Company-X often refers to the indicators respectively as:

- Utilisation, U – the usage rate of the equipment, the ratio of actual running of the equipment versus availability of the equipment
- Efficiency, E – the output-rate of the equipment, the ratio of actual speed versus the rated speed of the equipment
- Yield, Y – the quality rate of the equipment, the ratio of good units output versus of total units input to the equipment

Any differences between SEMI and Company-X will be explained later in this report.

A common practice in productivity improvement activities is to:

1. Calculate the indicator, e.g. utilisation of all the equipment in a line
2. Identify which equipment has the lowest indicator value
3. Create a Pareto chart of the reasons for loss on that equipment
4. Focus on reducing or eliminating the top contributors as indicated by the Pareto chart

The problem of using these indicators in isolation is that none convey the actual productivity of the equipment. Consider productivity in terms of units produced within a fixed time frame:

- If the equipment is not available for use, e.g. it breaks down, there will less processing time (hours) and therefore fewer units are produced
- If the equipment runs slower than its top speeds, its output-rate (units per hour) is decreased and therefore fewer units are produced
- If the equipment produces more defects, e.g. a shear die becomes dull, the fewer acceptable units are produced

A singular measure is required to reveal the all the productivity loss. Such losses constitute lost opportunity and non-value-added costs. These costs are of significant importance to any manufacturer; hidden costs in particular [8] & [9]. If a manufacturer assumes only loss of processing time as productivity loss, the cost of slow equipment will be hidden to them.

Utilisation, Efficiency and Yield each contribute to the ease of an equipment to produce quality units in a timely manner. As each of these indicators are a ratio (or percentage) whereby 1 (or 100%) represents the perfect state of the equipment, these indicators can be combined via multiplication of these indicators. This combination is a metric called Overall Equipment Effectiveness or OEE can be seen in Equation 1.

$$OEE = U \times E \times Y \tag{1}$$

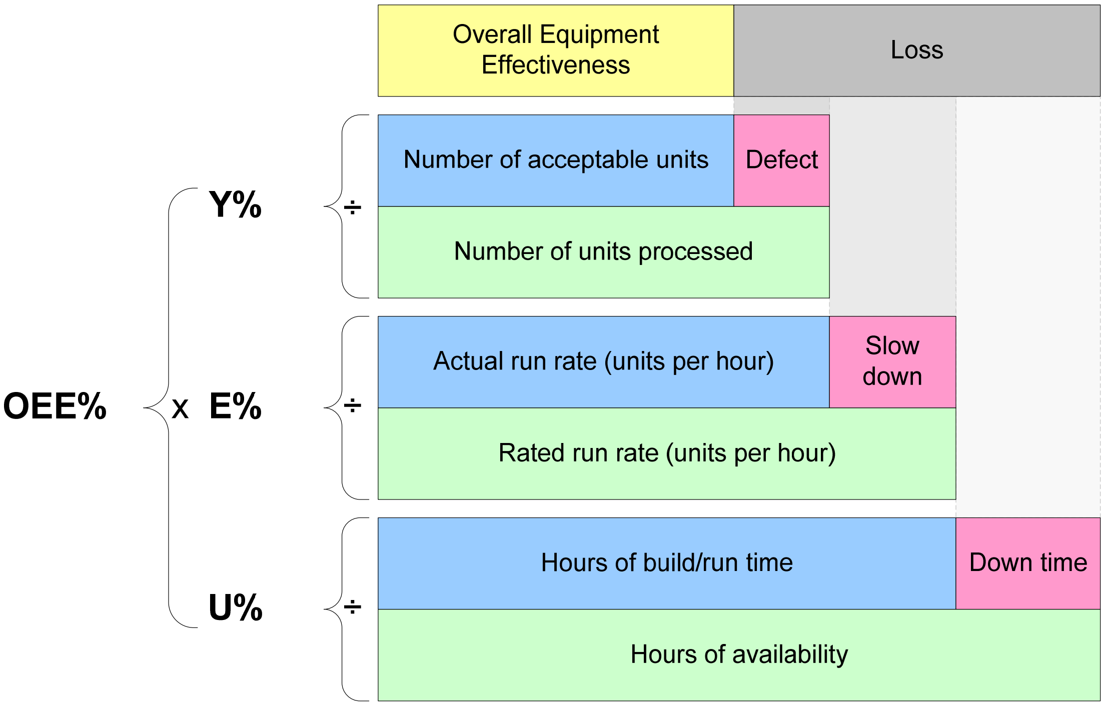


Figure 2-1 Graphical representation of OEE and Losses [10]

As can be seen in the Table 2-1, these three indicators compound each other such that slight losses in any or all three show the more significant loss.

Table 2-1 Cumulative effects of loss on OEE

Utilisation (U%)	Efficiency (E%)	Yield (Y%)	OEE %
0	0	0	0.0
10	10	10	0.1
20	20	20	0.8
30	30	30	2.7
50	50	50	12.5
60	60	60	21.6
75	75	75	42.2
90	90	90	72.9
95	95	95	85.7
99	99	99	97.0
100	100	100	100.0

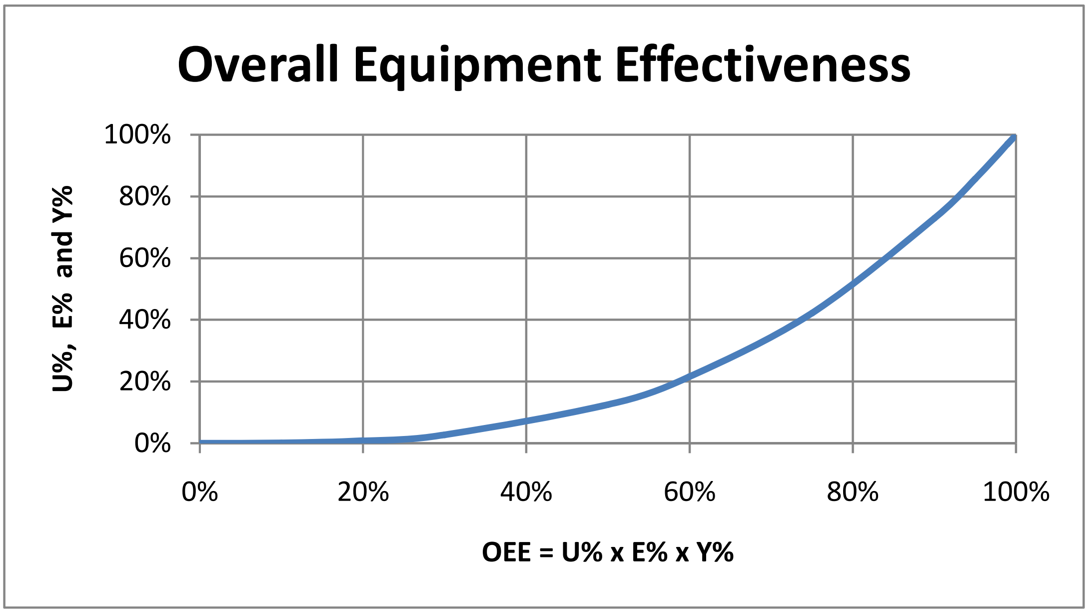


Figure 2-2 Graph showing accumulative affects of loss on OEE

The concept of an OEE of 1 (or 100%) representing the absolute best performance of a machine if often used independently of the three individual indicators. This aggregate shown the ration of how the equipment actually performed versus it perfect state.

The combined indicators often give the OEE metric its definition [11]:

> *[OEE …] indicates the relationship between the actual time that an equipment is producing achieving the specification and quality criteria, and the time that the equipment is schedule to be producing.*

While a ratio by its nature is dimensionless, i.e. it does not have a unit of measurement such as gram (g) or metre (m) deCosta (et al.), suggest that the key unit is time. Others make the case that it is units per a defined time period [12].

$$OEE = \frac{Output_{actual}}{Output_{reference}} \tag{2}$$

Equation 2 can similarly be interpreted with units of product as the unit, and is sometimes referred to as Concise OEE [13].

The following are examples of how Company-X uses the OEE metric. For equipment with a known capability (e.g. the number of good units per hour), it can be used to convey:

1. Potential additional capability – the capacity/throughput of the line if the manufacturing line was performing at 100% OEE [units/time]

2. Potential reduction in manufacturing time per manufacturing order – if line was performing at 100% OEE [time]
3. The number of units-worth of raw material that needs to be input to the manufacturing line to produce the desired number of acceptable units (due to yield loss) – based on current OEE [units]

Table 2-2 contains a worked example of each of these three conveyances: if the equipment has a known capacity of 100 units per hour was utilized 90% of the time, with an efficiency of 99% and a yield of 95%. The current manufacturing order is 200 acceptable units.

Table 2-2 Usage of the OEE metric

Understanding	Example Result
OEE	Utilisation x Efficiency x Yield = 0.9 x 0.99 x 0.95 = 0.85 or 85%
Potential additional capability	Current Capacity = 100 units per hour @ 0.85 Potential Capacity = (100 ÷ 0.85) = 117.6 units per hour @ 1
Potential reduction in manufacturing time	Goal: 200 acceptable units Current Capacity (@ 0.85) = 100 units per hour => Time = 120 min. Future (@100%) = 117.6 units per hour => Time = (120 ÷ [117.6 * 2]) * 200 = 102 min. {15% improvement}
Number of units needed to be input	Goal: 200 acceptable units Current manufacturing time (@0.85) = 2 hours Need:200 ÷ 0.85 = 235.3 ~ 236 sets of raw material to input into equipment

OEE has also been shown to have correlation with process capability metrics (e.g. C_{pk}) [14], and Failure Modes and Effect Analysis (FMEA) metrics [15], and Total Productive Maintenance (TPM) focus areas [16]; three other commonly used tools for maintaining and improving productivity.

2.2 Utilisation Indicator vs. Availability Efficiency

SEMI defines *Availably Efficiency, AE,* as [7]:

> *The fraction of total time that the equipment is in a condition to perform its intended function.*

$$AE = (Equipment\ Uptime) \div (Total\ Time) \tag{3}$$

"Equipment Uptime" can also be termed "Availability" in that the equipment is available to produce units, but may not be currently utilised for that function.

As understood in Company-X, Utilisation, U, is the ratio of time the equipment spent running i.e. producing product versus the total Available-Time:

$$U = \frac{T_{Run}}{T_{Avail}} \tag{4}$$

There is a distinctive difference between SEMI's standard and Company-X's definition. Uptime includes more than just running-time in that it is potential running time and not actual running-time. This means it that *Availability Efficiency* does not include minor stoppages and idle-time events due to operational losses. These losses are captured in the *Operational Efficiency* component of the *Performance Efficiency* indicator. This makes *Operation Efficiency* or Utilisation more difficult to document as unlike *Availability Efficiency* it requires capture and quantification of unplanned events [17].

Another difference in is that SEMI allows for "Engineering Time" to be included in "Equipment Uptime". Staff in Company-X different lines would argue if it similarly be counted with pure production time as T_{Run}. Other companies question similarly question if such non-productive activities can be considered as Down-Time even if the equipment is operable as these are activities that they would aspire to minimise [17].

Available time is typically the total calendar hours within a period of time less the hours of Scheduled-Down-Time.

$$U = \frac{T_{Run}}{T_{Avail}} = \frac{T_{Run}}{T_{Calendar} - T_{Schd}} \tag{5}$$

Scheduled-Down-Time events can include:

- Preventative Maintenance
- Retooling for next build
- Engineering testing.

If Running-Time is not explicitly measured, it is calculated by measuring the non-Running-Time and removing that from the calendar time. This non-Running-Time, or Down-Time, in turn is broken down into Scheduled-Down-Time, Unscheduled-Down-Time and Idle-Time. Idle-Time reflects the time the equipment was operational but was unable to process product. A common example of an idle condition is the equipment not have units feed into it, or the equipment is unable to index to the next unit as the line has stopped downstream.

$$U = \frac{T_{Run}}{T_{Avail}} = \frac{T_{Calendar} - T_{Schd} - T_{Unschd} - T_{Idle}}{T_{Calendar} - T_{Schd}} \tag{6}$$

If all machine time: Running-Time, Scheduled-Down-Time, Unscheduled-Down-Time and Idle-Time is explicitly captured, the total calendar time should equal the summation of all calculated time.

$$T_{Calendar} = T_{Total} = T_{Run} + T_{Schd} + T_{Unschd} + T_{Idle} \tag{7}$$

$$T_{Avail} = T_{Calendar} - T_{Schd} = T_{Total} - T_{Schd} \tag{8}$$

$$U = \frac{T_{Run}}{T_{Avail}} = \frac{T_{Run}}{T_{Total} - T_{Schd}} \tag{9}$$

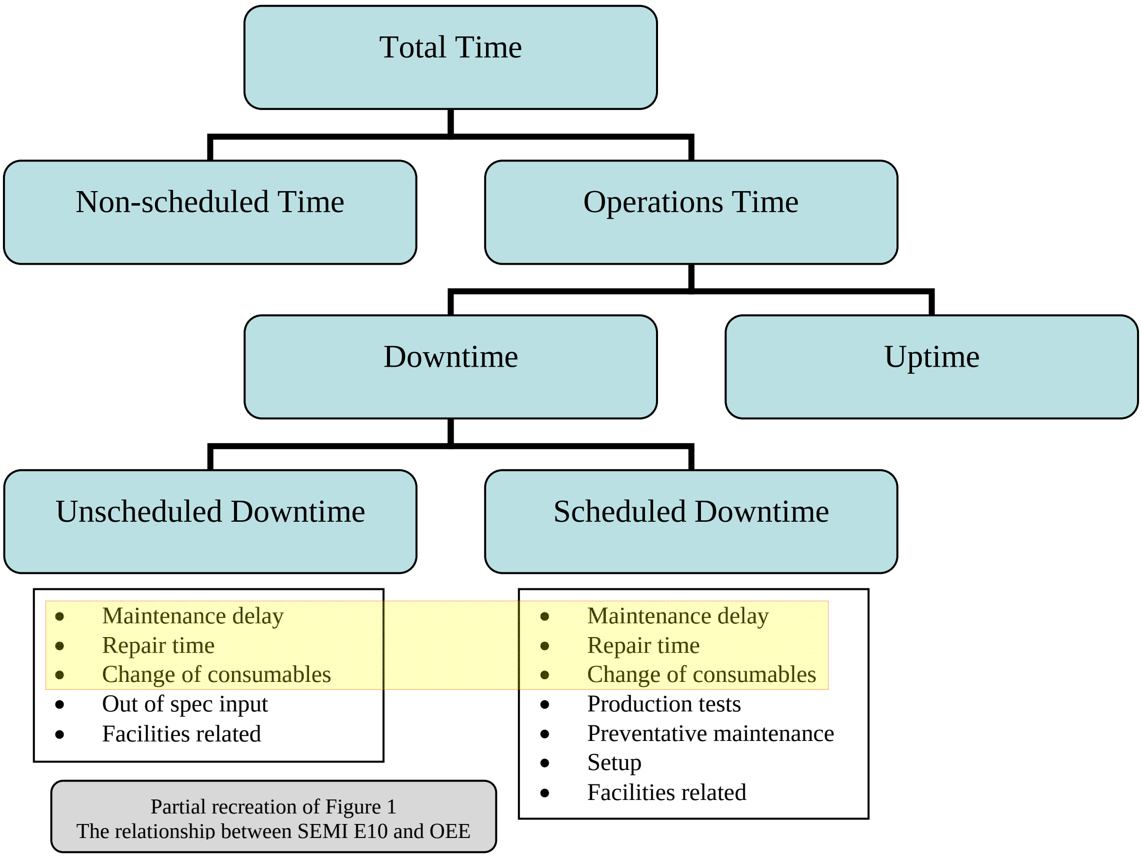


Figure 2-3 Classification ambiguity in SEMI E79 [7]

Within Company-X there has been ongoing debate about which events should really be classed as Scheduled-Down -Time and Unscheduled-Down-Time. Even in the SEMI E79' standard guidelines, Figure 2-3 shows 'Maintenance Delay', 'Changes of consumables' and 'Facilities related' under both the Unscheduled-Down-Time and Scheduled-Down-Time categories

The key reasons for the debate are the different focus and staffing of the lines. High-volume manufacturing lines are intended to run 24/7 (168 hours per week), while the

PTM and PDM lines are intended to run 24/5 (120 hours per week) assuming no overtime. There are those who contend that all lines should be measured equally, but in the HVM plant there are rarely product changeovers due to product-dedicated lines, no engineering testing and no room for overtime.

The simplest solution is to agree to use the straight dictionary definition of scheduled and unscheduled. The PTM environment, however, lends itself to confusion as debug-time is inherent and difficult to quantify beforehand to pragmatically schedule it. Therefore within Company-X, business rules had to be established to consistently communicate uptime/downtime, scheduled/unscheduled status of the equipment.

2.3 Efficiency Indicator vs. Performance Efficiency

With the portion of time in which the equipment was utilised understood, the next question of effectiveness is how well the equipment performed when it was running. SEMI defines *Performance Efficiency, PE,* as [7]:

> *The fraction of equipment uptime that the equipment is processing actual units at theoretical efficient rates.*

$$\begin{gathered} PE = (\text{Operational Efficiency}) \text{ X } (\text{Rate Efficiency}), \text{ or} \\ PE = OE \text{ X } RE \end{gathered} \tag{10}$$

$$OE = (\text{Production Time}) \div (\text{Equipment Uptime}) \tag{11}$$

$$RE = (\text{Theoretical Production Time for Actual Units}) \div (\text{Production Time}) \tag{12}$$

$$PE = (\text{Theoretical Production Time for Actual Units}) \div (\text{Equipment Uptime}) \tag{13}$$

The “Theoretical Production Time for Actual Units” value could be calculated as:

$$TPT \text{ for } AU = (\text{Processed units}) \text{ X } (\text{Theoretical Cycle-time}) \tag{14}$$

The Theoretical Cycle-time value still has to be determined. In Company-X’s case Equation 13 was typically used as a line metric with a “rule-of-thumb” Theoretical Cycle-time value, e.g. 1.86 seconds per units, was used. Theoretical Cycle-time can be selected from [18]:

1. The cycle-time rated by the equipments manufacturer
2. The shortest cycle-time on record for that equipment while utilised in production
3. The theoretical cycle-time on an ideal condition

The third option is not expanded upon. Rather than speculate, the first two options show a lot of room for ambiguity. The first is a measure of pure equipment speed; the second can include dependencies on loading and unloading of units to and from the equipment.

Company-X did not have a true equipment-level *Performance Efficiency* indicator. Their utilisation indicator already absorbed some of the *Operation Efficiency* portion of the *Performance Efficiency*. This is because Running-Time excludes the difference between “Equipment Uptime” and “Production Time”. What remains to be accounted for is purely *Rate Efficiency*, which Company-X simply referred to as Efficiency.

Efficiency can also be expressed in term of cycle-time [18]:

$$E = \frac{CT_{Theory}}{CT_{Actual}} \tag{15}$$

This equation can be altered to express Efficiency in terms of Units per Hour or UPH. This is particularly helpful when the cycle-time itself cannot be measured, but units can be counted and production time recorded:

$$UPH = \frac{3600}{CT} \tag{16}$$

This formula can be reworked to be expressed in terms of cycle-time, CT, which is often expressed in seconds (3600 seconds in an hour):

$$CT = \frac{3600}{UPH}\text{, assumes cycle-time is in seconds} \tag{17}$$

$$E = \frac{3600}{UPH_{Theory}} \div \frac{3600}{UPH_{Actual}} = \frac{3600}{UPH_{Theory}} \times \frac{UPH_{Actual}}{3600} = \frac{UPH_{Actual}}{UPH_{Theory}} \tag{18}$$

Improvement of efficiency within Company-X was viewed to be very difficult as where equipment-speed is immediately adjustable, via a motor-controller for example, it was set to 100% or top speed. Foster et al [19] show that with data speed loss analysis is possible and can lead to improved productivity.

2.4 Yield Indicator vs. Quality Efficiency

With the amount of time the equipment is running, utilisation, and the efficiency of the running-time to process units, *efficiency*, known the remaining overall effectiveness question is how many of those units produced are acceptable?

SEMI defines *Quality Efficiency, QE*, as [7]:

> *The theoretical production time for Effective Units[, the number of units processed by the equipment that were of acceptable quality,] divided by the theoretical production time for Actual Units[, the number of units processed by the equipment during production time].*

The SEMI standard does not suggest that there is a different theoretical production time between an "Actual", "Effective" or defective (not explicitly defined) unit. The worked example in Appendix 1 [7], show the same-time used. Thus allows the *QE* formula to be simplified:

$$QE = \frac{u_{Effect} \times T_{Theory}}{u_{Actual} \times T_{Theory}} = \frac{u_{Effect}}{u_{Actual}} \qquad (19)$$

This equation is similar to the classic yield formula, Equation 20, which was used in Company-X. Classic Yield, modelled in Figure 2-4, is the ratio of units input to the equipment to the units of acceptable quality output from the equipment. Rejects refer to scrapped or reworked units [20].

$$Y = \frac{u_{out}}{u_{in}} = \frac{u_{in} - u_{rejects}}{u_{in}} \tag{20}$$

Yield, most often expressed as a percentage, is use to express the ability of the equipment to produce quality product e.g. equipment with a yield of 90% will output 90 quality units for every 100 units input to the equipment.

It is also common practice to use the inverse of the yield indicator, referred to as the Defective Ratio: 100% - 90% = 10% defective. The circumstances where this cannot be used will be discussed in a later section.

$$D = \frac{u_{defect}}{u_{in}} = \frac{u_{in} - u_{out}}{u_{in}} \tag{21}$$

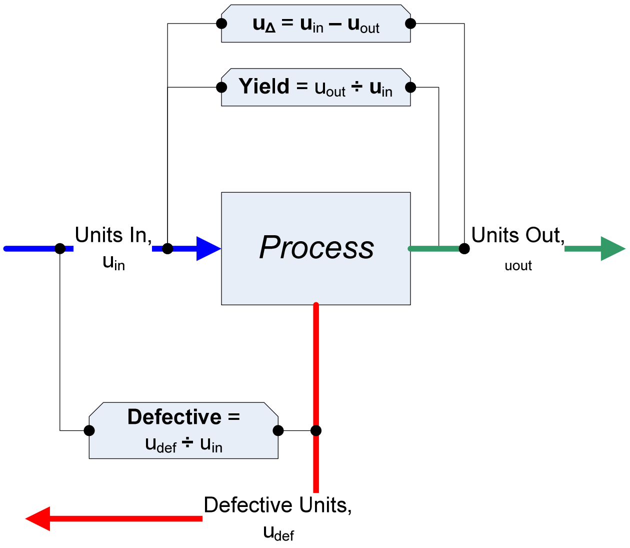


Figure 2-4 Basic model of capturing yield indicator from its factors

Pristine Yield, or Rolled Throughput Yield (RTY), is a yield indicator which more clearly reflects the cost of rework in the process [21].

Consider the classic model in Figure 2-4, with the addition of a rework loop, Figure 2-5.

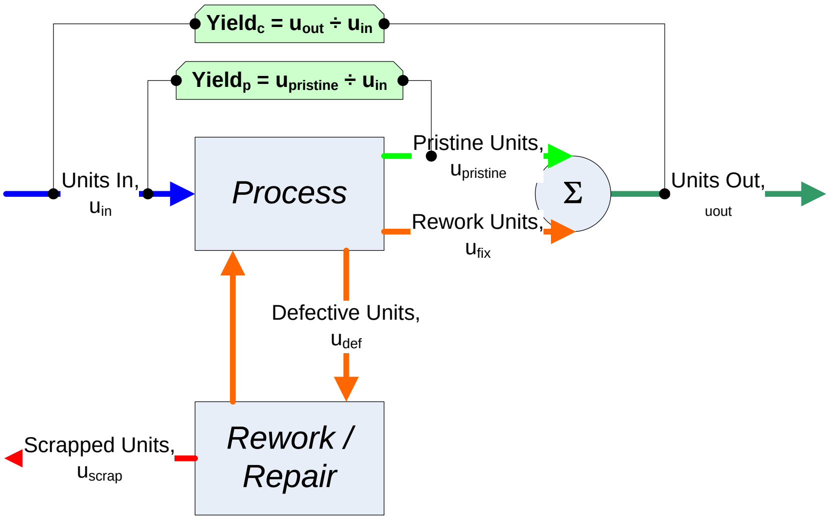


Figure 2-5 Model of capturing yield factors with pristine units

The unit-out count is a summation of the count of pristine units and reworked units.

$$u_{out} = u_{pristine} + u_{reworked} \tag{22}$$

Pristine meaning these are units which are produced by the equipment without failure, rework and or repair (right first time). A rework unit costs more to make than a pristine unit due to disposition time, debug time, repair time, resources, transport, reprocessing, etc. Looking at the classic yield indicator, it can include units that have been reworked multiple times.

In an example of there being two units per processed through some inspection or tester equipment: one unit passed normally, the other failed and is reworked three times before ultimately passing. With the classic model the units-out count would be two. Therefore the yield value would be 2÷2 = 100%. Such a value would indicate that there is no room for improvement with this product/line, and therefore the cost of rework would go unchecked.

The Rolled Throughput Yield, Y_{RT}, however which only counts the number of pristine units out would show a yield value of 1÷2 = 50%.

$$Y_{RT} = \frac{u_{pristine}}{u_{in}} \tag{23}$$

With this indicator, there is a relationship between the cost of rework and the processes productivity such that an improvement of the equipment will lower the costs.

2.5 Cause Data & Pareto Charts

Metrics and indicators are a necessary and powerful tool to track productivity, identify trends and present opportunities for improvement. Indicators will not provide enough information to capitalize on these opportunities [22]. It is not enough to know what your OEE is. It must be coupled with the information that indicates why the metric is as low (or high) as it is [3]. Indeed lack of this information is why establishment of OEE has proven difficult for many companies [23], [24].

For example, a yield indicator is only effective if the type and source of the defects are also known. From here forward in the report, the complementary data the provided context to performance indicators is referred to a cause data. This cause data can be used to determine trends and root-causes, and implement improvements internally within the company and external with equipment suppliers [25].

With the defect information that corresponds with the yield information, a Pareto chart like Figure 2-6 can be built to indicate the priority defects which should be tackled to improve the yield of any given equipment and therefore the line. A Pareto is recommended as it will highlight the fewest number of issues that have the highest impact [26].

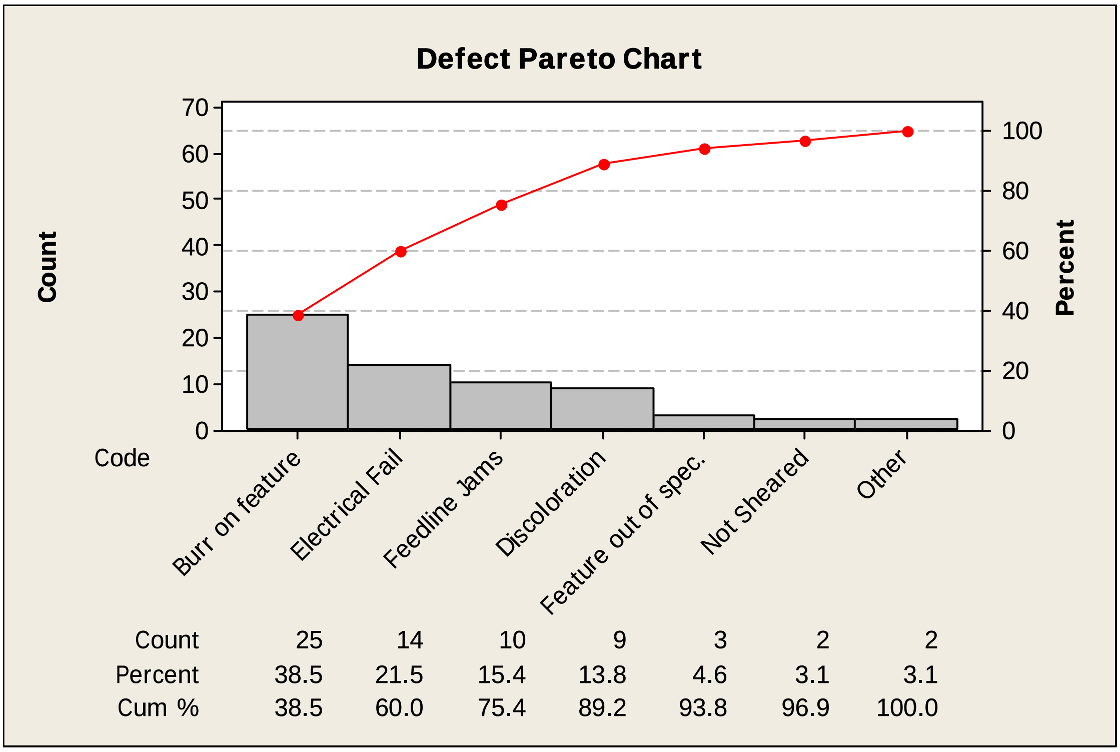


Figure 2-6 Example of a Pareto Chart

The “Grand Pareto” [27] is a concept where the cause information, specifically yield loss – defect information, from across the line is pooled together to make one overall Pareto. Rather than have individual defect Paretos for each singular piece of equipment, the data from all the equipment is combined. This compares and contrasts all issues across the line, so the biggest opportunity for improving product’s yield as a whole is undertaken.

This Grand Pareto concept was further developed into a “Weighted OEE Pareto” which is discussed in a later section.

2.6 Overall Effectiveness Line Metrics

No equipment operates in isolation [28]. Even a CNC machine is dependant on a process to supply it material and reset it for the next job in a timely manner. Equipment in a manufacturing line is dependant on the equipment up and down stream to it. The productivity of the line, and the appropriate loss and cause information is needed.

The system to be implemented in Company-X required the means to “roll-up” the metrics and indicators of each piece of equipment in a decoupled, modular or fully-coupled production line. While this is a topic that has been researched before, as Dal (et al.) put it [8]: “There appears to be little empirical evidence of OEE being deployed within batch manufacturing environments.” Muchiri and Pintelon go so far as not recommending OEE for batch-volume manufacturing due to the as often one instance of equipment can be used in place of another (say one requiring maintenance) and therefore the productivity of one does not affect the line [29]. However, others suggest an “Accumulative OEE” can use data from each equipment used by a batch-volume manufacturer [30].

As the overall effectiveness of a piece of equipment is an aggregate of three factors, a basic model for a line’s overall effectiveness (OLE) would start with being derived from its indicators.

$$OLE = U_{LINE} \times E_{LINE} \times Y_{LINE} \tag{24}$$

Two rule of thumb practices [31]:

- Average of all equipment in the line which will not account for contributing factors, e.g.

$$U_{LINE} = Avg\left(U_1, U_2, U_{3,} \ldots, U_n\right) \tag{25}$$

- Multiply the contribution of all equipment in the line which does not reflect the “bottleneck” of the line e.g.

$$E_{LINE} = Avg\left(E_1 \times E_2 \times E_3 \times \ldots \times E_n\right) \tag{26}$$

The line’s “bottleneck” is the equipment which is the proverbial weakest link in the chain. Its productivity is the lowest, so it will cause all equipment upstream to slow down as the feed the bottleneck. Likewise it will prevent the downstream processes from being used to their full potential. The processes up and downstream of the bottleneck will have their productivity directly impacted by the bottleneck and not through their own loss.

One proposed solution is base OLE on two indicators [31]:

$$OLE = LA \times LPQP \tag{27}$$

LA, or *Line availability,* being the ratio of the Running-Time of the last piece of equipment on the line versus the Availability-Time of the whole line. This simplifies the line’s utilisation down to how well the line’s final equipment is kept running.

LPQP, or Line production quality performance, is a merging of Efficiency and Yield indicators. LPPQ being the ratio of the amount of u_{out} at the last process times the bottleneck equipment’s actual cycle-time versus the Running-Time of the first equipment on the line. This simplifies the line’s yield and line’s efficiency into one factor. The line’s yield is represented by the number of pristine units at the end of the line. The line’s performance is represented by the actual speed of the bottleneck. The Running-Time of the first equipment is used as that is where the u_{in} of the line occurred.

$$OLE = \left(\frac{T^{n}_{Run}}{T^{Line}_{Avail}}\right) \times \left(\frac{\left[u^{n}_{out} \times CT^{BTN}_{Actual}\right]}{T^{1}_{Run}}\right) \tag{28}$$

While being model that is reasonable to implement its accuracy and use to Company-X gets called into question [12]:

> *OLE provides good results only if applied to a continuous production line: when buffers or decouplers are displaced between the machines, the hypothesis made to evaluate the*

> *[operational time of any specific machine] do not apply. Actually when there are buffers in the line, a [downstream] machine can keep on manufacturing even if the preceding machine is down and so on.*

The very nature of batch manufacturing on decoupled equipments results in Company-X having extensive buffers in the lines. There are often occurrences of upstream and downstream process running while some intermediate equipment is experiencing Scheduled-Down-Time.

A counter proposal is made by Braglia (et al.) [12] for the Overall Equipment Effectiveness of a Manufacturing Line (OEEML):

$$OEEML = \frac{CT_{Theory}^{BTN}}{CT_{Theory}^{n}} \times \left(A_{PM}^{n} \times A_{ext}^{n} \times OEE_{n} \right) \qquad (29)$$

The OEE of the line's last piece of equipment (OEE_n) is used in conjunction with:

- A_{ext} = utilisation loss due to circumstances independent of the equipment e.g.:
    - Not receiving parts from upstream due to some failure upstream
    - Not dispatching parts to downstream due to some failure downstream
- A_{PM} = utilisation loss due to preventative maintenance of the equipment
    - Preventative maintenance is not considered a loss for the equipment being serviced
    - The rest of the line is impacted as this equipment is unavailable
- The ratio of the ideal CT^{BTN} and CT^{n} allows for any performance losses not due to the bottleneck to be counted

2.7 Data Collection and Cross Functional Teams

The OEEML proposal [12] while arguably more accurate, is more complex than the OLE proposal. Complexity of the mathematics to derive a line metric from equipment indicators is not a critical issue to ensure a successful system. Indeed, the metric should be as simple as possible in reflecting where improvements should be made [32]. The four most critical issues are:

1. Ease of data-capture [22] & [23]
2. Data is accurate [22] & [33]
3. Consistent use of metrics [22] & [24]
4. Buy-in from management and users [22] & [34]

"If the magnitude and reasons for losses are not known, the activities will not be allocated towards solving the major loses in an optimal way" [3]. It stands to reason that the greater the ease of gathering this knowledge the more data there will be to solve the major losses. The data needs to be gathered, analysed and acted upon while there is opportunity to reap the benefit of improvement [35], e.g. before the next built of the same product which had low yield rates.

Bamber (et al.) [36], Nakajima [37], Liker [1], as well as other proponents of the principles of *Lean Manufacturing* within Company-X recommended empowering the equipment's operators, those closest to the line, to collect the loss and reason for loss. As these operators are also tasked with keeping the equipment fed and operating, the task of data-collection needs to be simplified.

For example, rather than have a form with the loss categories for every possible type of loss on the line, the form can be tailored to contain the losses for the equipment in question [5]. There are proponents for using digital collection into a spread-sheet, webpage or software application, over a pen and paper form. A digital form is not a replacement for easy categorisation. A digital form will allow for more efficient collation and reporting of the collected data. The design of digital forms is often biased towards the reporting and not the ease of collection. Engineering might want to capture the root-cause of every loss, but the level of detail that would require would typically require a lengthy and complex form, be it paper or digital. The more fields and choices provided the greater the risk of:

- 'Analysis paralysis', operator taking too long to decide, which itself could impact productivity
- 'Pick any', make a random choice to complete one task and move onto the next

With fewer choices, it is easier for multiple users to be consistent in their categorisation. The challenge becomes how (or who) to decide on the categories. While many papers cite Nakajima's six major categories of loss [37], some individually recommend specific interpretations. In comparing the whole they demonstrate difference in interpretations. Bamber (et al.) [36] shows the importance of using cross-functional teams (CFT) within a company to develop its "own classification framework for losses". Such a CFT could well be the same group tasked with improving productivity based on the data gathered [20], and will be best positioned to perform the necessary root-cause analysis [38].

This self-classification tends to relate to what the company's personnel already understand and is most likely to be maintained. This maintenance in turn will allow for metrics, indicators and cause-data to be consistent. Consistency in turn will allow for successful improvements to show up in the data. To this end, automation of the capture and classification will ensure consistency [9] while eliminating tedious, manual tasks [25]. Loughlin [39] recommends "Generation 3 OEE" system which integrates with the equipments controller (PC and/or PLC) to capture indicators and potentially categorise loss.

Even the OEE metric can be customised and tailored [34]. There are proponents of different flavours of OEE for different applications [40]:

- Simple OEE – Ratio of actual output versus theoretical output (same as discussed in previous section)
- Production OEE – OEE exclusive to production time, i.e. effectiveness of the equipment when processing units
- Demand OEE – OEE relative to the production schedule i.e. how effective the equipment is used during scheduled activities

All these different applications underscore the idea that a company needs to choose the classification and calculations that will allow them to learn and approve their productivity. This in turn will lead to acceptance of the system by users, with is critical for a system's continued success.

3 Development of Lean Data Collection

There is a paradox when it comes to data collection for equipment/process improvement within a manufacturing facility either attempting to or practicing Lean Manufacturing [1]. This will hereafter be referred to as the *Information Paradox*:

- Actions based on good information are VALUE ADDED.
- Actions to get good information are NON-VALUE ADDED.

While it is often acknowledged that there is waste inherent to any process that may never be feasible to eliminate, the bigger issue is that data collection is often an after-thought. The solution to break the *Information Paradox* is simple in concept: the process must provide good information with no extra work. The act of physically performing value-added tasks (work-flow) should result in the relevant data being generated and collected (data-flow).

Company-X's practices provide good illustration of how a process's data-flow that is disconnected from or done in addition to the process's work-flow causes data-integrity issues. Conversely, through leaning the process the data-flow can be integrated into the work-flow.

3.1 Initial Data-collection practices

Company-X's data-collection practice with respect to OEE is to capture and characterize all incidents of yield loss and utilisation loss that occur on any given line. A worst-case example best illustrates the waste present in their initial practice. The full process in this example may not be used on every instance of loss but there is the potential for it to occur.

The business process model shown in Figure 3-1 represents the initial process with the green squares showing the physical work the operator needs perform to get the equipment operational.

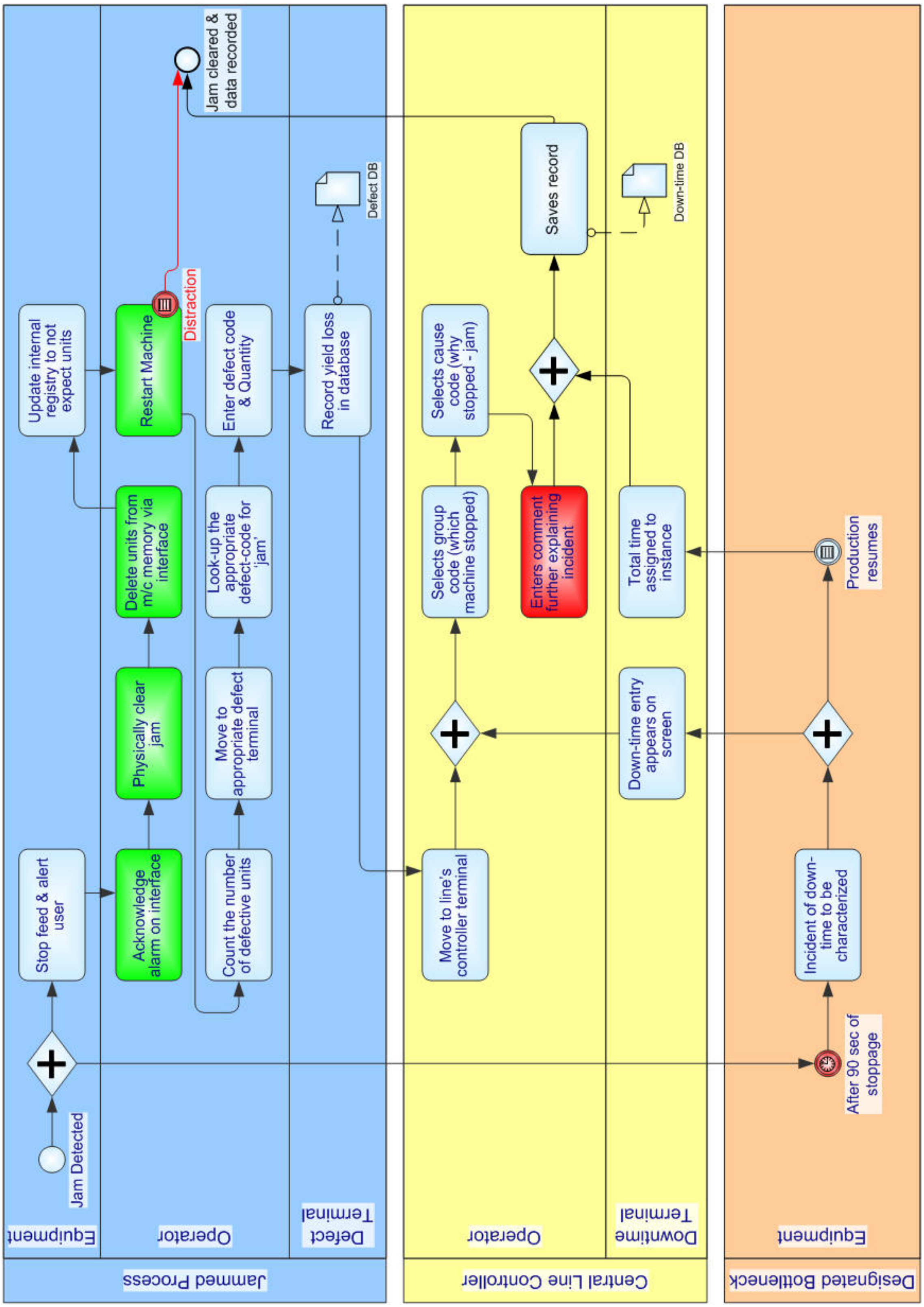


Figure 3-1 Data capture process with *muda*

These practices have some key flaws that warrant address:

1. It was possible to detect a defect incident and not record it (red shape and arrow in Figure 3-1's Jammed Process / Operator region)
    A. The operator was predisposed to remain monitoring the equipment where the incident just occurred
    B. The operator had to remember to move to the defect terminal and enter the relevant information
    C. If the distraction was due to another defect incident occurring, the initial incident might never be recorded
2. It was possible to detect a downtime incident and inaccurately categorise it:
    A. Operator had to travel from the equipment to a centralised computer system to determine if the system detected a downtime incident greater than ninety seconds
    B. The operator tended to check a couple of time per shift, by which time their memory of what caused each captured incident was poor.
    C. Additionally, users had to type comments (red shape in Figure 3-1's Central Line Controller / Operator region) to provide enough detail to categorise downtime incidents. This made the data highly inconsistent.
3. Only down-time incidents greater than ninety seconds were captured and recorded (red shape in Figure 3-1's Designated Bottleneck / Equipment region)
    A. This was an existing business rule at Company-X
    B. On HVM lines any downtime lower than that was considered 'minor' loss and resulted in productivity losses that were not reflected in any metric
4. The designed system had to be able to conclude that the need for all downtime incidents to be captured did not result in over tasking operators with data-collection activities.

3.2 Leaning the data-collection process

A cross-functional team was brought together to review the Initial Data-collection practices in Figure 3-1 as a Kaizen event [1]. The first suggestion was to remove the motion to other terminals to enter data by moving these terminals closer to the equipment. These "extra" terminals were originally created when the equipment was not networked and had no means to directly transmit data. Much of the equipment had since been updated to utilise local and wide area networks. That allows recording to and querying from databases. It was decided that rather than move a terminal with a single tracking application, the application itself could be placed on the equipment's graphical user interface.

The next suggestion was to have the equipments' software to record down-time incidents automatically as well as defect incidents. As will be shown later, Company's X's equipment has this capability, albeit in an inconsistent fashion. Additional programming and sensors would add this capability to all equipment.

The only critical issue with this suggestion is that the equipment may not automatically know the reason for which it is stopped. It will know that it is stopped and that units have been removed from it. The operator will need to provide the reason. Rather than type in the reason, the interface by which the operator provides this information can be setup to provide only the relevant categorization for that equipment. The value of typed comments was also demonstrated to be minimal and often used as a substitute for better categorization.

Figure 3-2 shows Company-X's current processes with proposed changes that reflect these ideas.

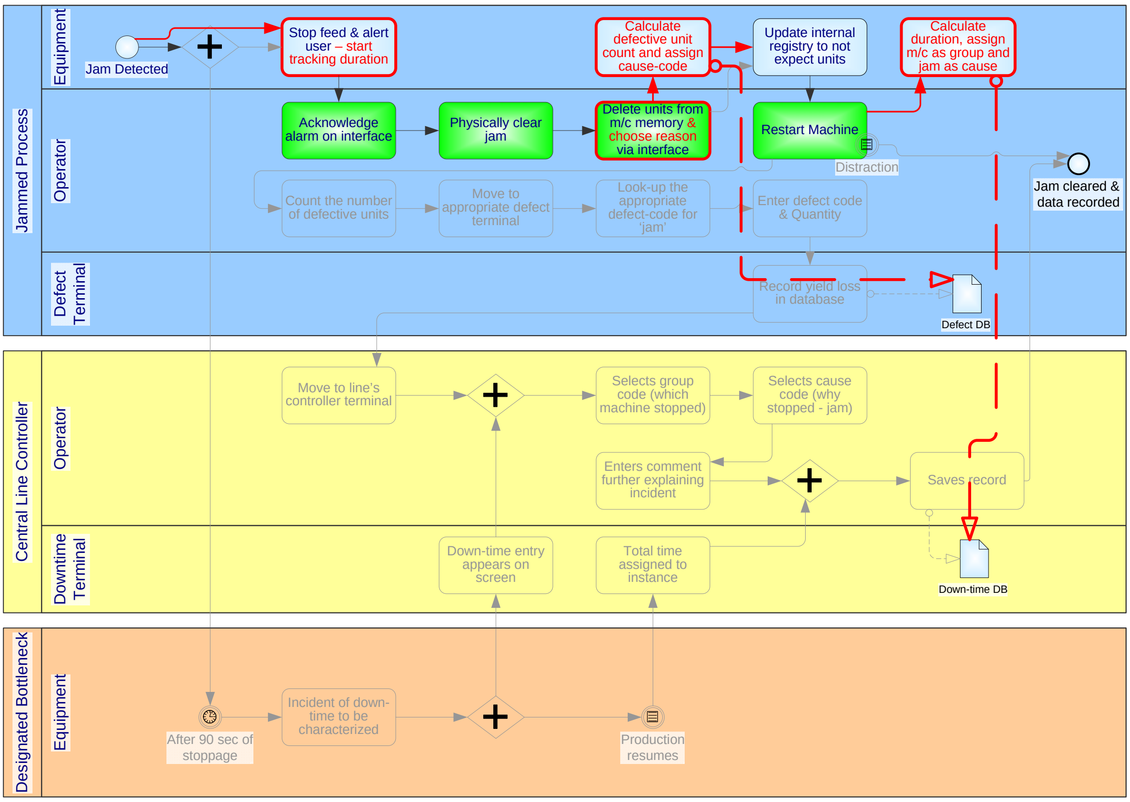


Figure 3-2 Data capture process with indicated changes

3.3 Proposed data-collection process

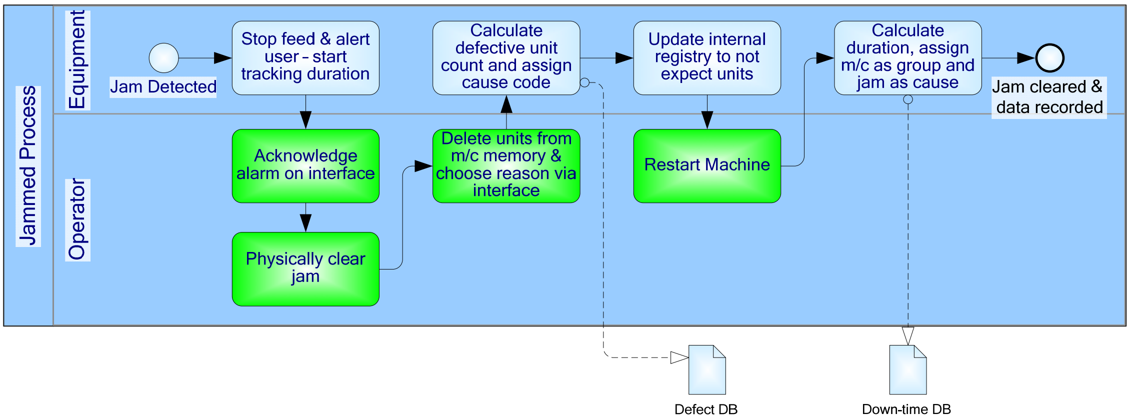


Figure 3-3 Proposed, lean data capture process

Figure 3-3 shows the final proposed data-capture process. Beyond being a more lean process and adhering to conceived solution of the *Information Paradox*, there are several key benefits of this proposed process over the existing process at Company-X:

- Data is captured at each equipment independently
- Data is captured before the equipment resumes running
- This capture model will work for all three phases of Company-X's manufacturing

- Overlapping down-time instances are captured
- Operator can focus on value-added process and not be concerned about extra data-capture tasks
- This model allows for equipment Running-Time and Idle-Time to be explicitly captured as each equipment will report out it's own time to a database
- Removal of defect capture terminals

3.4 Chapter Summary

The proposed data-collection process, Figure 3-3, formed a model which was then developed, tested and improved into the system that would be implemented.

4 Development of Utilisation Capture

As the proposed Lean data-collection process, Figure 3-3, allowed for all time to be captured and categorised, an indicator with explicit factors, Equations 7 & 9, were chosen:

1. Time where the equipment is running i.e. processing units, T_{Run}
2. Time where the equipment is idle, could have run but did not, T_{Idle} e.g. lack of units being feed into the equipment
3. Time where the equipment is unable to run due to some unscheduled event, T_{Unschd}
4. Time where the equipment is not run due to some scheduled event, T_{Schd}

The issues affecting the accuracy of these factors will now be examined. Particular emphasis will be placed on the issues which arose in developing the system for Equipment-Z.

4.1 Time where the equipment is running

Prior to this project, the only time captured within a Company-X line was the time a designated piece of equipment in the line had stopped for a duration greater than ninety seconds. Line Running-Time was inferred as calendar-time less all non-Running-Time. Equipment Running-Time could similarly be inferred as the calendar-time less the all non-Running-Time assigned to that particular equipment per Equation 6. This inference would ignore any incidents were multiple pieces of equipment experience overlapping or simultaneous downtime.

To address this inaccuracy, the Running-Time of each piece of equipment would have to be explicitly captured. Equipment-Z was pre-programmed to understand when it was running. The internal software sensed if:

- There was a unit ready to be processed
- There was an available space to unload the processed unit
- All internal stations were ready to process
- All the safety interlocks were closed

- The operator had pressed that start button

If the software determined that the answer to all these questions was yes, it concluded that the equipment was running. There was no issue with this logic, although the frequency at which this detection was performed came into question while improving the equipment's idle tracking (Section 4.2).

The key issue here is that while the equipment understood when it was running, it was not recording in a manner that would allow this information to be quickly queried and reported.

Prior to the project, the equipment's event log would record when it status turned to "Running", "Idle", "Alarmed" or "Stopped. This record occurred only at the start of the event and it could not therefore include the duration of the event. The basic structure of this event log can see in Table 4-1.

Table 4-1 Basic structure of Equipment-Z's event log

Event ID	Type	Event Text	Event Parameter	Event Timestamp
1002	Status	Machine Idle	2	03/09/08 12:54:09
1001	Status	Machine Running	1	03/09/08 13:15:48
1003	Status	Machine Stopped	3	03/09/08 13:56:10

From Table 4-1 it would be possible to record the difference between the timestamps of two records. The duration of the "Machine Running" for example would be the difference between 03/09/08 13:56:10 {when the equipment became "Stopped"} and 03/09/08 13:15:48 {when the equipment became "Running"}, forty minutes and twenty-two seconds.

While this calculation is simple, it adds a requirement that a regular query using Standard Query Language (SQL) from a data-table cannot meet. This is because SQL is only able to perform aggregate mathematics such as summation, average, maximum and minimum between records (rows of the table), and other mathematics such as subtraction between fields (columns of the table). It is unable to subtract one row from the next row.

There are two alternatives to provide the event duration:

1. Creation of a software process to extract these records two at a time, perform the subtraction math, and populate another table that can be easily queried for the duration
2. Have the equipment software calculate the event duration an post it to the event-log

The second alternative was chosen for variety of reasons:

- It allowed for the existing data-tables to be used, while the first alternative would require new data-tables
    - These data-tables would have to be created on a test database and not the live, production database
    - The need of the test database would have made any developing of the system on a line processing real units impossible
- The equipment could perform the calculation more quickly in real-time than any post-processing could
- The equipment's interface actively displays the event log on its user interface – operators would be able to see the durations as they were recorded

The equipment software was modified to perform the calculations and record the events per the process shown in Figure 4-1.

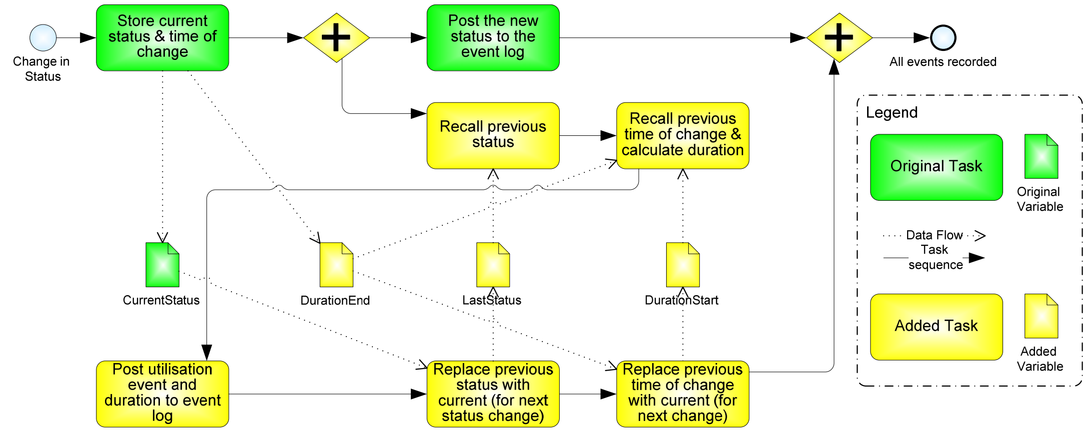


Figure 4-1 Process of capturing equipment time

Table 4-2 shows the events as this modified software would record them. Each change of status (status event) recorded was coupled with a completed utilisation event. The Event Parameter field for the utilisation events contains the duration of the completed utilisation event. This example shows the duration in seconds although more resolution, down to of a 10,000th of a millisecond, was available via the software.

Table 4-2 Equipment-Z's event log with utilisation events

Event ID	Type	Event Text	Event Parameter	Event Timestamp
1002	Status	Machine Idle	2	03/09/08 12:54:09
6001	Utilisation	Prod Run Time	7442	03/09/08 12:54:09
1001	Status	Machine Running	1	03/09/08 13:15:48
6002	Utilisation	Prod Idle Time	1299	03/09/08 13:15:48
1003	Status	Machine Stopped	3	03/09/08 13:56:10
6001	Utilisation	Prod Run Time	2422	03/09/08 13:56:10

As will be explored later, other information was "packeted" into the Event Text for ease of reporting. "Prod Run Time" was ultimately reserved for production running, and no other distinguishing information was needed.

4.2 Time where the equipment is idle

As Equipment-Z would be part of a coupled PDM or HMV line or a decoupled PTM line, there would be times the line would be down that were not induced by Equipment-Z. On these occasions, Equipment-Z would be able to run, but rendered idle. These incidents would need to be classified as such to allow them to be appropriately counted or discounted in utilisation and *OEE* reports.

Similar to running, Equipment-Z was pre-programmed to understand when it was idle. The internal software detected if:

- All internal stations were ready to process
- All the safety interlocks were closed
- The operator had pressed that start button

If these conditions were true, the equipment was able to run and the software will deem it to be running unless both of the following conditions were found not to be true:

- There was a unit about to be fed into equipment i.e. there are unit to process

- Completed units could be unloaded from the equipment i.e. the equipment could feed units to each internal operation

If both were not true, the software concluded the equipment was idle.

It was determined that this idle condition was only relevant during scheduled production runs as it would point to incidents when either units were not being fed or input to the equipment, or incidents were the equipment was unable to feed or output units. The former would point the cause to some ‘upstream’ cause, i.e. some issue had occurred to an equipment or process that precedes this equipment. The latter would point the cause to some ‘downstream’ cause, i.e. some issue had occurred to a piece of equipment or process that proceeds this equipment. Another potential source of the idle condition would be that operator has instructed the equipment to ‘run out’ or ‘clean-out’, which would instruct it not to take in new units and continue to process existing units.

This classification of ‘idle due to upstream or downstream failure’ or ‘operator directed’ needed to be included into Event Text. Equipment-Z’s software utilized many input-output signals (I/O) to make decisions. These same I/O were also used to determine the source of the idle condition and in certain circumstances provide the reason for the idle incident.

This programmed logic was used to create three elements comprising the Event Text output to the database:

- Utilisation event category
- Utilisation event reason
- Utilisation event sub-reason

The Event Text string delimited these elements by separating them with a vertical bar character “|” (ASCII code 124) as this character was not used in any other entries posted to the event log and could therefore be reliably used to separate out the elements in reporting. The format of the Event Text string would be “Category | Reason | Sub-reason”. Table 4-3 shows the categorisation used for the category of ‘Prod Idle Time’.

Table 4-3 Example of reasons (cause) of idle events

Event Reason	Event Sub-Reason
Auto Idle as there is no Product to Process	No units from upstream
	Upstream (master feed) process is idle or stopped
	Upstream (master feed) process is stopped
	User selected cleanout
Auto Idle as unable to Process Product	Downstream (slave feed) process is idle or stopped
	Downstream (slave feed) process is stopped
	Unable to unload units downstream
	Upstream (master feed) process is idle or stopped
	Upstream (master feed) process is stopped
Auto Idle due to Downstream Process	Unable to unload units downstream
Auto Idle due to unknown	Cause of idle condition is unknown
Auto Idle due to Upstream Process	No units from upstream
User selected to Clean Out Module	Reason for Clean Out is unknown

Equipment-Z‘s pre-existing code was the key source of inaccuracy in determining idle-time.

An independent software timer was used as such that every sixty seconds the software would determine if the equipment was processing units. It did this by looking at the I/O that signalled if all stations within the equipment were ready to process a unit. If all were, the I/O would be set to TRUE and the logic would determine the equipment to be idle. If any were not, the I/O would be set to FALSE and the logic would determine the equipment to be running.

The sixty second interval of this timer resulted in an up to sixty seconds delay from when the equipment truly became idle (or running) to when the software logic determined this occurrence. In addition to the delay, the I/O would cycle from FALSE to TRUE to FALSE and so on, on every cycle of the equipment’s feed-line. As this cycling was independent of the sensing timer, the detection of an idle condition was matter of coincidence rather than discerning logic.

Two changes were needed to address this circumstance:

1. Decrease the sensing timer to a shorter interval
2. Develop discriminating logic to determine when the process is idle

The timed-interval was dropped to one second as that was deemed to provide enough resolution for time tracking without impacting the cycle-time of the equipment.

Testing revealed that this rendered the code overly sensitive with the effect of every second or so, the utilisation-tracking software would cycle between running events and idle events. With the logic used, the equipment became idle for a portion of every machine-cycle just before it indexed a new unit into the equipment. Detection of this temporary idle-state was not valuable to characterising utilisation as Equipment-Z never actually stopped processing. As this pause was an inherent part of the machine-cycle it represented an efficiency loss rather than an utilisation loss.

To desensitise the utilisation logic to this pause, an additional input was added whereby the duration of this pause was analysed. If the duration exceeded a specified limit chosen to reflect the inherent efficiency loss, the equipment would be determined as idle. The question became what should be used as the value of this limit?

Under normal running, this pause would not last more than a few tenths of second. However, the duration of the pause was variable depending on what upstream equipment Equipment-Z was coupled to. As the software was written such that it could be ported to equipment other than Equipment-Z, it was simpler to set the allowable duration to a fixed number. This simplification also allowed for a more efficient processing time of the software. Short processing time is important as to ensure negligible impact to equipment cycle-time.

4.3 Time where the equipment is unable to run due to some unscheduled event

The system had to handle two key types of stoppages during production running:

1. Those triggered by Equipment-Z's internal controls
2. Those triggered by the operator

4.3.1 Equipment triggered unscheduled event

With its internal sensors and in-line process control mechanisms, Equipment-Z was able to alarm and stop itself whenever its software detected an inappropriate condition. This automatic stopping (or auto stop) provided the opportunity for the software to immediately detect and categorise the reason for the Unscheduled Down-Time event. Upon occurrence of these alarms, the utilisation-tracking software would define the Event Category as “Unscheduled Down Time”, the Event Reason as “Auto stop due to alarm from [appropriate station within Equipment-Z]”, and the Event Sub-reason would use the same verbiage used in the alarm’s pop-up displayed on the equipment’s interface to the operator.

While being a simple requirement to program into the utilisation-tracking software, it immediately proved to be a powerful tool. In the past, Company-X’s maintenance department reported on the number of occurrences of alarms to prioritise improvement opportunities. For the first time, the utilisation software provided the opportunity to quantify the impact of each alarm.

The pre-existing utilisation-tracking system only identified down-time events greater than ninety seconds. In the PTM and PDM lines, it would be common occurrence where the in-line control limits used in Equipment-Z for a given product were based on limits used on a product that had matured to HVM. These limits would not reflect the capability of the program in PTM and PDM and would effectively alarm and stop the equipment in circumstances were no action should be undertaken.

These “false calls”, or Type II errors, were a source of contention between manufacturing, manufacturing support and process engineering. It is the remit of process engineers to set the limits of the in-line process controls. Not understanding the impact of these false calls to manufacturing, the engineers would procrastinate on updating the equipment’s settings and merely instruct manufacturing to ignore the alarms. However, an ignored alarm would still have to be cleared by an operator and then the equipment restarted. As this acknowledging and clearing of the alarm and resuming of equipment typically took far less than ninety seconds, scores of these alarms could occur on a given crew and never be reflected in the existing performance metrics.

While not within the subject matter of this project, it is worth pointing out these “clear and go” practices also lead to valid alarms being accidentally cleared without proper response and various internal and external quality incidents.

4.3.2 Operator triggered unscheduled event

Within normal process running there will be incidents that require the operator to manually stop the equipment:

- Performing a process control check
- Removing units (jam, sampling, etc)
- Changing a manufacturing order
- Responding to off-line process control trend or failure
- Start of a non-production event (Scheduled-Down-Time)

To ensure that the appropriate cause information is captured, and that the capture method is compliant with the proposed process model in Figure 2-1, a mechanism had to be developed to ensure that the cause information was captured before running of the equipment could be resumed.

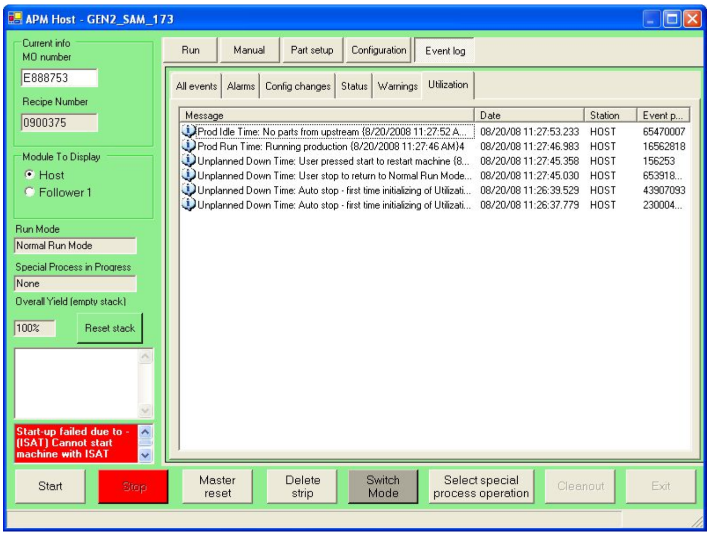
With Equipment-Z’s current interface, the operator would need to press specific buttons to remove units, perform a process control check or change a manufacturing order. With this known, the utilisation-tracking software was able to detect these button presses and use these occurrences to categorise the reason (and sub-reason) for the stoppage triggered by the operator (or any user). Each occurrence of a button press resulted in the software tracking a new utilisation event.

No specific pre-existing interface buttons were required to be pressed to respond to process control trend or failure, or the start of a non-production event. For that reason it became necessary for the utilisation-tracking software to prompt the user to select the appropriate reason for the stoppage. As the user could select the wrong option, this lack of automation posed a compromise to the integrity of captured data.

A cross-functional team (CFT) of manufacturing, training and engineering personnel was created with representatives from each of the Company-X’s PTM, PDM and HVM-focused plants. The developing system was installed in Equipment-Z on selected lines to allow the team to interact with the system. Daily reviews were undertaken to immediately address bugs (issues which required immediately address). Decisions were made at weekly reviews with the CFT. Changes driven by those decisions would be immediately implemented so they could be validated during the following week of testing. Through this repeated, testing and validating with the CFT:

- Choices were kept to a minimum
- Selection of main items would display any relevant sub-items to choose from
- Choices were kept to radio buttons and drop-down lists (for production events)
- Interface buttons were large to ensure that a gloved finger (manufacturing occurs in a clean-room environment) could easily pressed the desired button

Initial piloting showed that rather than have some options on the tracking interface and other options solely relying on the pre-existing buttons on Equipment-Z’s user interface, Figure 4-2, the operators preferred to have all options presented on a single interface Figure 4-3. This was easily facilitated and the equipment software was reworked such that the selecting the “Delete Strip” option on the utilisation-tracking interface would execute the same subroutines as pressing the “Delete Strip” button on Equipment-Z’s interface. The tracking interface, Figure 4-3, would be presented to the user anytime they pressed the “Stop” button, Figure 4-3. Note: Figure 4-3 shows that options were provided for each of the “non-production modes” (Section 4.4).



Current info
MO number: E888753
Recipe Number: 0900375

Module To Display
● Host
○ Follower 1

Run Mode: Normal Run Mode
Special Process in Progress: None
Overall Yield (empty stack): 100%

Start-up failed due to - (ISAT) Cannot start machine with ISAT

Message	Date	Station	Event p...
Prod Idle Time: No parts from upstream {8/20/2008 11:27:52 A...	08/20/08 11:27:53.233	HOST	65470007
Prod Run Time: Running production {8/20/2008 11:27:46 AM}4	08/20/08 11:27:46.983	HOST	16562818
Unplanned Down Time: User pressed start to restart machine {8...	08/20/08 11:27:45.358	HOST	156253
Unplanned Down Time: User stop to return to Normal Run Mode...	08/20/08 11:27:45.030	HOST	653918...
Unplanned Down Time: Auto stop - first time initializing of Utilizati...	08/20/08 11:26:39.529	HOST	43907093
Unplanned Down Time: Auto stop - first time initializing of Utilizati...	08/20/08 11:26:37.779	HOST	230004...

Figure 4-2 Equipment-Z's user interface showing Event Log

Please select reason for stopping machine:

- ● Delete Strip
- ○ Select Special Process Op.
- ○ MO Number Change
- ○ Process Reaction (PS)
- ○ Part Change / Set-up
- ○ Troubleshooting (Support)
- ○ Engineering Test
- ○ Scheduled Maintenance
- ○ Training
- ○ Sort Only Mode
- ○ Scheduled Down

Description of choice

Select to delete a strip.

Figure 4-3 Prompt to user to capture reason for stopping equipment

Piloting this software on a PTM line and a PDM line demonstrated easy user acceptance of the software. Despite minimal training, end-users demonstrated the ability to learn the interface quickly and make the right decision a high percentage of the time.

The user acceptance was so complete that most end-users questioned the system’s accuracy for a specific incident: “What does it do when I stop [Equipment-Z] by opening one of its doors, rather than pressing the stop button?” Where other equipment used by Company-X contains large robotics requiring the use of light curtains and locking doors for operator safety, Equipment-Z only requires safety interlocks such that the equipment will stop if an interlock is broken. For this reason, it becomes a common habit of operators of Equipment-Z not to use the stop button and simply open a door, which breaks a safety interlock. The end-users instantly noticed that they were not presented with the utilisation-tracking interface.

The resolution of this issue was already programmed into the system. Upon breaking a safety interlock, the equipment would automatically alarm and stop. This alarm event would be captured by the utilisation-tracking software as an “auto stop”. This would continue to be tracked as such until either the operator restarted the equipment or pressed one of the interface buttons (e.g. “Delete Strip”) which the utilisation-tracking software would recognise as reasons for a “user stop”.

While there were suggestions to also present the utilisation-tracking interface when these interlock alarms occurred, this would only be specific to Equipment-Z. As this would be against the intent for this software to be universal for any of Company-X's equipment, this suggestion was not pursued. Additional justification was the occurrence of a faulty safety interlock that was intermittently sensing a closed door as open. Such occurrences would be legitimately due to the equipment and not the operator. Prompting the operator would result in confusion and likely induce inaccuracies. Those suggesting this alternative were satisfied with the implemented process as it was acknowledged that the captured data would show if the operators were unduly opening the equipment's door without taking action.

4.4 Time where the equipment is not run due to some scheduled event

Equipment-Z had no means to automatically discerning that it was stopped for a Scheduled-Down-Time or Unscheduled-Down-Time event. The utilisation-tracking system therefore had to prompt the operator for this information. To achieve this, a "mode" system was created whereby each of these scheduled events was deemed a mode, and the operator would "switch mode" at the start of a any given event.

4.4.1 Switching Modes

While there was debate about the nature of and what constituted scheduled and unscheduled events, there was no debate about what events other than production occurred on the company's equipment:

- Product change / Set-up, e.g. converting to equipment to run a different product
- Engineering testing, e.g. qualification of new tooling, products, etc.
- Scheduled Maintenance, e.g. preventative maintenance or equipment modification activities
- Training, e.g. equipment is used for operator training
- Scheduled down, e.g. no builds planned on that line

A mode was created for each of the five non-production listed above as well as the following:

- Normal Run (Production)
- Process Reaction

- Troubleshooting
- Sort Only mode

Equipment-Z’s interface software included some of these modes, but the practice of switching modes was not used widespread outside of PTM as there was little delineation between the different modes. The three modes existing in Equipment-Z were, Troubleshooting (occasionally used), Setup (never used) and Sort Only (rarely used). Some equipment processed a Dry Cycle mode that would occasionally be used by the maintenance department.

Each mode was modified or created to have a discrete significance and allow for tailored event categorization for the group that would use that mode (Table 4-4, Table 4-5).

Table 4-4 The various activities and modes that can occur on Equipment-Z

Mode	Significance	Event Category
Normal Run (Production)	Used when the equipment is scheduled to be running product and able to run good product	Prod Run Time / Prod Idle Time / Unscheduled Down Time
Process Reaction	Used when the operator needed to take action described by their Out of Control Action Plan	Unscheduled Down Time
Product change / Set-up	Used when the equipment was altered and qualified for a different product	Scheduled Setup Time
Trouble-shooting	Used when manufacturing support had to address an issue with the equipment or tooling as part of an unplanned activity that needed immediate address	Unscheduled Down Time
Engineering Test	Used when an engineering activity was planned	Eng Test Time
Scheduled Maintenance	Used by maintenance department when they worked on equipment	Scheduled Maint Time
Training	Used by training department (or trainers) when availing of otherwise idle equipment	Scheduled Training Time
Custom Mode	Certain equipment in Company-X has specific modes pre-defined for specific functions	(*as defined by equipment software*)
Scheduled Down	Used when by the crew whom left the line in the absence of being relieved by a crew	Scheduled Down Time

Table 4-5 Need for further categorisation modes that can occur on Equipment-Z

Mode	Further categorisation	
	Need?	**Reason**
Normal Run (Production)	Yes	As described previously for automatic and user stoppages, and idle events
Process Reaction	Yes	It was important to understand what operator was responding to
Product change / Set-up	Yes	Company-X recognised different type of changeovers and wanted to set appropriate goals for each
Trouble-shooting	Yes	It was important to understand what support was responding to
Engineering Test	Yes	As these activities were planned events, it was important to understand which activity occurred and if the actual time spent matched the schedule
Scheduled Maintenance	Yes	This was used to categorize preventative work, planned correction work and modification work
Training	No	Two options were provided to the user, but these were to emulate the 'Normal Run" mode and "Setup mode"
Custom Mode	No	No
Scheduled Down	Yes	Per the pre-existing system, lunch-breaks and line meetings were distinct from the absence of a crew

4.4.2 Incentives to make the correct selection

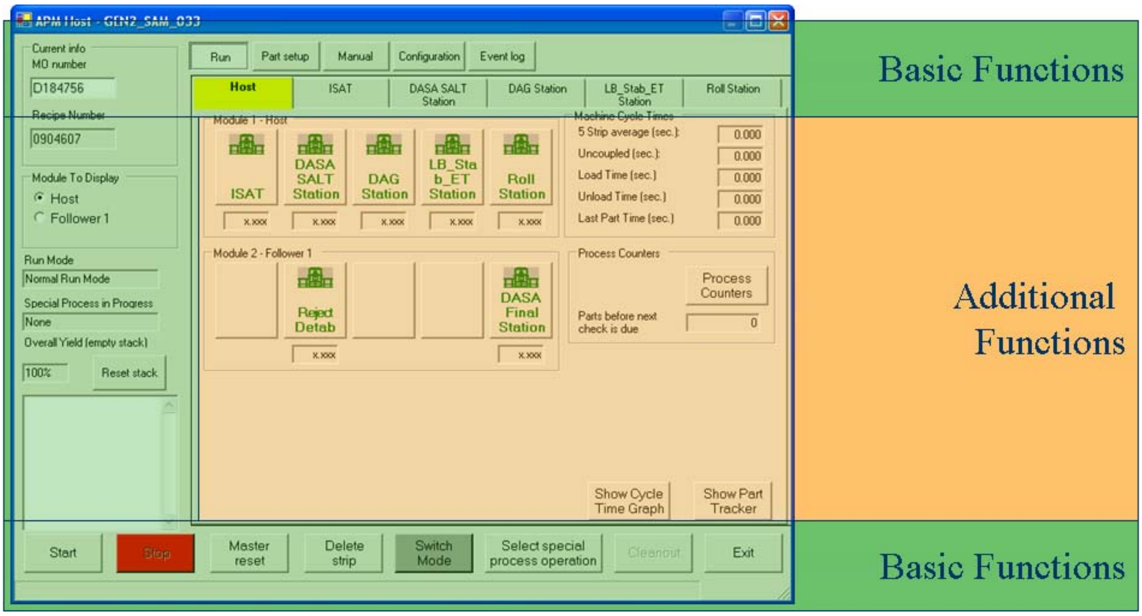
With the exception of "Normal Run" mode (NRM) it was only important to track the duration of the event rather then differentiating the time the equipment was idle, running or stopped during the event. The utilisation-tracking system needed to be signalled when a new event commenced. This commencement would signal the completion of the previous event, thereby triggering the system to record the event duration of the previous event and start tracking the new event, per the process in Figure 4-1.

The biggest accuracy issue was the user would fail to interface with the utilisation-tracking system and the time would continue to be allocated to the current event, rather the new event. To counteract this, a number of incentives were planned:

- Focused functionality
- Visible current status
- Activity goals

4.4.3 Focused functionality

The interface of Equipment-Z provided a lot of functionality to the operator, as well as any support personnel. As can been seen in Figure 4-4, all of the functions needed during normal production running were immediately accessible. These are dubbed “basic functions”. The various tabs and buttons on the upper portion of the interface allowed for viewing of the equipments settings, manual control screen and in-line control status. These screens provided functions where by the user could change a setting or manually index the feed-line or change the position of a motor-controlled stage. These functions are dubbed “additional functions” as they would not be typically used during normal production.



Current info
MO number: D184756
Recipe Number: 0904607
Module To Display: ● Host ○ Follower 1
Run Mode: Normal Run Mode
Special Process in Progress: None
Overall Yield (empty stack): 100%

Machine Cycle Times
5 Strip average (sec.): 0.000
Uncoupled (sec.): 0.000
Load Time (sec.): 0.000
Unload Time (sec.): 0.000
Last Part Time (sec.): 0.000

Parts before next check is due: 0

Figure 4-4 Basic & Additional function of Equipment-Z's interface

Unlike other equipment in Company-X, Equipment-Z’s interface did not require a password to access these additional functions. These were readily available at any time except when the equipment was actively processing units. At such time, the interface was disabled such that the user could view the screens, but not trigger any of the functions.

As these additional functions were not pertinent to a production event, the equipment interface software was altered to disable the additional functions while the equipment was in Normal Run Mode. These additional functions would only be enabled when the user switched the equipment’s mode to denote an activity whereby these functions were required.

This concept of focusing the functionality per the required activity and developing modes per distinct activity lead to providing a requirement for the user to switch mode at the start of an activity, thus signalling a change to the utilisation-tracking software. Table 4-6 shows the functionality that was made accessible to each mode.

Table 4-6 The functionality of each mode programmed into Equipment Z

MODE	Enabled functions	Extra Mode Features
Normal Run (Production)	Basic only	Run, Idle and Stop states are tracked
Process Reaction	Basic & Additional	Will automatically switch to Normal Run mode to reduce operator tasks
Product change / Setup	Basic & Additional	None
Trouble-shooting	Basic & Additional	To prevent escapement of defective product, all units processed in this mode would be immediately rejected
Engineering Test	Basic & Additional	Setting that were otherwise controlled via configuration management could be overridden for testing, per test plan
Scheduled Maintenance	Basic & Additional	None
Scheduled Down	“Switch Mode” button only	Entire interface was disabled to ensure any change to the equipment was logged in the absence of a scheduled crew.

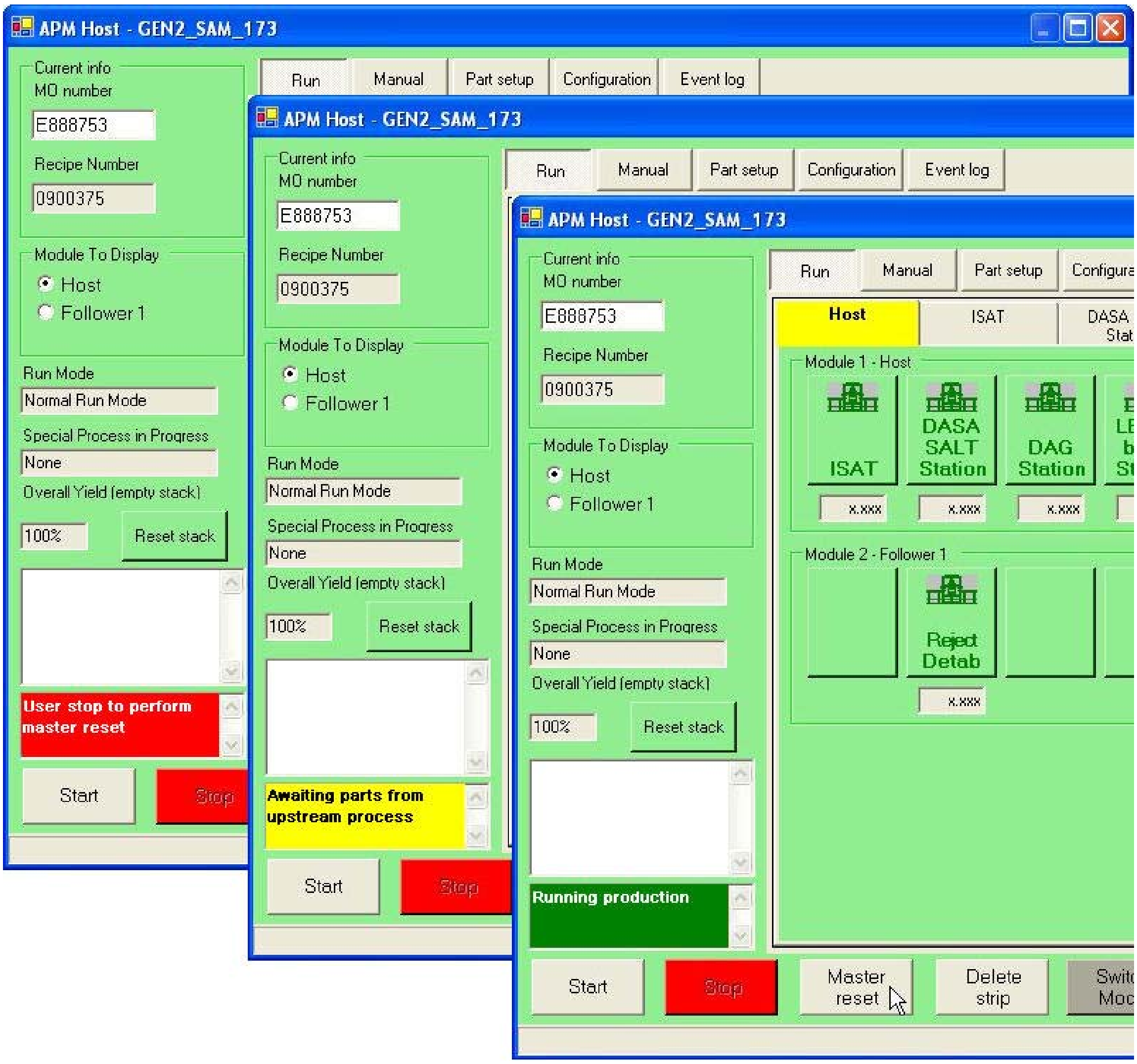
It was suggested by the maintenance department that switching to Scheduled Down mode could trigger all non-essential processes within the equipment to shut-down; a low-power mode for energy conservation.

4.4.4 Visible current status

Company-X had trained its operators and support staff to understand that positives of good utilisation of the equipment. It did not, however, provide visual cues regarding the status of the equipment. The modification of Equipment-Z’s software to incorporate the functionality of utilisation-tracking software provided two opportunities to provide visual cues.

The first was the displaying of the current utilisation status within the basic function section of the Equipment-Z interface. This would display the text of the current status per Figure 4-5, which would ultimate be recorded in the event log at the completion of the event. This text-box in which this status was displayed was also colour-coded to indicate whether this status has a positive or negative affect on the equipment's utilisation indicator:

- Red would denote a negative event, namely any event categorised as "Unscheduled Down Time"
- Yellow would denote a negative event not due to this equipment, namely any event categorised as "Prod Idle Time"
- Green would denote a positive, namely any event not categorised as "Unscheduled Down Time" or "Prod Idle Time"



MO number: E888753
Recipe Number: 0900375
Module To Display: ● Host ○ Follower 1
Run Mode: Normal Run Mode
Special Process in Progress: None
Overall Yield (empty stack): 100%

User stop to perform master reset

Awaiting parts from upstream process

Running production

Figure 4-5 "Traffic-light" colour-coding of utilisation impact

The second form of visual cues came from the idea of colour-coding the different modes. This coding would allow anyone to glance at the equipment's interface an immediately ascertain what type of activity was immediately in progress. This concept pre-existed in Company-X which utilized red, yellow and orange as described by Table 4-7. This coding was expanded to all the modes. Colours needed to be clearly distinguishable even when looking at distance and at an angle to the interface (a touch screen monitor) from which would tint or tone the colour.

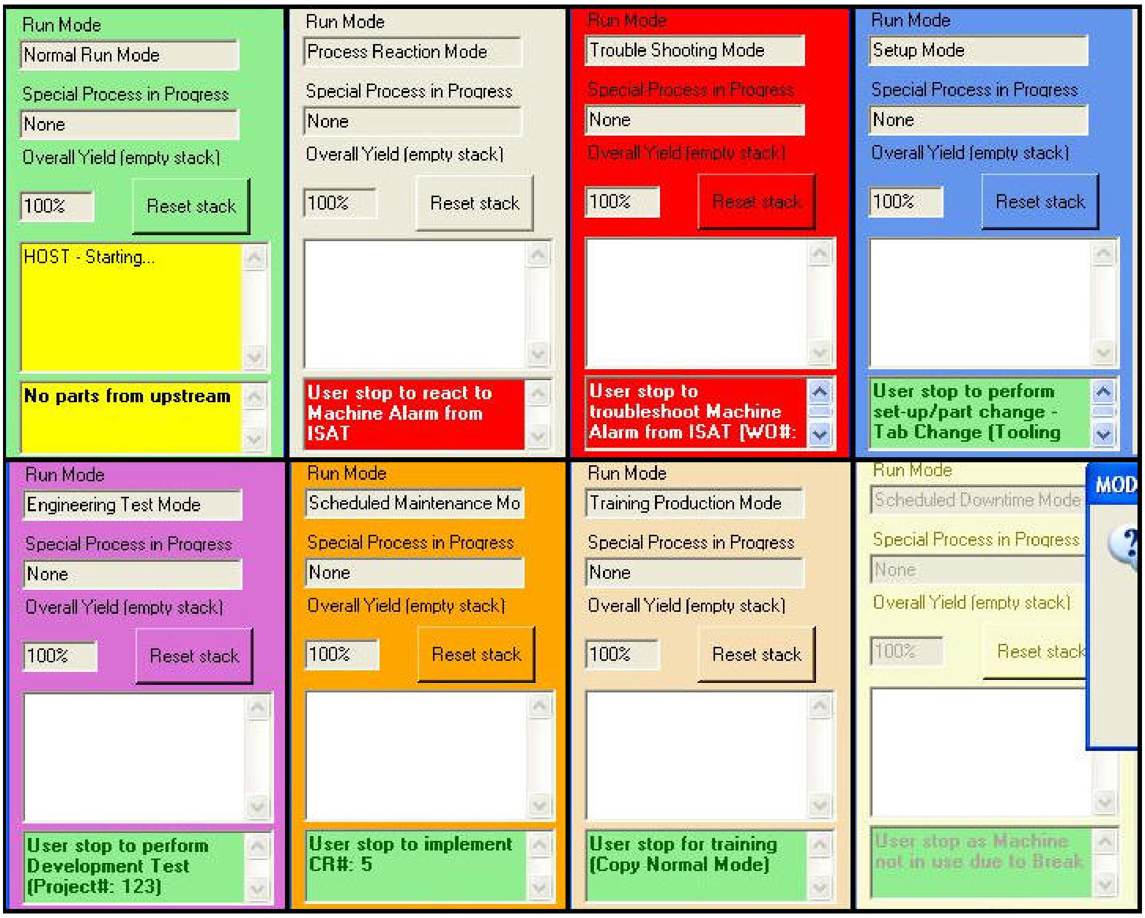
Table 4-7 Colour-coding of equipment modes

Mode	Prior to Project	Initial Pilot	Final Design
Normal Run (Production)	Grey	Grey	*Green*
Process Reaction	(none)	Iliac	*Grey*
Product change / Set-up	(none)	Blue	Blue
Troubleshooting	Red	Red	Red
Engineering Test	(none)	Green	*Iliac*
Scheduled Maintenance	Orange {Dry cycle}	Orange	Orange
Training	(none)	Wheat	Wheat
Custom Mode	Yellow {Sort Only}	Yellow	Yellow
Scheduled Down	(none)	White	White

Before this system was piloted, the default colour of the interface was the standard Microsoft Windows shade of grey. At the initial pilot, it was planned that this would remain as it was. As the engineering testing was common place on the PTM and PDM lines and regarded as a positive utilisation as it was a scheduled event, the decision was made to have that mode be green.

What was remarkable about the psychology of the colours was the department trainer who facilitated the training of personnel for the pilot, and whom fully understood the colour convention used, admitted at the end of the pilot that every time he saw a green interface, he immediately inferred that the equipment was “running good product” before he would correct himself. This feedback was echoed by all users including those whom operated all equipment with gray interfaces for the last fifteen years. Upon this feedback the final design colours were set per Table 4-7 & Figure 4-6.

The utilisation-tracking interface, Figure 4-3, was also programmed to change to the appropriate mode colour when that mode option was selected. This reinforced the coding and the idea of selecting the appropriate mode for the appropriate task.


Run Mode
Normal Run Mode
Special Process in Progress
None
Overall Yield (empty stack)
100%
HOST - Starting...
No parts from upstream

Run Mode
Process Reaction Mode
Special Process in Progress
None
Overall Yield (empty stack)
100%
User stop to react to Machine Alarm from ISAT

Run Mode
Trouble Shooting Mode
Special Process in Progress
None
Overall Yield (empty stack)
100%
User stop to troubleshoot Machine Alarm from ISAT (WO#:

Run Mode
Setup Mode
Special Process in Progress
None
Overall Yield (empty stack)
100%
User stop to perform set-up/part change - Tab Change (Tooling

Run Mode
Engineering Test Mode
Special Process in Progress
None
Overall Yield (empty stack)
100%
User stop to perform Development Test (Project#: 123)

Run Mode
Scheduled Maintenance Mo
Special Process in Progress
None
Overall Yield (empty stack)
100%
User stop to implement CR#: 5

Run Mode
Training Production Mode
Special Process in Progress
None
Overall Yield (empty stack)
100%
User stop for training (Copy Normal Mode)

Run Mode
Scheduled Downtime Mode
Special Process in Progress
None
Overall Yield (empty stack)
100%
User stop as Machine not in use due to Break

Figure 4-6 Colour-coding of equipment modes

4.4.5 Activity goals

The final and most important incentive to use the utilisation-tracking system as designed is company goals. The OEE metric or the indicators are only valuable if they are used. The project sponsors of this effort within Company-X understood that they would need to champion and monitor the usage of the final system.

To highlight the importance of the system to their personnel, Company-X's managers would use the captured utilisation indicators, as well as the underlying factors and cause data, to establish goals and priorities. It was intended these goals would be determined and compliance to the goals reported (in real-time and/or periodically) to manufacturing and support personnel.

Some of examples of this reporting and prioritising were conceptualised during this project by the targeted end-users. Numbers are provided below to highlight the concept:

- Manufacturing department:
    - Utilisation per manufacturing order exceeding 90%
    - Software changeover in under 1 hours
    - Tab to tab changeover in under 2 hours
    - Full tooling changeover in under 8 hours
- Training department:
    - 100% of scheduled activities completed as schedules per week
- Maintenance department:
    - 100% of scheduled activities completed as schedules per week
    - 5% reduction in troubleshooting events on Equipment-Z by end of fiscal year.
- Engineering department:
    - 100% of scheduled activities completed as schedules per week
    - Improve Equipment-Z’s utilisation by 5% by end of fiscal year

4.5 Reliability

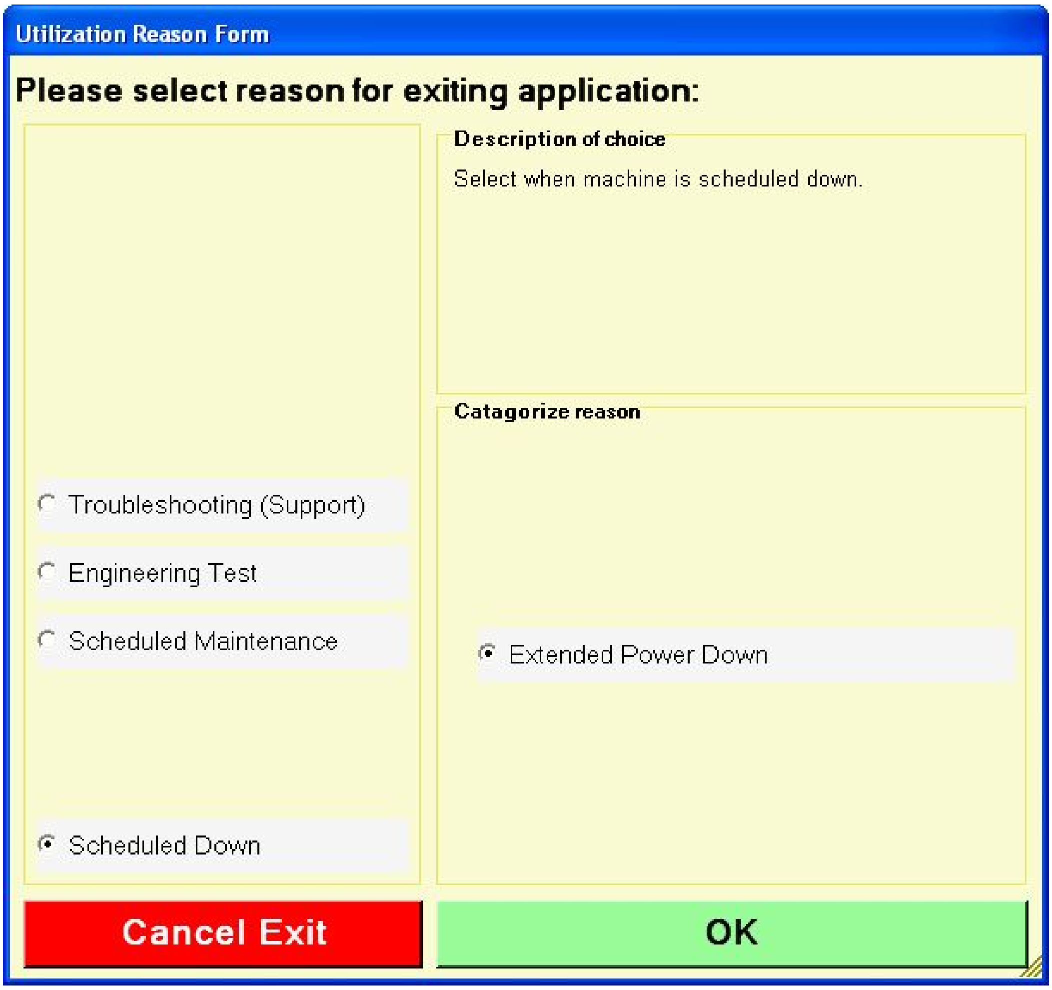
Beyond the accuracy issues relating to the capture of each of the factors, two issues of reliable capture of the data arose. The first was that time would have to be tracked even when the equipment was powered down. The equipment’s software and hardware performed the tracking and powering down was a common requirement of maintenance activities.

The second was that recording the data only when a new event commenced would be not provide reliable real-time feedback. For example a twelve-hour event of Scheduled Down-Time would only be recorded on the twelfth hour with no record of the current event during the first to eleventh hour.

Worse still would be a combination of the two issues. An unplanned interruption such as a power outage could occur on the tenth hour of the Scheduled Down-Time event. To combat both of these issues, restoration and incremental recording processes had to be developed.

4.5.1 Restoration recording

Very early in the project it became clear that routine activities would require restarting the equipment software, powering down the equipment's computer and even powering down the equipment entirely. To ensure complete utilisation-tracking, a step was implemented requiring the user to log why the closing was required before the interface application would close Figure 4-7.



Utilization Reason Form

Please select reason for exiting application:

Description of choice

Select when machine is scheduled down.

Catagorize reason

○ Troubleshooting (Support)
○ Engineering Test
○ Scheduled Maintenance
● Scheduled Down

● Extended Power Down

Figure 4-7 User prompt when exiting Equipment-Z's user interface

With the reason captured, the tracking system would immediately record this new event, albeit with a sub-second duration and allow the interface application to close. The interface application was already programmed with a mechanism to query the event log to determine if it was last closed at the request of the user or if some unpredicted event occurred. This programming was expanded to query the last captured utilisation event. If the application was properly closed, the last event would be that immediately recorded prior to the application being terminated.

With this last utilisation event known, the same category, reason, sub-reason and event timestamp could immediately be used by the utilisation-tracking software. The software was able to calculate the duration the application was down via the current time and the record’s timestamp. Upon making this calculation, the system would immediately:

1. Record this “turned-off” event
2. Restore the application to the same mode it was in prior to requested close out
3. Resume the tracking of the activity which prompted the termination

If upon restart of the application, the software determined that the application was not properly terminated i.e. it was not requested by the user, the utilisation-tracking software would prompt the user to provide a reason for the abnormal termination Figure 4-8.

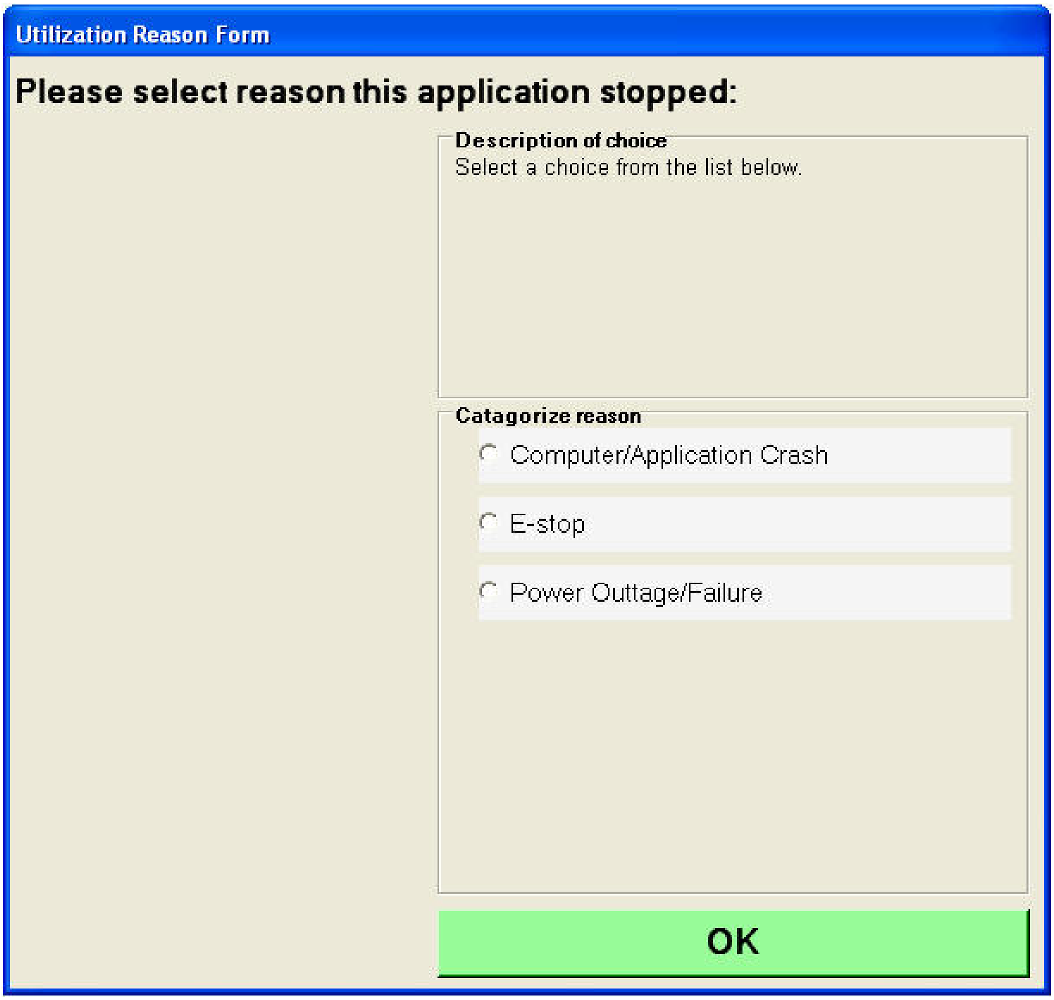


Figure 4-8 User prompt when restarting Equipment-Z's user interface after abnormal exit

Once the user provided the appropriate reason, the system will look up the last known utilisation event and:

1. Record the reason for the abnormal stoppage using the difference between the current time and the last known event's timestamp as the duration
2. Prompt the user for the activity that is now being performed, in the same manner of switch mode
3. Resume the tracking of the activity which the user inputted from the previous step

As the process that recorded the current event before termination of the application was not triggered, it would not be appropriate to assume the last known event is correct. It was determined with Company-X's end-users that it was more accurate to prompt for a reason.

4.5.2 Incremental recording

In the last example, a situation where Equipment-Z's interface application is abnormally and unpredictably terminated, the restoration recording process inferred the timestamp of the last recorded utilisation event as the start of the abnormal termination event. For this reason the resolution of the data-capture was an important contributor to the accuracy of the timestamp.

Consider the following example. The crew of A-shift finishes a day of continuous production knowing that the line will remain inactive during B-shift as no activities or crew is scheduled. Following the new business rules, the operator of Equipment-Z informs it of the Scheduled Down-Time event and leaves the line. The utilisation-tracking system captures the time of previous event, namely running-time. It knows it is currently in a Scheduled Down-Time mode, but it will not record this fact until Equipment-Z is put into a new mode. Ten hours into the twelve hours of Scheduled-Down-Time, a failure occurs killing all power to the line and instantly terminating Equipment-Z's interface application and utilisation tracking. Two hours later the operators of C-shift arrive on the line to find that power has been restored, but Equipment-Z needs to be initialised. When the interface application restarts and the utilisation-tracker attempts to restore itself, the operator informs the system that a power failure occurs. The system identifies the last known event as "running production". It assigns twelve hours to an Unscheduled-Down-Time event (power failure) rather than ten hours to an Unscheduled-Down-Time event and two hours to an Unscheduled-Down-Time event.

It should be also be noted that even without the failure, were a manager to query the database for the utilisation of the line over the last 24 hours at any point during the Scheduled-Down-Time , the results would not include the fact of the Scheduled-Down-Time .

For both of these reasons it was decided that the utilisation-tracking system needed to record the current status after some discrete interval of time where the status did not change. After reviewing this requirement with end-users it was determined that a fifteen minute interval was a reasonable resolution of time although it could be changed in the future. In the failure example above, this resolution would represent the margin of error in the time assigned to Scheduled Down-Time event (9.75-10 hours) and the time assigned to power failure (2-2.25 hours). Any “real-time” report would also be up to the last 15 minutes.

The solution of recording events after fifteen minutes without event changes impacted the ease of generating reports from the event data. This is due to the fact that there would be multiple records for a single event e.g. a 60 minute event would have four 15 minute records.

Table 4-8 Example of reporting errors

Category	Reason	Duration (hh:mm:ss)	Timestamp
Prod Run Time	Running production	00:15:00	07/08/08 13:28:35
Prod Run Time	Running production	00:15:00	07/08/08 13:43:35
Prod Run Time	Running production	00:15:00	07/08/08 13:58:35
Prod Run Time	Running production	00:15:00	07/08/08 14:13:35
Total Time = 01:00:00 (sum of all records) Number of occurrences = 4 (record count) Average event time = 00:15:00 (total / record count) Longest period of sustained running = 00:15:00 (max. value of durations)			

Table 4-8 shows that despite a full hour of sustained running, basic reporting tools would return a time of fifteen minutes. A reporting system needs to understand that these four records belong to the same event. The solution was to add another element to the Event Text to denote a unique event.

When a record was generated from the changing of the utilisation status, this unique-event flag would be set to 1. When a record was generated from the incremental recording time, the unique-event flag would be set to 0. This allowed for more accurate basic reporting as seen in Table 4-9, and allows for a transformation routine to roll-up the data as seen in Table 4-10.

Table 4-9 Example of solution to basic reporting errors

Category	Reason	Unique Event	Duration (hh:mm:ss)	Timestamp
Prod Run Time	Running production	1	00:15:00	07/08/08 13:28:35
Prod Run Time	Running production	0	00:15:00	07/08/08 13:43:35
Prod Run Time	Running production	0	00:15:00	07/08/08 13:58:35
Prod Run Time	Running production	0	00:15:00	07/08/08 14:13:35
Total Time = 01:00:00 (sum of all records) Number of occurrences = 1 (sum of unique event flag) Average event time = 01:00:00 (total / unique event count)				

Table 4-10 Example of improved reporting with transformed data

Category	Reason	Duration (hh:mm:ss)	Timestamp
Prod Run Time	Running production	01:00:00	07/08/08 14:13:35
Longest period of sustained running = 01:00:00 (max. value of durations)			

4.6 Final development at Company-X

Upon completion of a pilot on HVM lines the most negative feedback was the fact that the system prompted the user every time they pressed the stop button on the interface. The user acceptance was lower than previous pilots on PTM and PDM lines due to:

- The perceived increase in utilisation delay due to entering data
- The amount of data captured for none normal production events – events they had previously recorded to the detail that PTM and PDM required

For the most part, the resistance was from people peripheral to the pilot, i.e. those in a supporting role to manufacturing and not the actual personnel responsible for data-capture. As is true with any significant process change there were those whom were resistant to any change. Rather than allow pure perception make any final decisions, data was reviewed by the personnel involved in development and piloting.

The piloted system was programmed to start tracking the Unscheduled Down-Time from the instant the user pressed Equipment-Z’s stop-button. However, the system would not know the true reason for the stoppage and would assign the time as “User stop - awaiting reason". Once the user interacted with the interface such they provided a true reason, a new event was started and time assigned to that. Review of the number of occurrences and duration of these "User stop - awaiting reason" events allowed the user response and input time to be accurately tracked. As the users were not aware of this specific data being collected, they were unable to skew the results by deviating from their regular practice.

"User stop - awaiting reason" events recorded during an 11 day pilot displayed in Figure 4-9:

- 198 occurrences
- Total duration of 1.10 hours
- Average of 21 sec.
- Median of 5.9 sec.
- Minimum of 1.4 sec
- Maximum of 899.3 sec. (15 minutes)
- Only two occurrences exceeded 100 sec.

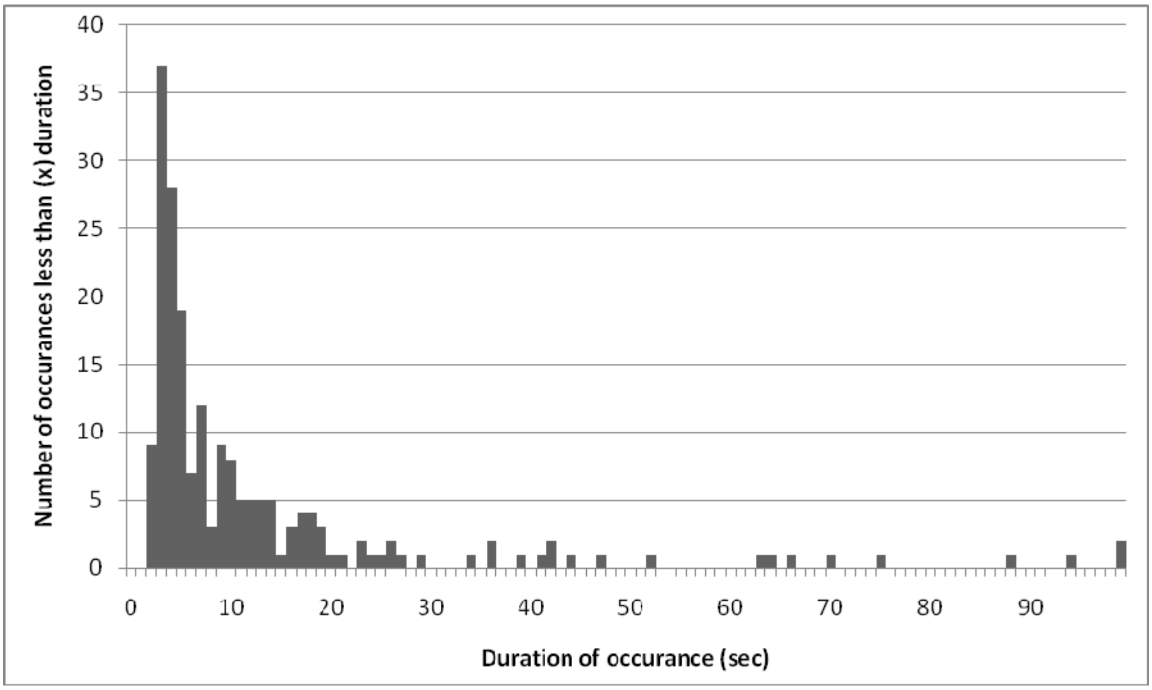


Figure 4-9 User response time to utilisation-tracking interface

It was accepted that this total time was low and more reflective of sub-ninety second downtime that had not been previously tracked rather than the data entry time.

Nevertheless, it was determined that another draft and pilot of the system would occur with several modifications to the software. The key changes proposed were:

- Removal of prompt when user pressed stop
- Changes to Process Reaction Mode
- Removal of various entry fields on interface

There was contention that these proposed changes would remove value from the data collected. Because of this agreed the plan was to:

1. Affect the changes within the software so that they could be later reversed
2. Use pilot of system to gain company-wide buy-in
3. Implement system on all Equipment-Zs with in the company
4. Use the data collected to determine if the reversal of changes was necessary

More simply put, even a stripped-down version of the system being implemented would allow the paradigm from line only metrics shift to equipment and line metrics.

The key changes with the perceived benefits and impacts will now be examined.

4.6.1 Removal of prompt when user pressed stop

In the piloted system, stopping the equipment under normal run mode would result in a prompt to appear. The other modes did not prompt the user as it was only the commencement and completion of these modes that was important. The updated version would remove the prompting of the user when they pressed Equipment-Z's stop-button.

This change would result in all data being captured from the use of Equipment-Z's interface and not the utilisation tracking form see in Figure 4-3.

The perceived benefits of this change were:

- It makes normal run mode more constant with the other modes
- The more tracking done without direct user choice the via a prompt:
    - Fewer data-entry activities perceived by the user
    - More accurate data collected

The perceived impacts were:

- Response times would be slower as the prompting created a sense of urgency
- Switching modes would take longer as users would now have to press the 'switch mode' button to display an equivalent prompt

As previously stated, these perceptions could be proven or disproved by running the system with this change and without this change in the same manufacturing lines, with the same personnel for the same duration of time. A side-by-side data analysis would conclude which method had the most delay before data-entry.

4.6.2 Changes to Process Reaction Mode

Originally Process Reaction Mode was programmed such that it would be used when the operator was required to make a short, single stop to address an issue. This assumed that upon resumption of running product, the equipment was back to running Normal Run Mode. All time in Process Reaction Mode was classified as 'Unscheduled Down Time". This made sense in the PTM and PDM lines where Troubleshooting Mode would be used for more significant stops.

The situation within the HVM plants proved not to be the same. Troubleshooting mode was deliberately avoided as it had the consequence of rejecting all units processed while the Equipment-Z was in that mode. The need to react to process issues while lower in occurrence in HVM often required a short interval of time with frequent stopping and restarting of the equipment. The piloted system proved cumbersome as the user had to frequently switch mode to unlock the additional functions.

With these two sets of requirements known, the various end-users collaborated to find a better alternative to meet all requirements:

- Pressing the 'Start' button in Process Reaction Mode would no longer automatically switch the equipment into Normal Run Mode.
- Switching to Normal Run Mode would occur in the following manner:
    - User pressed 'Switch Mode' button and selects Normal Run Mode
    - Equipment processed 120 units without stopping
        - Meeting this criteria would automatically switch the equipment into Normal Run Mode

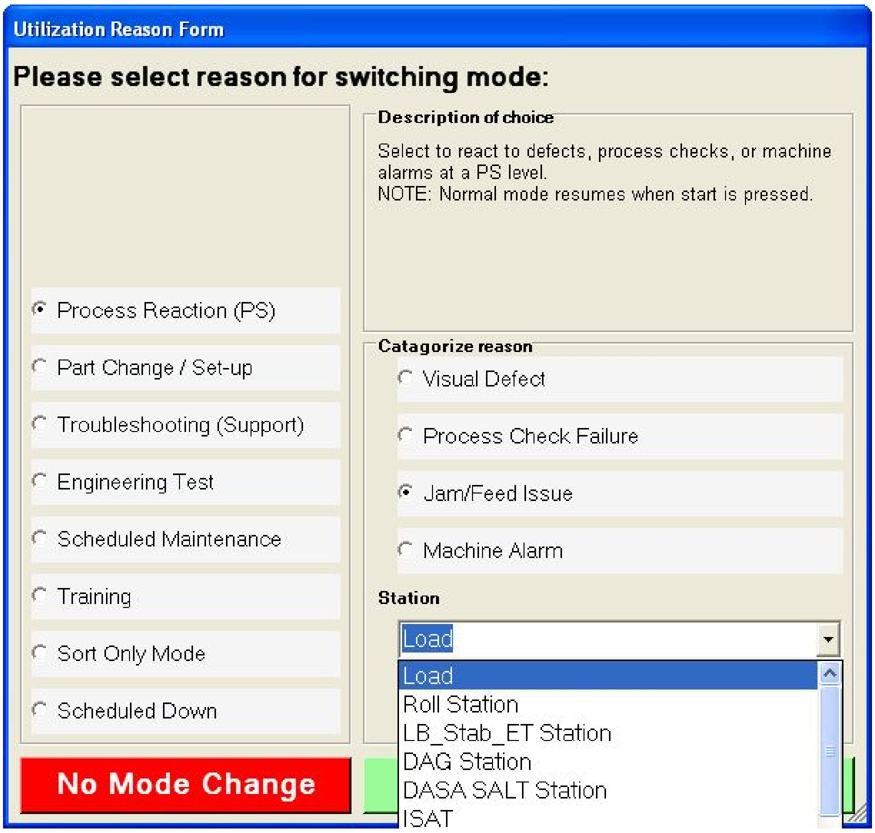
        - Equipment software would make the change with no prompting or warning to the user
        - User would clearly see the change due to the colour-coding of the modes

- Utilisation events would no longer be classified solely as "Unscheduled Down Time", rather it would be treated similarly similar to NRM:
    - While the equipment was running: "Prod Run Time"
    - While the equipment was idle: "Prod Idle Time" with automatic assignment
    - While the equipment was stopped: "Unscheduled Down Time" with the reason provided by the user when they initially switched to Process Reaction Mode

These changes were seen as improving the categorisation of the utilisation data. Also there was no perceived impact to user acceptance of given the collaborative efforts of the various end-users to determine these changes.

4.6.3 Removal of various entry fields on interface

In initial development, considerable thought was put into determining what cause-information would need to be coupled with any event captured to give it context for decision-making. An example is the drop-down fields provided when the user is switching into Process Reaction Mode as is seen in Figure 4-10 & Figure 4-11.



Utilization Reason Form

Please select reason for switching mode:

● Process Reaction (PS)
○ Part Change / Set-up
○ Troubleshooting (Support)
○ Engineering Test
○ Scheduled Maintenance
○ Training
○ Sort Only Mode
○ Scheduled Down

Description of choice

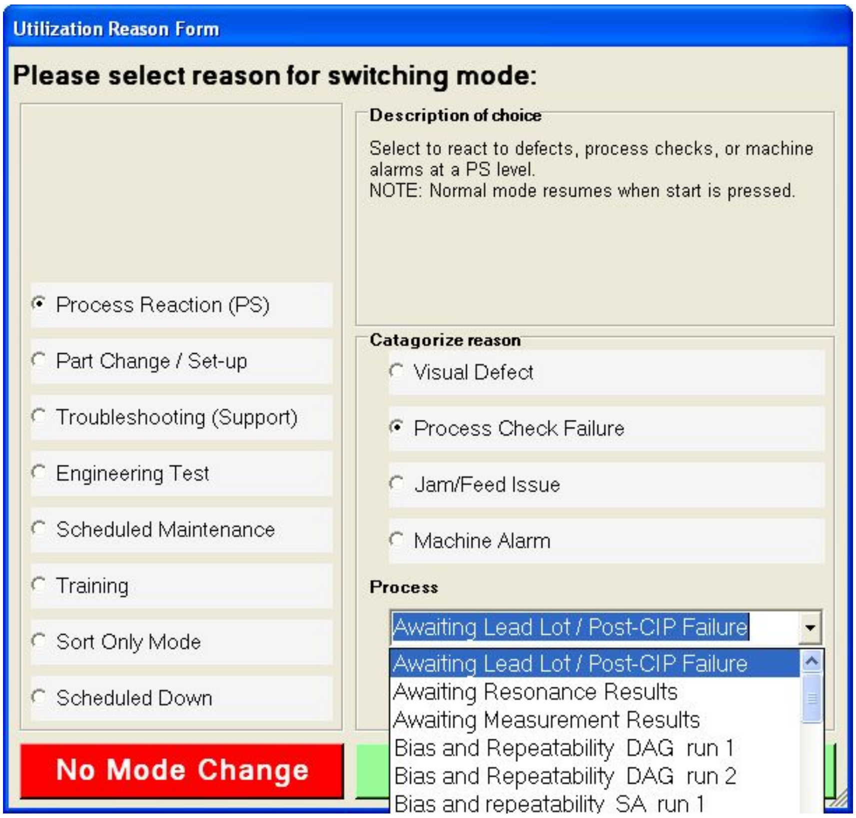
Select to react to defects, process checks, or machine alarms at a PS level.
NOTE: Normal mode resumes when start is pressed.

Catagorize reason

○ Visual Defect
○ Process Check Failure
● Jam/Feed Issue
○ Machine Alarm

Station: Load

Figure 4-10 Example of interface when responding to a feed-line jam



Utilization Reason Form

Please select reason for switching mode:

● Process Reaction (PS)
○ Part Change / Set-up
○ Troubleshooting (Support)
○ Engineering Test
○ Scheduled Maintenance
○ Training
○ Sort Only Mode
○ Scheduled Down

Description of choice

Select to react to defects, process checks, or machine alarms at a PS level.
NOTE: Normal mode resumes when start is pressed.

Catagorize reason

○ Visual Defect
● Process Check Failure
○ Jam/Feed Issue
○ Machine Alarm

Process: Awaiting Lead Lot / Post-CIP Failure

Figure 4-11 Example of interface when responding to a process check failure

In the example in Figure 4-10: while the down-time spent responding to the occurrence of a jam is important to track, the first question engineering would pose in analysing trends would be “What station is causing the jams?” Similarly in Figure 4-11: it would not be enough to see that process check failure was the cause of down-time, the specific process check that failed would be needed to make valuable decisions.

However, these were examples of the fields the end-user group wished to remove as they could not perceive the benefit of this initial information versus the cost of the time to select the right option. It was this type of change to the system, more than the others which would have been made reversible. The true benefit of this presence or absence of these fields could only be ascertained when the various departments started to avail of the data collected.

4.7 Reconciling PTM, PDM & HVM utilisation indicators

Within Company-X’s HVM lines, only Production Run Time is deemed good use of the equipment. As the product/program is fully developed, engineering and training time do not typically occur. Similarly, as a line is typically reserved for one program until it is discontinued, setup time does not occur beyond the initial configuration of the line.

Within the PTM and PDM lines there are scheduled engineering, setup and training activities, as well as production. These activities were critical to successful operation of these lines.

Practice at Company-X was to use a utilisation metric that was designed for the HVM lines. This metric was pushed by management onto the PTM and PDM lines. In of itself, it allowed comparison of a products performance throughout its life-cycle. However, the metric was not accepted by PTM and PDM as particularly beneficial as it did little for them to improve on their non-production utilisation goals such as maximizing engineering testing on PTM lines and decreasing it on PDM lines.

The key point of categorising the activities performed on the equipment in the manner described is that it would provide the means for each manufacturing environment to take appropriate action based on the utilisation data and on whether they were PTM, PDM or HVM centric. Table 4-11 shows how each phase focused on either improving utilisation by minimising or maximising certain activities, or merely understanding the time spent in each activity as there was not active goal set.

Table 4-11 Activity goals per phase of program life-cycle

MODE	PTM	PDM	HVM
Production Run Time	Understand	Maximise	Maximise
Production Idle Time	Understand	Understand	Minimise
Unscheduled Down Time	Understand	Minimise	Minimise
Scheduled Setup Time	Minimise	Understand	Minimise
Engineering Test Time	Maximise	Minimise	Minimise
Scheduled Maintenance Time	Understand	Understand	Understand
Scheduled Training Time	Understand	Understand	Understand
Scheduled Down Time	Minimise	Minimise	Minimise

When users understood how each phase looked at each activity, they began to rethink and seem to accept a different utilisation formula than one that outright penalised engineering, setup and training activity. In HVM, these were effectively treated as Unscheduled-Down-Time, and therefore included as Available-Time, T_{AVAIL}. PTM and PDM management wanted to effectively treat these as running time as they considered this positive utilisation.

The emerging compromise was to return to the industry definitions used for utilisation and treat these scheduled activities as Scheduled Down-Time. The allowed Company-X's utilisation metric to focus on utilisation with respect to producing units of product while not penalising required development activities as the Scheduled-Down-Time is removed from calendar-time to deduce Available-Time per Equation 8.

4.8 Chapter Summary

The system was developed to explicitly capture and categorise all time events into production (running, idle, unscheduled down) time and non-production scheduled (setup, engineering, maintenance) time. Wherever possible the equipment's computer-controller performed these activities automatically. When it was necessary, the system would force the equipment operator to provide the minimally needed information. With the utilisation indicator portion designed, development moved to efficiency and yield indicators.

5 Development of Efficiency & Yield Capture

5.1 Efficiency Capture

The efficiency indicators, Equations 15 and 18, require the capture of two out of the four unique factors:

- The fastest time the equipment is rated or bench-marked to be able to process a unit; known as rated cycle-time, CT_{Rated}
- The actual time spent by the equipment to process a unit; known as actual cycle-time, CT_{Actual}
- The greatest number of units the equipment is rated or bench-marked to be able to process a in fixed time period, typically expressed in terms of an hour; known as rated output-rate, UPH_{Rated}
- The actual number of units the equipment processed a in fixed time period, typically expressed in terms of an hour; known as actual output-rate UPH_{Actual}

As explained in Section 2.3, cycle-time can be calculated from output-rate. For this reason only two of these four factors need to be captured. Each of these factors present their own data-capture issues which be now be examined.

5.1.1 Rated Cycle-time and Output-rate

Most of Company-X's equipment consists of various components purchased from Original Equipment Manufacturers (OEM), and then assembled by Company-X's personnel. While the components could well have cycle-times rated and specified by their OEM, the equipment assembled and tailored by Company-X would not immediately have a rated cycle-time.

The obvious solution is that Company-X would need to establish its own rating of its equipment. Company-X does have a rating for its HMV lines but not necessarily the individual pieces of equipment that comprise the line. Equipment ratings however could easily be established through historical data.

As was stated for cycle-time, the same is true for output-rate.

5.1.2 Actual Cycle-time

Automatic cycle-time capture requires the means to capture the time sent processing each unit individually. This method requires the intelligence of the equipment to independently capture and record the time when an individual unit enters the equipment to the time that unit is fully processed and leaves the equipment.

Some months prior to the commencement of this project, a separate effort was completed for Equipment-Z to capture and record the actual cycle-time. As it had multiple internal stations and a feed-system which transported each cavity of each carrier to the each station, the cycle-time tracking system recorded:

- The cycle-time of each station per unit
- The wait-time for the upstream process to load a carrier into the equipment
- The wait-time for the downstream process to unload a carrier from the equipment
- The cycle time of the equipment to move a unit to the next station and process it – which was a function of:
    - Upstream wait-time
    - Downstream wait-time
    - The parallel processing-times of all the individual stations

As the starting and stopping of times were tied to the PLC controllers of Equipment-Z the accuracy of these times is not in dispute. What is remarkable is that these times were used only to improve the cycle-time of Equipment-Z and not used in a manner to calculate the efficiency of Equipment-Z. One reason was the lack of a benchmarked or rated cycle-time, which resulted in losses that were not quantifiable, and therefore could not be categorized.

Another remarkable feature of this cycle-time tracking was the concept of steady-state and non-steady-state cycle-time. The engineers who designed and implemented this system understood that the cycle-time would change based on environmental differences. For example, if the equipment was full i.e. it was processing a full set of carriers which in turn had units in all cavities, and the upstream and downstream process were immediately ready to load and unload, then Equipment-Z was deemed to be in steady-state and all recorded times were categorised as such.

When Equipment-Z was in non-steady-state, there was the risk that the captured times would be impacted such that they would not accurately reflect the actual cycle-time of the equipment. Examples of these impacts were:

- Increase in station processing-time as Equipment-Z has to warm up due to being idle for some time
- Decrease in overall processing time as feed-system immediately indexes a second time as no units were presented to any stations

The engineers using the cycle-time tracking system would filter out the non-steady-state information and only deem the steady-state information as the true speed of the equipment.

With respect to OEE, this steady-state cycle-time seems to be a closer reflection of the actual cycle-time in that is not convoluted with yield and utilisation losses from upstream or downstream equipment in the same line. The average of the recorded cycle-times for time-period should be compared to the rated cycle-time to compute the efficiency indicator.

5.1.3 Actual Output-rate

For a given period of time, the capture of the actual output-rate requires the capture of two factors:

- The number of units processed
- The duration of processing time

Per the proposed utilisation-tracking system the run time of the equipment, T_{Run}, will be captured and recorded, which can serve as the duration of processing time. As will be seen later, the yield-tracking system will count the number of units fed into to the equipment, u_{in}, which can serve as the number of units processed.

This makes it possible to use the utilisation and yield factors to as efficiency factors, assuming T_{Run} is in hours:

$$UPH_{Actual} = \frac{u_{In}}{T_{Run}} \tag{30}$$

The issue of capturing the cause-information of efficiency loss still needs to be addressed.

5.1.4 Proposed standard method for Actual values

Aside from accuracy, the ease of capturing the factors and cause-information should be the deciding criteria over choosing to calculate the equipment's efficiency from cycle-time or output rate. For Equipment-Z, the current capture of cycle-time sets the standard for Company-X as it directly captures and records cycle-time. More importantly, the manner in which it captures overall processing-time, up and downstream wait-times, and individual station processing times will allow for some cause of loss to be assigned. Engineering staff at Company-X would deduce and infer an assignable cause to cycle-time losses. A more refined system could have the intelligence to determine and record the assignable cause as the cycle-time information was simultaneously recorded.

The alternative of using utilisation and yield factors, Equation 30, results in no efficiency loss cause-information being captured, only utilisation and yield loss. This effectively disqualifies this alternative, as improvement activities cannot be determined without cause-information.

Unfortunately, factors external to this project resulted in its cessation before this proposal could be progressed (Appendix B).

5.2 Yield Capture

The classic and rolling throughput yield indicators both require three unique factors that must be measured from the equipment:

1. Count of the number of units input to the equipment, u_{in}
2. Count of the number of (pristine) units output from the equipment, u_{out}
3. Count of the number of defective units created by the equipment, u_{def}

Issues which will impact the accuracy of capturing these factors will be now be reviewed. These issues exist throughout Company-X when reviewing its collective equipment and would need to be tackled by any proposed system to provide accurate equipment-level metrics.

5.2.1 Count of the number of units input to the equipment

The reliability and accuracy of count of the number of units input to the equipment can be impacted by:

- Use of accumulators e.g. bowl-feeder, hoppers, stackers, etc.
- Use of carriers in equipment e.g. cassette, traveller, palette, etc.
- Use of machine-cycle counts

Accumulators represent an accuracy issue as the count of the raw units loaded into the equipment is captured, u_{load}, but not the number of raw units actually processed, u_{in}, as is illustrate in Figure 5-1. A commonplace example of this is equipment that uses a bowl-feeder. Units loaded into the bowl-feeder are counted (often by weight) before being placed into the feeder. Unless the bowl-feeder is allowed to completely empty, this count will not match the input count to the equipment. By their nature, bowl-feeders must always contain a certain a certain quantity to ensure specific feed-rate into the equipment and are therefore unlikely to be emptied out during production.

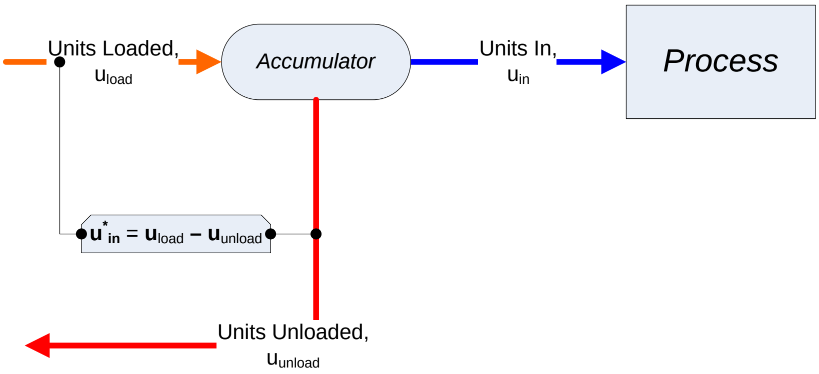


Figure 5-1 Yield tracking is complicated when accumulator are used

A practical way to compensate for this is to count the quantity remaining in the bowl-feeder upon the completion of the processing and subtract this from the quantity original loaded to deduce the units inputted to the process. This should be classified a “post-processing” factor rather than a “live” factor as we can only determine it after the processing is completed. While still having merit, metrics captured and reported in real-time with the processing allows for prompt reaction to issues as they arise.

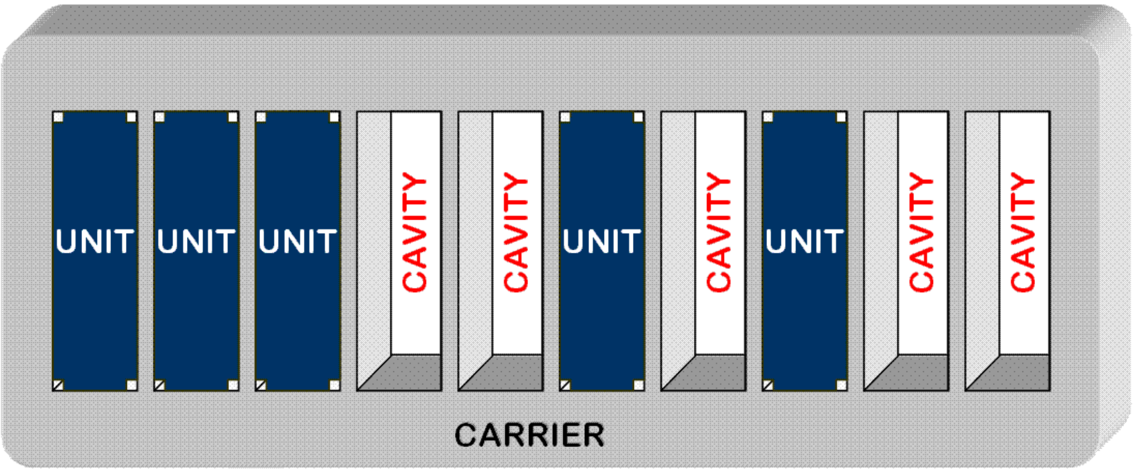


Figure 5-2 Representation of carrier used to transport unit through the manufacturing line

Carriers, Figure 5-2, are commonly used in manufacturing to transport batches of units between equipment and/or through equipment. A carrier has number of cavities in which will contain the units. Carriers represent an accuracy issue to u_{in} as the number of carriers is often counted rather than the number of filled cavities as illustrated in Figure 5-3. The carrier count assumes all available cavities contain a unit that can be processed.

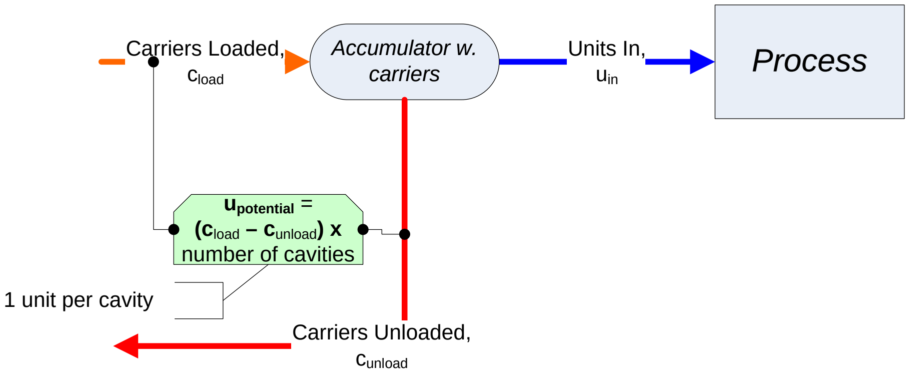


Figure 5-3 Yield tracking is complicated when carriers are used

For many pieces of equipment, the assumption of a full carrier may be a low risk as the actual occurrence of an empty cavity might be incredibly low or impossible. However, this risk should be understood as it will not be possible to classify this as a reason for a yield loss. Should this occur, it will be added to the “unknown” category and will artificially lower the yield of this equipment when the actual loss was induced earlier in the line.

In essence a count of carriers provides a count of potential units and not the absolute count of units in.

$$u_{Potential} = Carrier_{In} \times cavities \tag{1}$$

While also ensuring the accuracy of the yield of this equipment being able to discern the units actually input to the equipment provides the means to validate the yields of previous equipment in the line.

Defective units on a carrier are similar to empty cavities on the carrier in that there is not a unit that can be processed. Some of Company-X's equipment, including Equipment-Z, has the ability to identify and skip the processing of these defective units. This is ideal as they should not counted either as units input to the equipment, output from the equipment or defective due to the equipment. Thus $u_{Potential}$ is not used as an estimate of u_{In}, but rather it is used as an independent factor.

Use of a machine-cycle count in the place of a units inputted count present similar accuracy issues as carriers. If the equipment cycles irrespective of available unit and/or a non-defective unit then this clearly cannot represent the quantity of units to be processed.

To summarize, the most accurate count of units fed into the equipment will differentiate units that are both non-defective from previous equipment in the line and are actively received/processed by the equipment. This can be achieved by placing a sensor (proximity sensor, IR sensor, etc) to detect units present at the first point of work within the equipment. If it is possible for defective units to be present, a more difficult problem is presented. The equipment needs some means to determine defective units from pristine units. The unit needs some mark, identifier or feature to signal it as defective. The equipment needs to some means to sense this "signal".

Examples of signalling and sensing defective units include:

- Vision system to read a mark (ink spot, lasered dot, missing tab) from a region of the unit used to communicate pristine condition
    - Upstream equipment (or operator) must mark the inspected region once unit is found to be defective.
- Barcode scanner to read the unit's barcode identifier and query a database which has the unit's pristine or defective condition recorded

  - Upstream equipment (or operator) must log the unit as defective in the database once unit is found to be defective.

Company-X deploys "unit present" sensors in Equipment-Z, as well as a mechanism that effectively removes a defective unit from the carrier when an upstream process determines the unit is defective.

5.2.2 Count of the number of units output from the equipment

The reliability and accuracy of count of the number of units output from the equipment can be impacted by:

- Use of accumulators e.g. bowl-feeder, hoppers, stackers, etc.
- Use of carriers in equipment e.g. cassette, traveller, palette, etc.
- Use of machine-cycle counts
- Post process capture of defective units

The issues that affect the accuracy of the unit-inputted, u_{in}, also affect the output count, u_{out}. The most significant issue is the determining of units that are defective as these must be excluded from the output count.

While the accuracy of the defective count will be review in Section 5.2.3, there is still a commonly used assumption that results in accuracy issues: the number of units output equals the number of units in minus the number of defective units, as illustrated by Figure 5-4.

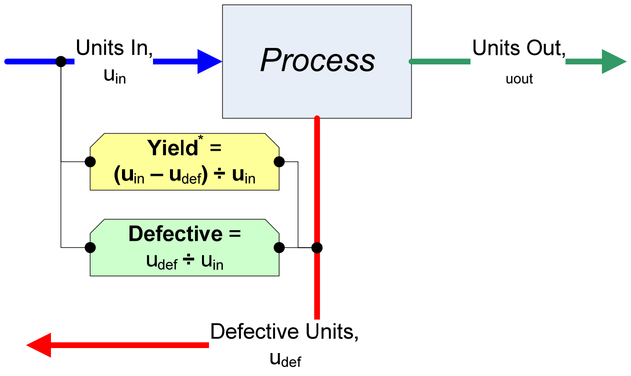


Figure 5-4 Yield tracking is complicated when units out is assumed

In essence, this assumes that the delta between the out and in counts equals the defective count.

$$u_{In} - u_{Out} = u_{\Delta} \tag{31}$$

$$u_{Def} = u_{\Delta} \tag{32}$$

$$u_{Out} = u_{In} - u_{Def} \tag{33}$$

On paper this makes sense, but in practical application this can present a problem. It is important to consider what can be considered a defective unit. A defective unit should be one that has a known and documented non-conformance. Therefore a unit can only be considered defective if there is categorisation of defect data associated with it.

Within Company-X there is equipment where it is possible for units to fall from the feed-line. This lost product was not classed as defective and it can go unaccounted for during a manufacturing order. In this example, it is easy to see how there was a difference between the quantities expected downstream and those actually received. These differences are problematic as there is not a clear assignable cause captured in real-time. A post-build investigation must occur to determine and record the cause or yield loss.

$$u_{Def} \neq u_{\Delta} \tag{34}$$

Explicitly counting units out from equipment independently of the defective units allows the distinction between the in-out delta and the defective count. This allows any post-build investigation to focus at the specific equipment rather than having to first troubleshoot all the upstream equipment to determine the source. Additionally, seeing this distinction in real-time will provide those closest to the equipment the opportunity of identifying the source of the discrepancy and possibly correct it before the processing is completed.

A cost-benefit analysis may determine for a specific application that the sensing of all three factors is not appropriate. Equipment-Z indeed has a unit-out sensor. When a unit expected to exit the equipment fails to be present, Equipment-Z's programming will alarm and stop the line. To resume the line, the operator is forced to classify the loss, and as such this loss is recorded. This methodology makes Equipment-Z's unit counts the most accurate in Company-X, effectively ensuring Equation 32 is always true.

5.2.3 Count of the number of defective units created by the equipment

The reliability and accuracy of count of the number of defective units created by the equipment can be impacted by:

- Post-process capture of defective units
- Ability to remove units from equipment without disposition

As explained in the previous section, it is important to distinguish defective units as having cause-information, i.e. specifically documented non-conformance. An accurate count of defective units is dependant on using the systems in place to identify and document the defective units created by the equipment.

Very few, if any, equipment has built-in capability to test and identify every possible defect that can be induced by the equipment. For example, equipment that connects a resistor to a circuit-board may test the connectivity of the resistor and the quality of the solder joints used, but will it consider the edge of the circuit board for abrasions due to a burr on the clamping fixture holding the board in place for processing?

Testing, measuring and inspecting for every possible defect at every piece of equipment is costly and impractical. It is a reality of manufacturing that issues will be identified after they occur and it is possible this identification will occur downstream of the equipment where it occurs. It is for this reason Company-X utilises dedicated inspection processes. These processes are defined at appropriate points on the line to visually inspect for attribute defects/conformance and measure for variable or functionality defects/conformance.

Rather than discuss and debate how to make these inspection processes effective, this work focuses on how to best create the factor and cause data. There are two strategies commonly deployed to handle this circumstance:

1. Both factor and cause are assigned to the “source” equipment determined to cause the defect and not the inspection process
    A. The outputted unit and defective unit counts for the source equipment are retroactively changed.
    B. Equipment Pareto shows loss
2. The factor is assigned to the inspection process

A. Being part of the line, the detected loss is ultimately accounted for

B. The cause data is used in a Grand Pareto and not equipment's Pareto

An argument can be made for the assigning of data to the source of the incident rather than the location it was discovered, as it would more clearly represent the productivity of the specific equipment. However there is a more critical circumstance to guide the decision: when do we want someone to respond to this yield loss?

A real-time capture system is truly beneficial as it presents information to those in the position to make an immediate improvement to the equipment. Whichever strategy is chosen, only building a mechanism to empower operators to make improvements during the processing will improve the final outcome of the build.

Whether the inspection is built-in to the equipment or accomplished via a separate inspection process/equipment, the biggest root-cause of defect inaccuracies is the lack of a disposition i.e. requiring the defect to be determined, classified and recorded. Any system needs to account for and assign cause to every unit that is not output from the equipment.

As discussed earlier, Company-X's current disposition practices are very disconnected from regular production practices. In fact, they are run counter to each other. Any tool that requires even a perceived loss in productivity in order to record the cause the reasons for a loss of productivity will be ill-received by the operators tasked with maintaining productivity. If the disposition practice provides the ability for the operator to, in their mind, avoid further impact to productivity by skipping the disposition of yield defects, some will undoubtedly avail of it.

Returning to the example in Section 5.2.2 where units could fall off the feed-line. A practice needs to be established to ensure the appropriate disposition of these units. This disposition may involve scrapping the units, or the reworking, testing and returning of the units to the appropriate equipment on the line. Regardless of the outcome of the disposition, these units have not completed the regular equipment and the productivity factors should reflect this.

5.2.4 Recommended Yield Capture System

While there are certainly cases where two out of the three yield factors can be used, and the third one inferred, for all the reasons explained in the previous sections this is not recommended.

Whilst potentially being the more difficult system to implement, the system that provides the simplest, clearest factors is one that independently counts for a given piece of equipment:

1. The good units actually received by the equipment’s value-added process
2. The good units actually output by the equipment
3. The units rendered defective by equipment as and categorised as such

These factors will function no matter how complex the feed-process to the equipment might be in terms of having accumulators and/or carriers. They provide the means to ensure that the difference between the count of units fed to the equipment less those output from the machine matches the count of defective unit, Equation 31 & Equation 34. They also provide the means to ensure that the count of units fed from one piece of equipment on the line matches the count of units fed into the line’s next piece of equipment.

Any difference in these values will highlight some inability of the system to accurately count the units. This should trigger investigation as some as yet unforeseen source of loss has occurred. Therefore being able to compare the factors can validate the integrity of the factors and the system.

The further a system must deviate from this model, the more convoluted the factor and cause information becomes as approximations for these three factors must be used.

5.2.5 Systems at Company-X & Equipment-Z

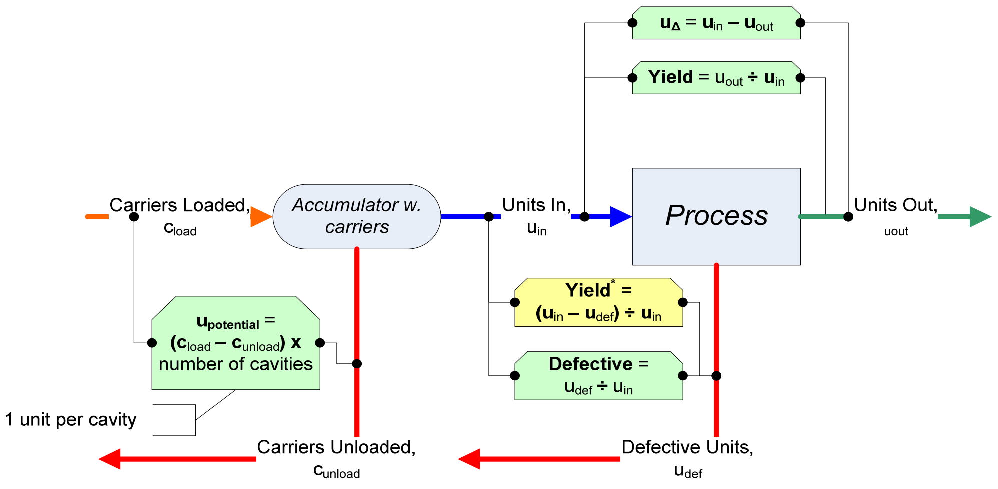


Figure 5-5 Yield tracking model to address carriers and accumulators

The universe of equipment used in Company-X, and specifically Equipment-Z embodies all of the previously stated circumstances that can lead to inaccuracies as illustrated in Figure 5-5.

Equipment-Z however had been engineered to address each of these circumstances:

- Use of accumulators is countered with Equipment-Z recording each unit it processes.
- Use of carriers in equipment is countered with Equipment-Z sensing if each cavity in the carrier is filled, as part of its inputted unit count.
- Use of machine-cycle counts is only used for maintaining Equipment-Z and not OEE
- Ability to remove units from equipment without disposition is impossible with Equipment-Z as many of its stations will sense an expected unit is missing, alarm and stop the equipment, and will prompt the operator to disposition

Equipment-Z also has built-in inspection capabilities. When a unit is found to in violation of a predetermined process tolerance, the Equipment-Z's software will update its internal registry of the unit's status from pristine to defective. When the carrier is fully processed by Equipment-Z, it updates the defect database with the number of defects and the number of units that were found to be defective.

This automatic detection and disposition is coupled with the fact that Equipment-Z already matches the "Lean Data Collection Model" with respect to capturing and recording defect incidents. There are only four legitimate reasons for a carrier of units to be physically removed from the Equipment-Z and require an operator to explain the cause of the removal:

- Feed-line jam, or clearing some obstruction
- Collection of sample units for some audit or process control check
- Collection of units for engineering testing
- A discrepancy between Equipment-Z's internal registry and built-in inspections, e.g. carrier fell of the line, requiring a physical clearing of the feed-line

Other equipment at Company-X has the some of the capabilities as Equipment-Z.

Table 5-1 Breakdown of yield capture issues per Company-X's equipment

	In count method	**Empty cavity sensing**	**Pristine detection**	**Automatic disposition**	**Possible removal without disposition**
A	Via carrier sensor	Database look-up	Database look-up	N/A	Yes
C	Machine-cycle count	No – carrier always filled	No – assumption of pristine	N/A	Yes
E	Via cavity sensor	Via cavity sensor & camera	No – assumption of pristine	No – post-process inspection	Yes
F	Via carrier sensor	No – erroneously assumes filled	Yes – camera	Camera-detected defects	Yes
G	Via unit inspection camera	Via unit inspection camera	Via unit inspection camera	Yes	No
Z	Via unit sensor	Via unit sensor	Via unit sensor	Yes	No

While it is widely accepted that Equipment-Z has proven the benefit and importance of retrofitting equipment to have the same capabilities there has not been warranted urgency to prioritise the work that would be involved. Part of the original intent of this project was to show the benefit of a complete OEE capture method on a single piece of stand-alone equipment, and use the implementation of the OEE method to justify and prioritize the work of retrofitting all equipment.

5.3 Chapter Summary

The system was developed to use cycle-time values explicitly captured by Equipment-Z's computer-controller rather than calculating cycle-time from independently captured counts of Units In and Production Run Time events. This would allow cause-information to be simultaneously captured. As Equipment-Z had many potential circumstances that could lead to errors in the counting of Unit In, Unit Out and Defective Units it was built with independent sensors to accurately perform the counts. These three independent counts became the planned design for the yield capture system.

With the means to capture all three OEE indicators and their related cause-information designed, attention turned to how to aggregate the data.

6 Developing Pareto & Line Metrics

6.1 "Grand Pareto" & OEE Pareto

It is common practice to use a Pareto Chart to prioritise work on yield loss of a piece of equipment, or using the Grand Pareto concept, a whole line. As OEE consists of three independent indicators each with their own types of loss, there needs to be a means of comparing and contrasting each to ensure focus on the correct issues if OEE is to be improved.

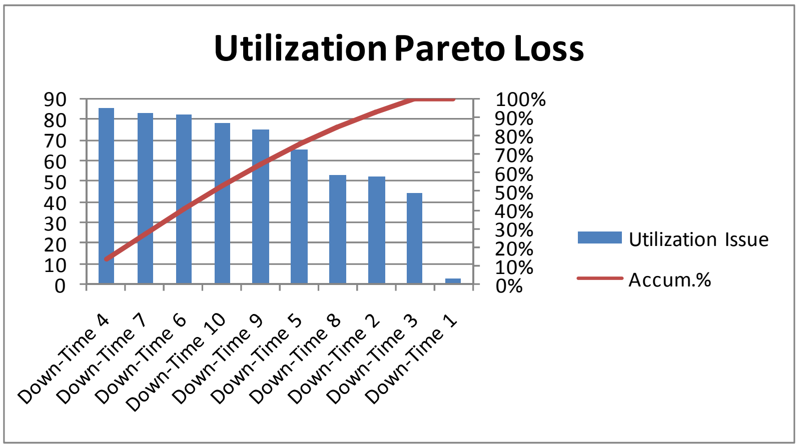


Figure 6-1 Pareto of utilisation loss

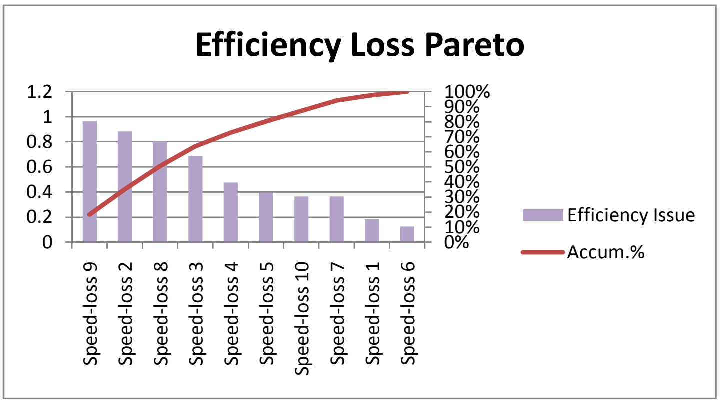


Figure 6-2 Pareto of efficiency loss

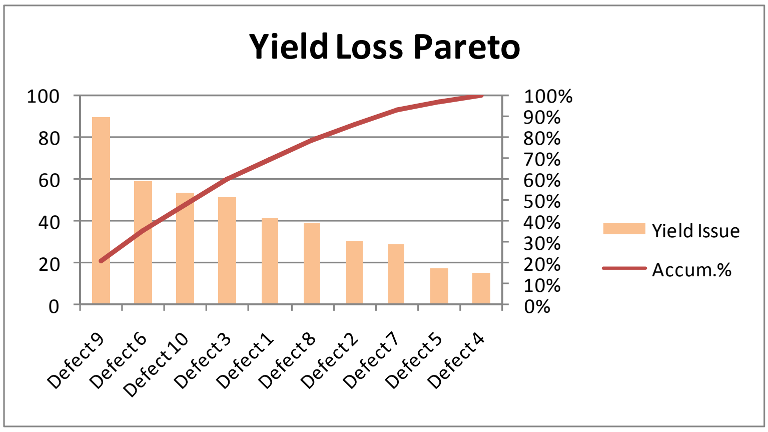


Figure 6-3 Pareto of yield loss

Imagine three sets of engineering teams assigned to a particular line. One team is responsible for improving utilisation, another for improving efficiency (cycle-time) and a third for yield. With their separate areas of responsibilities, it would be typical for each team to construct a Pareto of the known issues to prioritize focus items. If each team were to work on their top issue, Figure 6-1, Figure 6-2 & Figure 6-3 and the 1st column of the Table 6-1 show what their priority would be.

If a 'Grand Pareto' [27] approach is taken whereby all the records of loss from the whole line are brought together a different picture emerges, as may be seen in Figure 6-4 below.

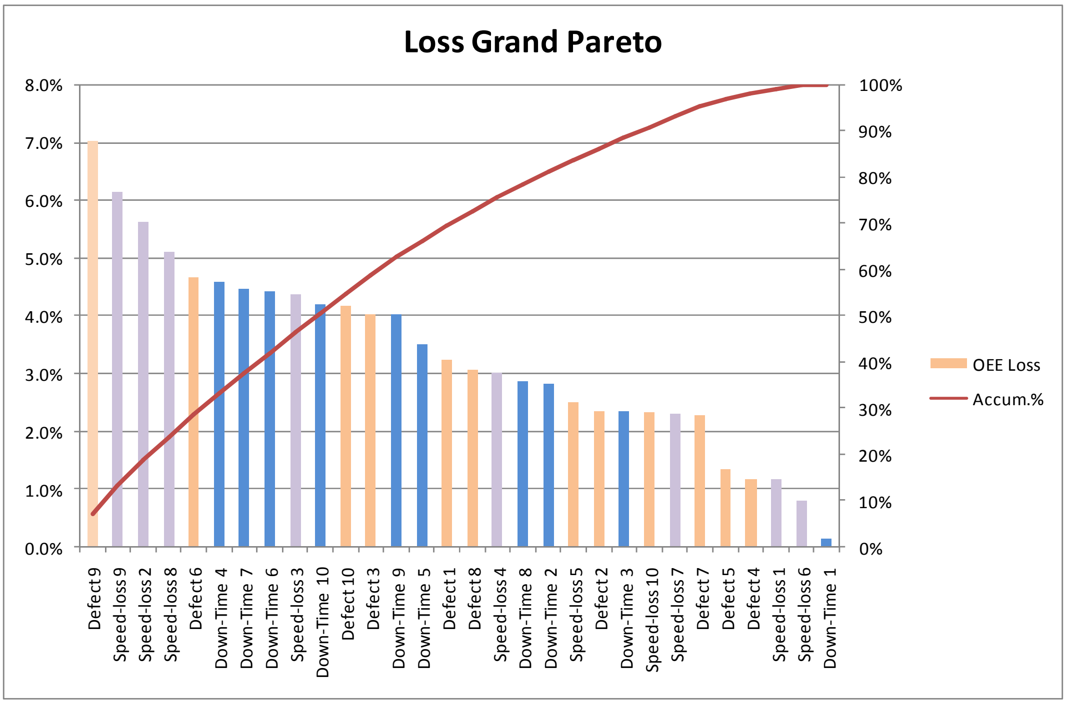


Figure 6-4 Pareto of all OEE loss

This Pareto expresses each loss as a percentage of the total loss for that particular indicator, and plots all three indicators side by side. In this instance, the engineering team assigned to utilisation issues should instead work on an efficiency issue as that takes higher priority (2nd column of Table 6-1).

One issue with using the Grand Pareto method with all OEE loss is that it would assume that 1% of utilisation loss is equal to 1% of efficiency loss and is equal to 1% of yield loss. This may or may not be the case. Within Company-X, an important factor for consideration was "opportunity cost".

The principle of "diminishing returns" needs to be considered. Company-X's protocol was to first take the simpler and less costly opportunities to improve. Therefore the investment required to improve a line from 74% to 75% will be lower than that to improve from 99% to 100%. As the line improves the remaining opportunities have a smaller gain and a larger cost.

To illustrate let's assume the line in this example is performing at 77% OEE which has a *U%* x *E%* x *Y%* breakdown of 90% x 95% x 90%. In this case, efficiency has less opportunity for improvement (5%) compared to utilisation or yield (10%). If each of the losses per indicator was weighted by the opportunity to improve, a clearer picture of improvement opportunities appears. In the OEE = 90% x 95% x 90% example, the Weighted OEE Pareto in Figure 6-5 allows a clear picture of priority incorporating ease of opportunity (3rd column of Table 6-1).

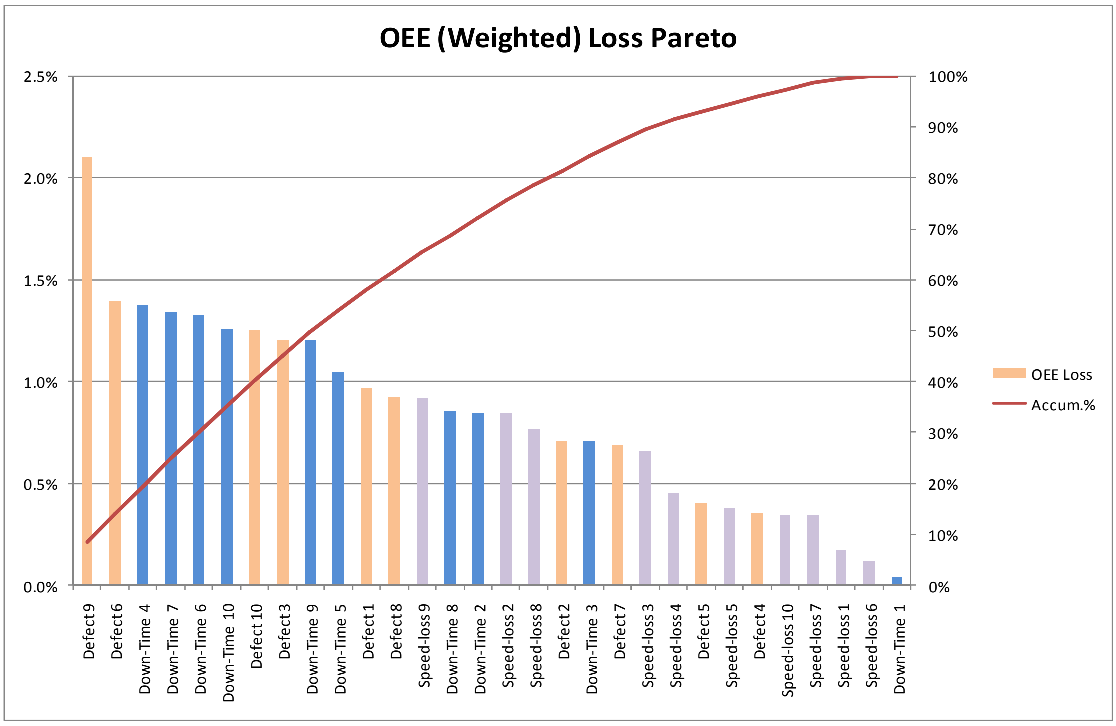


Figure 6-5 Pareto of weighted OEE loss

The OEE Loss Pareto with losses weighted for opportunity-to-improve was a planned tool in the overall system this project was scoped to deliver.

Table 6-1 Top three losses from the previous Pareto charts

Individual Pareto Charts	“Grand” OEE Pareto Chart	OEE Loss Pareto
Down-Time 4 Speed-loss 9 Defect 9	Defect 9 Speed-loss 9 Speed-loss 2	Defect 9 Defect 6 Down-Time 4

6.2 Line productivity as a function of equipment productivity

Prior to the premature cancellation of the project, there was no opportunity to put many proposed concepts to the test. The previous section covered the combining of assignable cause information for a line. This section of the thesis will outline the key concepts on deriving line metrics and indicators from the equipment metrics and indicators that the proposed system would have captured.

6.2.1 Overall Line Effectiveness

While deriving the overall line’s effectiveness (OLE) from the overall effectiveness metrics of each of the line’s was briefly considered, it stands to reason that as an equipment’s overall effectiveness is derived from its utilisation, efficiency and yield indicators, a line’s metric should be derived from its indicators.

$$OLE = U_{LINE} \times E_{LINE} \times Y_{LINE} \tag{35}$$

The burden of the calculating the accumulative contribution of each equipment's productivity to the line's productivity falls to how the three line indicators are calculated.

6.2.2 Utilisation

Company-X's current line-level utilisation metric is actually an equipment-level metric. The bottleneck of the line is determined and Down-Time events with duration greater than 90 seconds are captured and categorised. If this equipment the true bottleneck of the line then there is no argument that the bottleneck equipment's utilisation is an accurate reflection of the line's utilisation. This is certainly true from the standpoint that improving the throughput on equipment upstream or downstream of the bottleneck equipment will not improve the throughput of the line.

What is questionable is how Company-X determines the bottleneck equipment. The bottleneck designation is assigned to Equipment-E, which is present on all lines regardless of product or lifecycle phase. This established standard comes from historical performance from a routing (order of equipment through which units are processed) that is no longer in use. This legacy practice is routinely challenged by time-studies performed by the company's industrial engineers and become a point of contention for the equipment-focused engineering group.

Equipment-level OEE metric captured at all the line's equipment independently would allow for dynamic designation of bottleneck. This allows a simple refinement of the existing line-level utilisation indicator to use the utilisation of the equipment determined to be the bottleneck.

Another concept that was being considered was to sum the different factors of utilisation for all equipment on a line, Equation 9, to determine the overall utilisation independent of the throughput bottleneck. The reasoning of this was the equipment earlier in the PTM and PDM lines would routinely be utilised for engineering testing or training as manufacturing build was still progressing through the remainder of the line. This summation might better reflect the true utilisation of the line's equipment when different equipment on the line was used concurrently for production and non-production activities.

Expanding on Equation 9,
$$U_{LINE} = \frac{\sum_M T_{Run\,M}}{\sum_M T_{Avail\,M}} = \frac{\sum_M T_{Run\,M}}{\sum_M T_{Total\,M} - \sum_M T_{Schd\,M}} \tag{36}$$

6.2.3 Efficiency

While utilisation calculated independently of the line's bottleneck was considered, there did not seem to be an alternative with respect to efficiency. The bottleneck equipment is by definition that with the slowest cycle-time or lowest throughput in the manufacturing line. The efficiency of the line cannot improve unless the efficiency of the bottleneck is improved.

The question becomes whether the bottleneck is determined via OEE – which includes upstream utilisation, efficiency and yield losses in the line, or based on which equipment has the lowest rated throughput or longest cycle-time.

For example, the equipment with the longest rated cycle-time on the line is a clear contender for being the actual bottleneck. Indeed, if the line is full of pristine units and all upstream equipment is running, it will be the bottleneck. However, the performance of the upstream and even downstream equipment may move the functional bottleneck to elsewhere on the line.

Per their definitions, each indicator should perform independently of the other indicator. As efficiency is the only indicator that incorporates equipments cycle-time, it was determined lowest rated cycle-time of all the line's equipment would be used as the line's rated cycle-time. The line's actual cycle-time would be the highest actual cycle-time of all the line's equipment.

$$E_{LINE} = \frac{CT_{Rated\,MIN}}{CT_{Actual\,MAX}} \tag{37}$$

These two factors represent the best possible performance of the line and would compare it the worst actual performance of the line. In theory they would represent the how far the line is from performing at the 100% efficiency.

6.2.4 Yield

The classic yield model for a line is to treat the line as if it as a singular piece of equipment with many stations and operations.

$$Y_{LINE} = \frac{u_{out\,M}}{u_{in1}} \quad \text{, where M is the last equipment on the line} \tag{38}$$

Figure 6-6 Line Yield treating all equipment as one large process

Defective units from each process will still have to be counted, with the summation of which accounting for the line's defective count.

$$Defective_{LINE} = \frac{\sum_{M} u_{Def\ M}}{u_{In1}} \tag{39}$$

This model goes hand-in-hand with the recommend process model, but does not utilize all the information available in the most optimal manner. While the yield metric will be technically accurate, it will not reflect any rework or additional non-value added operations that occurred to achieve this yield. Such additional activities are unlikely to be accounted for in the profit-margin of each individual unit and therefore reduction of such will remove impact to the bottom-line.

The proposed equipment-level yield indicator already includes the concept of only including pristine, non-reworked units as part of the count of units outputted. To combine the rolled throughput yield of a series of equipment into a single Line Yield, the ratios are multiplied.

$$Y_{LINE} = Y_1 \times Y_2 \times \ldots \times Y_M \tag{40}$$

While rework loops at Company-X are extremely rare, this practice of explicitly combining the yield indicators of all of the line's equipment was the planned line method to derive the line's yield.

6.3 Chapter Summary

The Weighted OEE Pareto provided the means to compare all potential opportunities (utilisation gains, efficiency gains and yield gains) for improving OEE against each other, and rank them in importance.

An Overall Line Efficiency (OLE) metric would be determined from multiplying line-indicators. The line-indicators would in turn be calculated from all independently captured equipment-indicators of all the equipment in the line.

7 Conclusions & Recommendations

7.1 Conclusions

An OEE tracking system that added little if any extra non-value added work on equipment operators was created. Such a system categorised its factors and sources of loss in a manner than allowed all PTM, PDM and HVM departments focus on their specific goals yet also allowed for correlation of performance between the phases of program life-cycle.

An utilisation tracking system was designed to interact with an equipment's controller to capture and categorise all time spent on the equipment. It also ensured that the time the equipment spent powered down is captured. The captured data required minimal user input and was used to accurately determine the equipment's utilisation. This utilisation indicator provided the same functionality as the Availability Efficiency and Operating Efficiency metrics as defined by SEMI E79.

An efficiency tracking system was designed to interact with an equipment's computer-controller to capture and categorise the equipment's cycle-time. Cycle-time was categorized as steady-state and non-steady-state such that:

- Historical steady-state cycle-times from multiple instance of Equipment-Z were used to determine Equipment-Z's Rated Cycle-Time.
- Steady-state cycle-time, or some function of non-steady-state cycle-time to estimate steady-state, were used as Actual Cycle-Time in real time.

This efficiency indicator provided the same functionality as the Rated Efficiency metric as defined by SEMI E79.

A yield tracking system was designed to interact with an equipment's controller to capture the number of units actually loaded and unloaded from the equipment as well as the number of defective units. It also categorised, with minimal user input as needed, the number and classification of defects detected on defective units. This yield indicator provided the same functionality as the Quality Efficiency metric as defined by SEMI.

OEE metrics are only valuable if the sources of OEE loss are prioritised for focused improvement. Rather than focus on utilisation, efficiency and yield independently these OEE losses were weighted based on opportunity and compared in the same Pareto chart.

This system was implemented on Equipment-Z on selected pilot PTM, PDM and HVM lines at Company-X. End-users of the system and the captured data approved a final refinement of the utilisation tracking software. Implementation was approved pending validation of those refinements. The same tracking systems used on Equipment-Z could be implemented on Company-X's other equipment.

7.2 Recommendations

The following would have been developed further had opportunity allowed.

Automatic classification of efficiency loss: While the existing system at Company-X allowed for the automatic detection of steady-state and non-steady-state, it only provided the raw data from which engineering would have to infer opportunities for improvement. Ideally the system would know the conditions which constituted the equipment's rated cycle-time, and would be able to deduce and assign causes of loss automatically. For example, if the rated cycle-time included a "waiting for upstream time" to be 1 second or less, and the signal from the upstream process occurred after 2 seconds, the monitoring software could recorded a speed loss of 1 second due to waiting for upstream equipment.

Determining Overall Line Efficiency as a function of the line's equipment's OEE metrics: Company-X as well as other manufacturers require the ability to correlate the current performance of individual stand-alone equipment used for batch-volume production during prototyping, to the future performance of fully coupled dedicated equipment in a high-volume manufacturing line. It was proven that the same system can work on a piece of equipment be it stand-alone or coupled, or used for batch-volume or high-volume. Upon implementing this system on all equipment across the line, the various proposed formulae in Section 6.2 could be evaluated.

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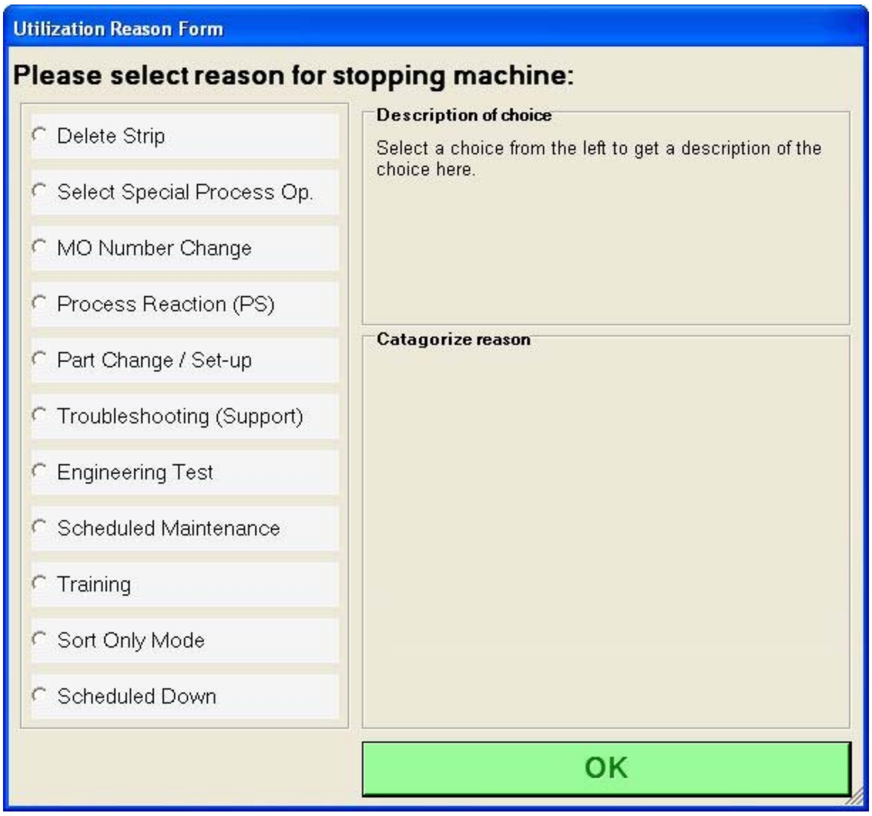
Appendix – A

The appendix describes more in more detail the proposed changes to the utilisation tracking system.

Changes to Normal Run Mode (NRM)

1. User will <u>no longer</u> be presented option screen when they press stop {Figure A-1}.
    A. Machine already logs when user selects any of the *Basic* functions {Figure A-2}.
    B. User will have to press the **Switch Mode** button when the need to access the other modes.



Utilization Reason Form

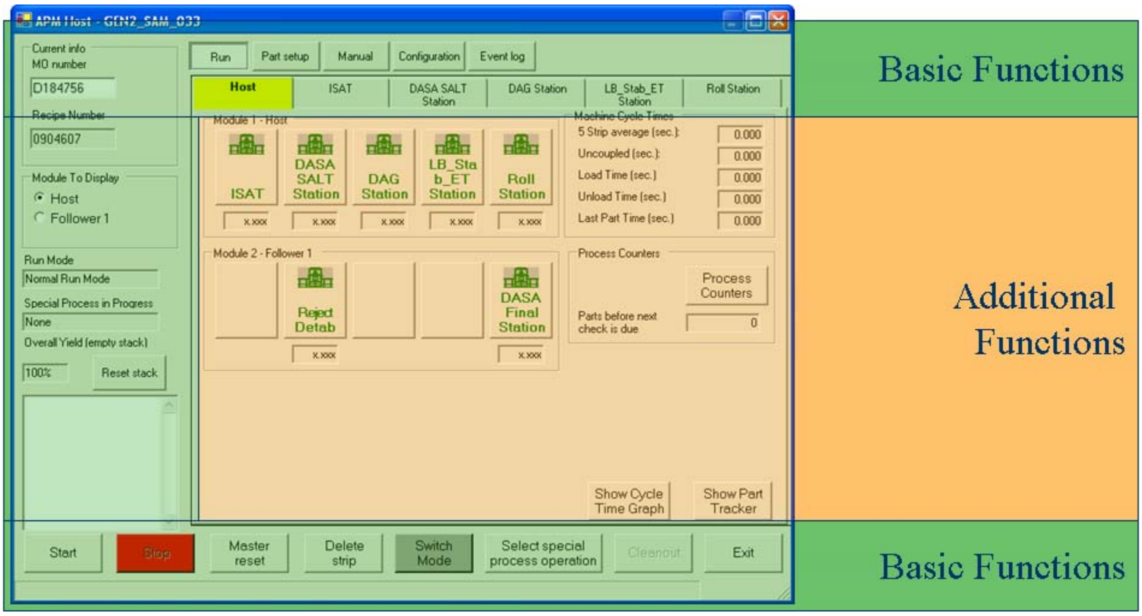
Please select reason for stopping machine:

Description of choice

Select a choice from the left to get a description of the choice here.

Catagorize reason

Figure A-1 – User will no longer see this prompt when they press stop



APM Host - GEN2_SAM_033

Current info
MO number: D184756
Recipe Number: 0904607

Module To Display: ● Host ○ Follower 1

Run Mode: Normal Run Mode
Special Process in Progress: None
Overall Yield (empty stack): 100%

Machine Cycle Times
5 Strip average (sec.): 0.000
Uncoupled (sec.): 0.000
Load Time (sec.): 0.000
Unload Time (sec.): 0.000
Last Part Time (sec.): 0.000

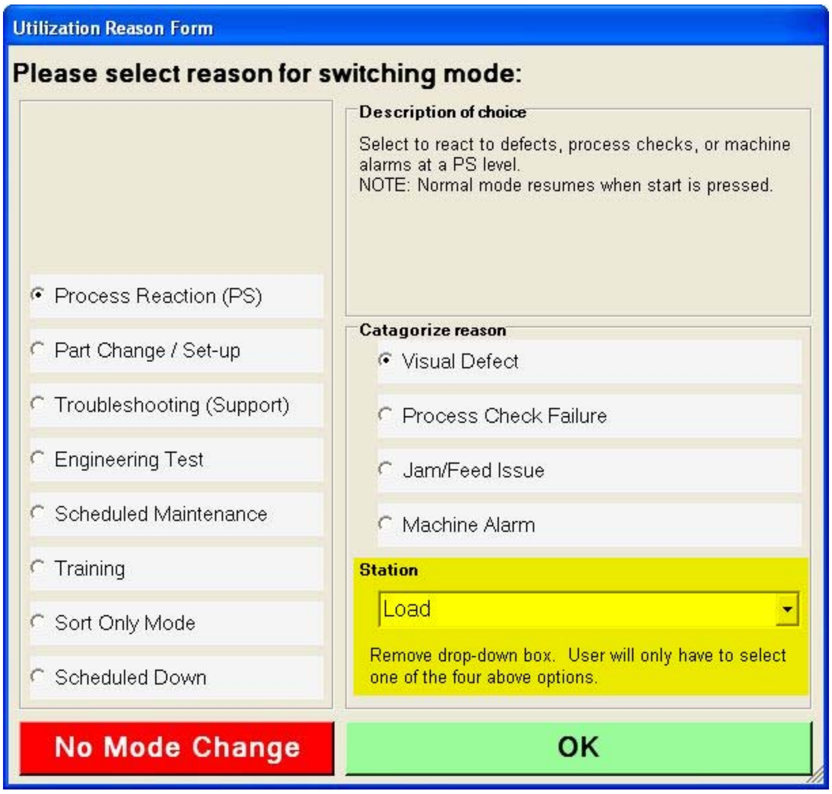
Process Counters
Parts before next check is due: 0

Figure A-2 – Basic & Additional Functions on APM Host interface

Changes to Process Reaction Mode (PRM)

This mode is needed for immediate and swift reaction to process control & minor product quality issues. Such reaction may require multiple stops to the process. This mode should not be used when there is a reasonable risk of building product out of specification.

1. User will <u>no longer</u> be presented a drop-down box for “Station” or “Process” option screen when they press stop {FigureA-3}.



Please select reason for switching mode:

- ● Process Reaction (PS)
- ○ Part Change / Set-up
- ○ Troubleshooting (Support)
- ○ Engineering Test
- ○ Scheduled Maintenance
- ○ Training
- ○ Sort Only Mode
- ○ Scheduled Down

Description of choice

Select to react to defects, process checks, or machine alarms at a PS level.
NOTE: Normal mode resumes when start is pressed.

Catagorize reason

- ● Visual Defect
- ○ Process Check Failure
- ○ Jam/Feed Issue
- ○ Machine Alarm

Station: Load

Remove drop-down box. User will only have to select one of the four above options.

Figure A-3 – Highlighted input will be removed

2. Pressing **Start** in PRM will no longer automatically switch the machine into NRM.
   A. Switching to NRM will occur in the following manner:
      i. User pressed **Switch Mode** and selects “Normal Run Mode”
      ii. Machine processes 10 carriers without stopping
         (a) This will occur automatically, no pop-up or prompting
   B. Utilisation will no longer be classified as “ Time”, rather it will be similar to NRM:
      i. While the machine is running: “Prod Run Time”
      ii. While the machine is idle: “Prod Idle Time” with automatic assignment.
      iii. While the machine is stopped: “Unscheduled Down Time” with the reason entered by the user when they switched mode being assigned.

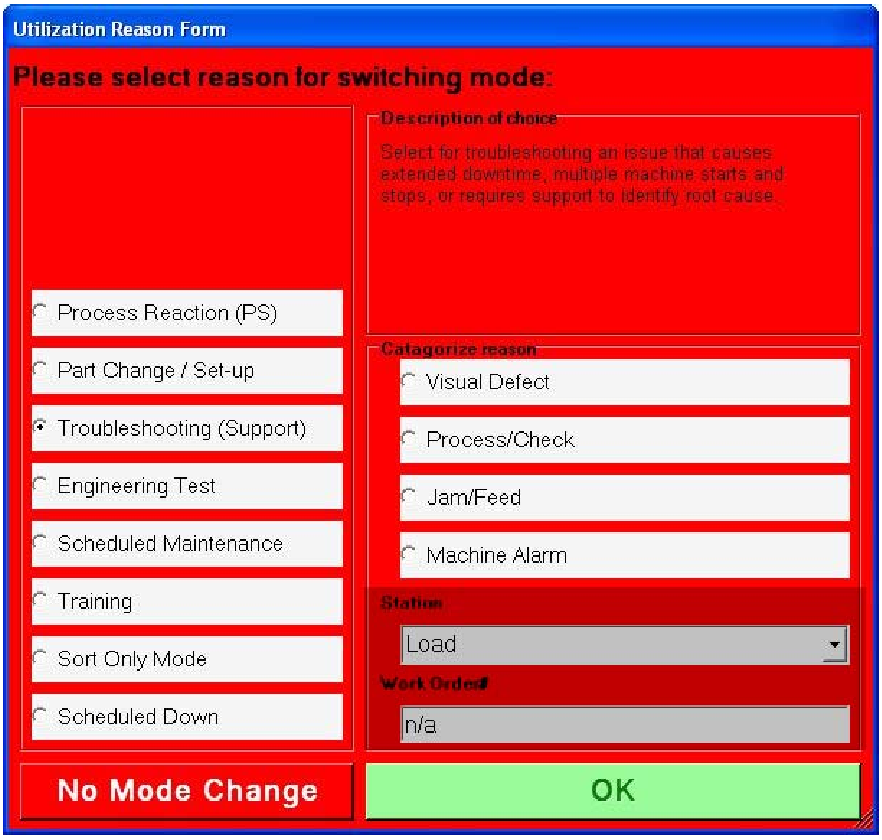
Changes to Product change / Setup Mode (SM)

There were no changes requested. It was acknowledged that the issue of accidentally leaving the machine in this mode when there is no schedule crew would only be addressed by using the captured data to improve setup times.

Changes to Troubleshooting Mode (TSM)

Similar changes as described in PRM. This mode is needed for troubleshooting issues in the proto-type manufacturing lines and program development lines. This mode will rarely be used by high-volume manufacturing lines.

3. Removed required input {Figure A-4}:
   A. User will <u>no longer</u> be presented a drop-down box for "Station" or "Process" option screen when they press stop
   B. User will <u>no longer</u> have to enter maintenance work order number.



Utilization Reason Form

Please select reason for switching mode:

○ Process Reaction (PS)
○ Part Change / Set-up
● Troubleshooting (Support)
○ Engineering Test
○ Scheduled Maintenance
○ Training
○ Sort Only Mode
○ Scheduled Down

Description of choice

Select for troubleshooting an issue that causes extended downtime, multiple machine starts and stops, or requires support to identify root cause.

Catagorize reason

○ Visual Defect
○ Process/Check
○ Jam/Feed
○ Machine Alarm

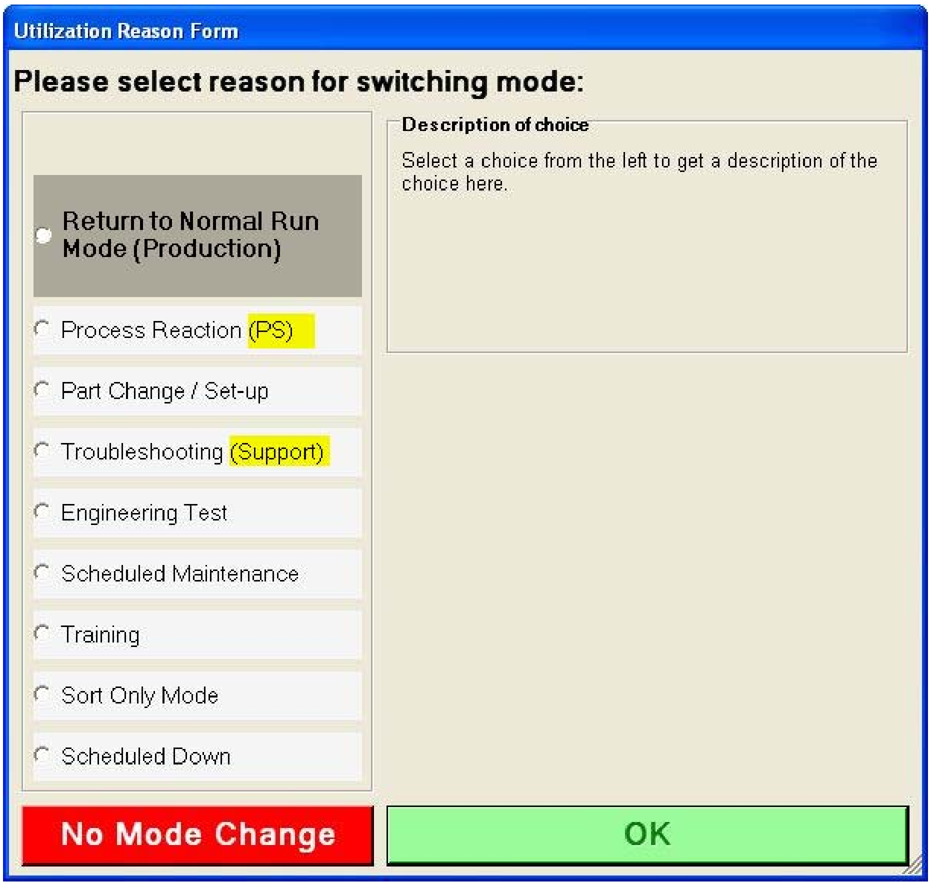
Station: Load

Work Order#: n/a

Figure A-4 – Shaded input will be removed

4. Verbiage of "(PS)" & "(Support)" will be removed from Switch Mode pop-up. {Figure A-5}.
   A. Appropriate personnel will be trained to understand the appropriate mode they should use.

B. Note: PS or process specialist is the term used by Company-X to describe operators



Utilization Reason Form

Please select reason for switching mode:

● Return to Normal Run Mode (Production)
○ Process Reaction (PS)
○ Part Change / Set-up
○ Troubleshooting (Support)
○ Engineering Test
○ Scheduled Maintenance
○ Training
○ Sort Only Mode
○ Scheduled Down

Description of choice

Select a choice from the left to get a description of the choice here.

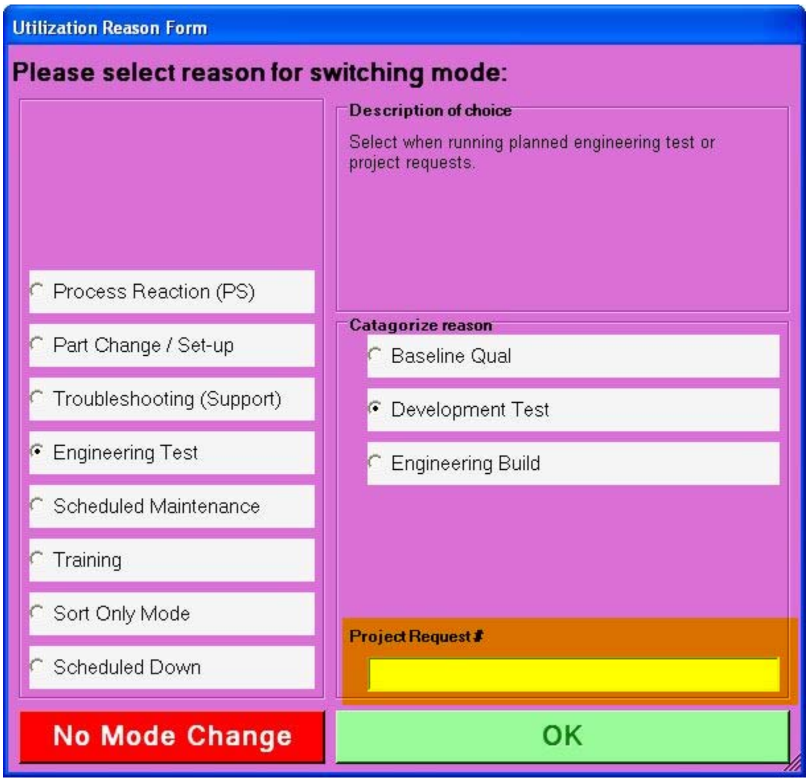
Figure A-5 – Highlighted verbiage will be removed

Changes to Engineering Test Mode (ETM)

There were multiple instances in the DC were testing occurred without a test request. The test request system was intended for program development and does not cover Process Definition Engineer testing.

5. Removed required input {Figure A-6}:

A. User will <u>no longer</u> be requested to provide Project#.



Please select reason for switching mode:

○ Process Reaction (PS)
○ Part Change / Set-up
○ Troubleshooting (Support)
● Engineering Test
○ Scheduled Maintenance
○ Training
○ Sort Only Mode
○ Scheduled Down

Select when running planned engineering test or project requests.

○ Baseline Qual
● Development Test
○ Engineering Build

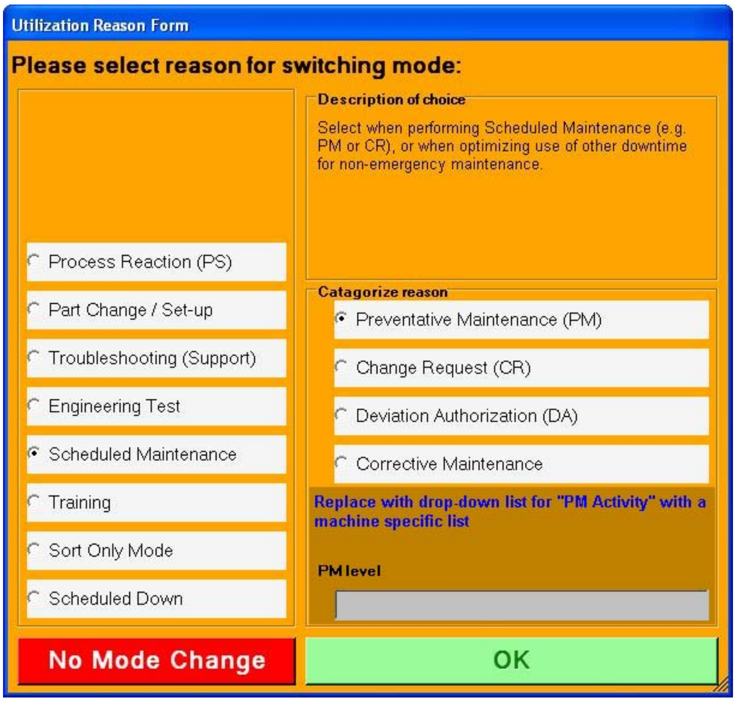
Figure A-6 – Highlighted input will be removed

Changes to Schedule Maintenance Mode (SMM)

6. Add detail: "PM Level" is not adequate to describe what preventative maintenance occurred{Figure A-7}::

   A. Various PM measures are taken that are not part of the PM level procedures e.g. gas refill

   B. Need to provide a customizable choice-list for the specific machine that includes the levels.



Utilization Reason Form

Please select reason for switching mode:

○ Process Reaction (PS)
○ Part Change / Set-up
○ Troubleshooting (Support)
○ Engineering Test
● Scheduled Maintenance
○ Training
○ Sort Only Mode
○ Scheduled Down

Description of choice

Select when performing Scheduled Maintenance (e.g. PM or CR), or when optimizing use of other downtime for non-emergency maintenance.

Catagorize reason

● Preventative Maintenance (PM)
○ Change Request (CR)
○ Deviation Authorization (DA)
○ Corrective Maintenance

Replace with drop-down list for "PM Activity" with a machine specific list

PM level

Figure A-7 – Shaded text field will be replaced by drop-down list

Changes to Training Mode (TM)

There were no changes requested.

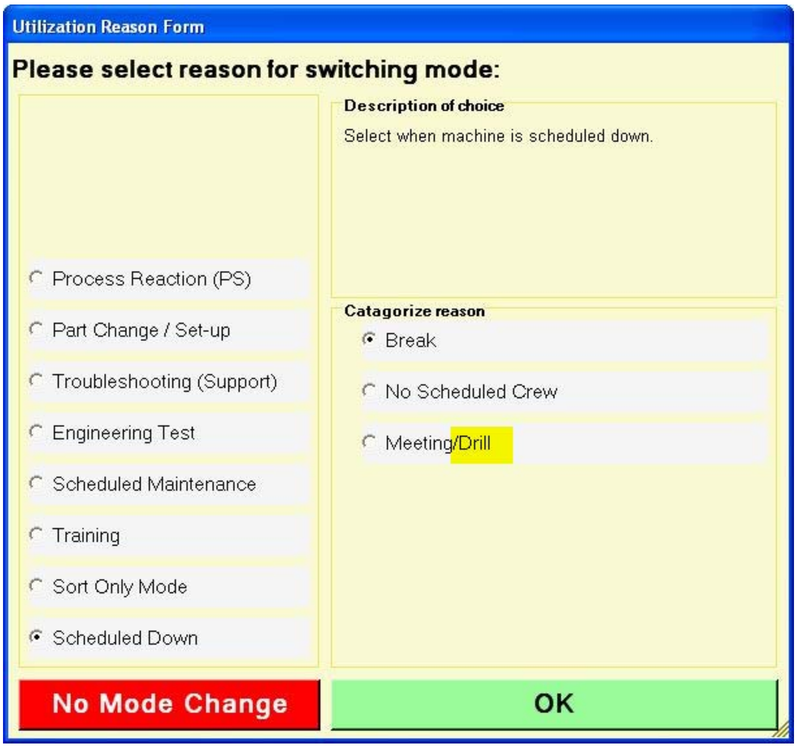
Changes to Custom Mode (CM)

There is one customizable mode for each piece of equipment. There were no changes requested.

Changes to Scheduled Down Mode (SDM)

Feedback was received asking what would happen if staff went on break and left the machine running. The machine would automatically assign the reason for any automatic stop.

7. Replace “Meeting/Drill” with “Meeting” {Figure A-8}:
    A. Unit staff are instructed to leave the unit immediately during a drill and therefore this will not be selected, or worse, it could cause confusion.



Utilization Reason Form

Please select reason for switching mode:

○ Process Reaction (PS)
○ Part Change / Set-up
○ Troubleshooting (Support)
○ Engineering Test
○ Scheduled Maintenance
○ Training
○ Sort Only Mode
● Scheduled Down

Description of choice

Select when machine is scheduled down.

Catagorize reason

● Break
○ No Scheduled Crew
○ Meeting/Drill

Figure A-8 – Highlighted verbiage will be removed

Appendix – B: Changes within Company-X and impact to project

Despite the backing of management from the manufacturing and engineering departments at each of the company's plants, progress on the design and development of the OEE tracking system was fraught with setbacks. These are likely typical for many manufacturing environments with multiple overlapping departments and different management in different locations.

None of these setbacks were as significant as the company's need to restructure in December 2008, the full affects of which were not completely understood until June 2009. One of the HVM-focused plants was closed, with the PTM/PDM-focused plant gaining HVM duties. Approximately 25% of the work-force were either laid-off or voluntarily departed the company. This all resulted in:

- The dissolution of the department that commissioned the project
- The loss of all major project sponsors, via reassignment or departure
- A significant change of internal goals and focus on surviving the global economic recession

The long-term effort for a company-wide implementation of the system was shelved. The completed development and implementation of the designed system on a single set of equipment did not make business sense.

OEE improvement was no longer a priority at Company-X as demand had dropped to level where there was excess capacity. The software and documented development activities, results and decision were retained. Assuming the company's survival and growth OEE improvement would be needed in the future. At such time a system that was already proved to capture utilisation, efficiency and yield could be implemented on Equipment-Z. In turn Equipment-Z would serve as the model needed to implement all throughout the line.