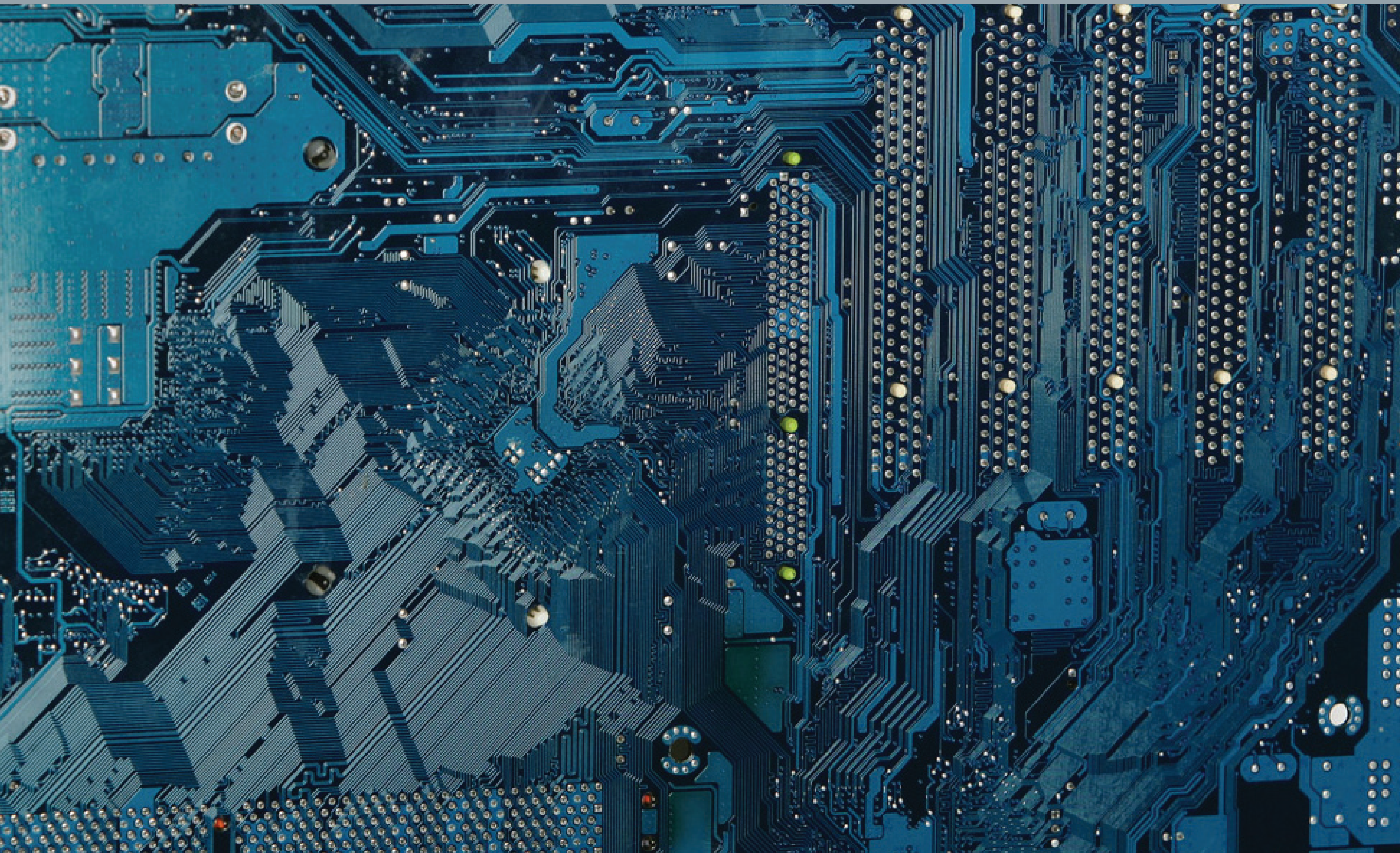

USING AVAILABILITY ANALYSIS TO REDUCE TOTAL COST OF OWNERSHIP

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Total Cost of Ownership (TCO) gained popularity with electronics manufacturers in the early 1990's when many industries, especially semiconductor equipment users, wanted to recognize that the procurement decision encompassed much more than the initial acquisition (purchase) cost. Indeed, if you consider costs associated with owning and operating the asset over its entire useful life, it is common for operational costs to considerably exceed acquisition costs.

This article introduces a TCO model that has been developed by Agilent Technologies. A key component of the TCO model is the notion of downtime mitigation. By way of example, the article shows how availability analysis can be used to improve system uptime and reduce the cost to own and operate the equipment.

Total Cost of Ownership Modeling

TCO is defined to be the total cost to own and operate a piece of equipment over its useful life. Agilent Technologies has developed a TCO model comprised of the two core elements of capital expenses (acquisition costs) and operating expenses that describe these costs at a high level. Modeling of capital expenses is fairly straightforward with depreciation schedules being the principle area of variation. Capital expenses generally are costs (C_{acq}) incurred to acquire and install the equipment. Operating expenses provide an area for much greater latitude in terms of what is included in the TCO model and how the cost components are represented. The TCO model presented in this article structures operating expenses in the following manner:

- Preventive Maintenance – C_{pm}
- Corrective Maintenance – C_{cm}
- Downtime Mitigation – C_{dm}
- Technology Refresh – C_{tr}
- Training & Education – C_{te}
- Resale value or disposal cost – C_{rv}
- Other – C_o

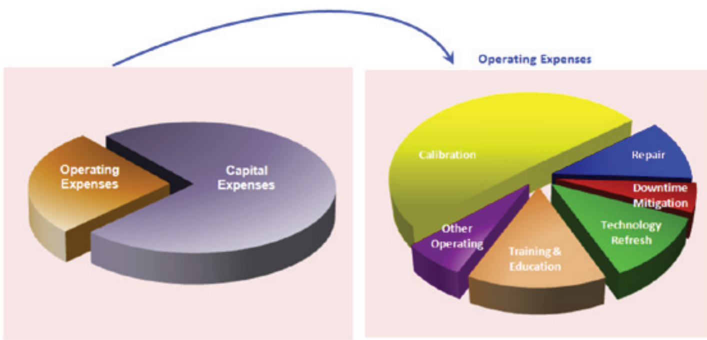

Figure 1. Capital Expenses and Operating Expenses represented in the TCO model.

The Total Cost of Ownership equation is given by:

$$TCO = C_{acq} + C_{pm} + C_{cm} + C_{dm} + C_{tr} + C_{te\,+}\, C_{rv} + C_{o}$$

Agilent Technologies is a leader in the electronic Test & Measurement industry. Typically calibration of the equipment is the single largest cost component of preventive maintenance expenses. In this regard, calibration cycle period is the single largest lever to pull on to reduce such metrology costs. Other important variables beyond just the cost to perform a calibration include cal turnaround time (TAT), logistical costs and any "repair" costs required to adjust the product back into calibration. Preventive maintenance costs would also include other periodically scheduled actions such as proactive replacement of subassemblies that tend to exhibit wear out phenomena.

Corrective maintenance generally refers to unplanned downing events such as equipment failure. For the purposes of this TCO model, corrective maintenance costs are represented by the cost to perform the repair, re-calibrate after the repair, logistics to remove, ship and re-install, and performance verification of the equipment. The cost to perform the repair can be represented by either a contracted repair agreement or, if the owner wishes, to "self-insure" on a Per Incident (P.I.) basis. Annual P.I. repair expenses are modeled as the expected annual value calculated by multiplying the P.I. cost times the probability of failure occurring in a one year period. While at first glance it may appear that a P.I. strategy is the lower cost option, one must also consider that a repair contract usually results in a lower repair TAT and therefore lower downtime. A downtime cost penalty must be applied to recognize the fact that the equipment was unavailable for use by the owner. This is accomplished by applying a cost driver variable, such as a weekly rental rate proxy, to the cost equation such that:

Cost of Unavailability = (purchase price) x (rental rate proxy) x (repair TAT)

Weekly rental rates for performance measurement equipment typically run in the range of 2-5% of the purchase price.

The consequences of unplanned corrective maintenance events such as equipment failure can be extremely costly, even disastrous, for the enterprise. For instance, if a test system goes down in a volume manufacturing environment or in a critical R&D application, the impact can be lost sales and missed business opportunities that may cost the enterprise millions of dollars. Because of difficulties in quantifying and predicting the outcome of such events, the TCO model does not place this aspect of the cost element under the heading of corrective maintenance. Instead, these sort of "catastrophic" costs are addressed through cost avoidance measures and strategies described in the Downtime Mitigation section that follows later in this article.

Technology Refresh (sometimes termed Product Migration) refers to situations where equipment owners wish to upgrade their assets to products with increased levels of measurement capability or increased levels of measurement speed. Typically the largest component of product migration costs is the investment required by equipment owners to ensure backward/forward compatibility of the new piece of equipment in their test process. Costs associated with developing/editing test code to ensure compatibility in the test process can be quite high. These are one-time expenses that should be amortized over the installed base of equipment that derive the benefit.

At the end of the equipment's useful life, the asset is disposed of either by selling, trading in for credit, or having the equipment recycled. The first two options are treated as a negative cost in the TCO model. High resale value becomes a strategic advantage for suppliers of superior quality products when one looks at the TCO algorithm.

Other TCO costs that a business may wish to incorporate into the calculation include energy, floor space and consumable materials.

Next, we turn our attention to a critical TCO component the author refers to as Downtime Mitigation. This is an area in which reliability and quality professionals play a crucial role.

Downtime Mitigation

As mentioned earlier, unplanned downing events (failures) are probabilistic in nature with the potential for catastrophically high costs to the business. This makes it difficult to attach a cost estimate that is both accurate and believable. A better approach is to develop and implement operational strategies that mitigate (or eliminate) the effects of unplanned downing events. Engineering and management have a number of downtime mitigation strategies to select from, including:

1) High Reliability
   - Select a product that offers leading edge reliability.
2) Low Repair TAT
   - Select a return-to-depot service provider that offers lowest possible repair TAT.
   - Perform on-site repair, either by contracting with a service provider or by developing the capability internally.
   - Purchase extended warranty service contracts to reduce or eliminate logistical, administrative and procurement delays.

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3) Capacity
   - Purchase extra manufacturing test capacity and hold in reserve.
   - Purchase spare equipment.
   - For self-maintainers, purchase spare parts.

The approach suggested in this article is to develop and implement a downtime mitigation strategy that enables the business to deliver on its commitments to customers while minimizing TCO. One way to evaluate these strategies is to conduct Availability analyses and select the option that strikes an optimum balance between maximizing system Availability (i.e. minimizing downtime), minimizing costs to implement the strategy, and minimizing ongoing operating costs.

Some factors at work in the TCO algorithm cause costs to vary over time. Reliability characteristics of equipment (influencing repair costs and downtime costs) and calibration cycle period (influencing metrology costs) are examples of two such factors. In order for businesses to properly plan for future operating costs, it is important that TCO costs be modeled over time (see Figure 2).

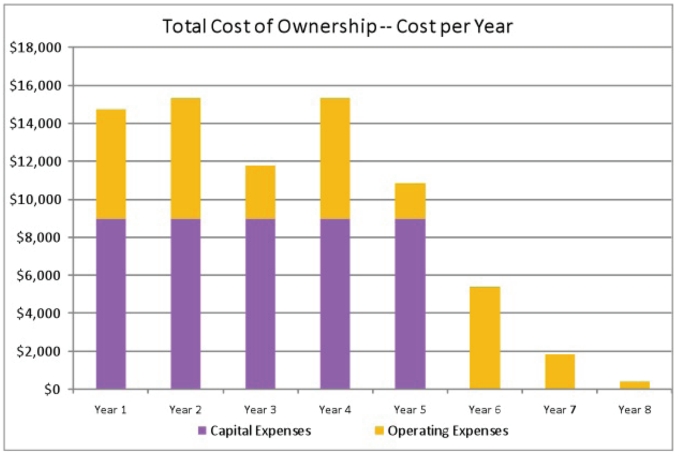

Figure 2. Total Cost of Ownership over time.

The example discussed later in this article illustrates the impact of these factors on a business' gross margins.

Availability

Availability is defined to be the probability that a given piece of equipment or system meets its intended function at a specified point in time. Factors that influence the Availability equation include the equipment's hazard function (instantaneous failure rate), repair TAT distribution, calibration TAT distribution and customer use model. Using specialized software and knowledge of product reliability and maintainability (R&M), we can model complex systems to arrive at a deep understanding of the variables that drive Availability of the "system."

Availability analysis at the system and subsystem levels provides clarity on the key drivers that most impact Uptime and TCO, thus enabling the business to make process recommendations for improving performance of the test system. From a thorough understanding of R&M mechanisms at work will come creative solutions to increase Availability and reduce TCO.

Recall that Availability is defined as the probability that an item will be available when it is called upon for duty. Availability can also be thought of as the proportion of total time that an item is available for use. The underlying factors that influence availability are reliability and maintainability. Reliability is the probability that an item meets its intended function over a given timeframe and in a given environment. Maintainability is a measure of the ability to restore an item to a specified condition when a maintenance action is performed.

Three common measures of availability are Inherent Availability, Achieved Availability and Operational Availability. Inherent Availability is the ideal situation where the repair action occurs without delay, i.e. immediately when the item fails. Consequently, Inherent Availability is the simplest to model and is defined as:

$$A_i = \gamma / (\gamma + \lambda)$$

where γ = repair rate and λ = failure rate.

Assuming constant repair rate and constant failure rate, the simplified form of the Inherent Availability equation becomes:

$$A_i = MTBF / (MTBF + MTTR)$$

where MTBF is the mean time between failure and MTTR is the mean time to repair.

Achieved Availability is like Inherent Availability in that corrective maintenance actions are assumed to take place immediately upon failure. However, Achieved Availability also takes into account preventive maintenance actions. It is defined as:

$$A_a = MTBMA / (MTBMA + MMT)$$

where MTBMA is the mean time between both corrective and preventive maintenance actions and MMT is the mean maintenance action time.

Operational Availability best represents what is likely to occur in real life. It takes Achieved Availability one step further by accounting for the fact that most maintenance actions are not instantaneous, e.g. factors such as logistical delays in dispatching maintenance crews and delays in delivering replacement parts to repair depots. It is defined as

$$A_o = MTBMA / (MTBMA + MDT)$$

where MDT is the mean down time.

The example that follows employs Operational Availability methods.

Manufacturing of a New Microwave Device

Now let's turn our attention back to using Availability analysis methodologies to evaluate downtime mitigation strategies with the objective of minimizing TCO while still delivering on customer commitments.

We start by looking at a manufacturing operation that will produce a new microwave component. This new product is expected to be in manufacture for two years before being discontinued. Part of the manufacturing process includes final test where the device under test undergoes a complex suite of measurements. These tests are performed by an elaborate test system comprised of three measurement subsystem instruments (A, B and C) in which each has its own set of reliability characteristics. The Test System ABC is configured such that the subsystems are in series reliability-wise as shown in Figure 3.

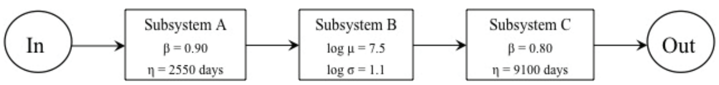

Figure 3. Reliability representation of Test System ABC.

Reliability characteristics for Test System ABC:

Subsystem A: 2-parameter Weibull distribution with shape parameter (β) = 0.9 and scale parameter (η) = 2550

Subsystem B: lognormal distribution with logmean (μ) = 7.5 and logstdev (σ) = 1.1

Subsystem C: 2-parameter Weibull distribution with shape parameter (β) = 0.8 and scale parameter (η) = 9100

The manufacturing floor is comprised of 20 identical but independently-operated Test Systems ABC as shown in Figure 4. The production process runs 24x7 and is 100% utilized. When one of the Test Systems goes down, the remaining 19 systems continue to run uninterrupted, however manufacturing output of the microwave device is temporarily lost until the failed system can be brought online again. For each minute of lost test time due to corrective maintenance, the enterprise loses $4.00 of gross margin (sometimes referred to as gross profit).[*]

[*] Gross margin = Net Sales minus Cost of Goods Sold

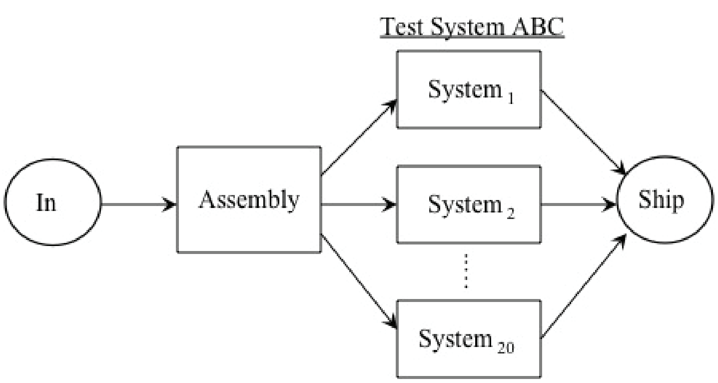

Figure 4. Manufacturing process flow.

Downtime Mitigation Strategies

Management has provided reliability engineering with the following four downtime mitigation scenarios for evaluation. They would like a recommendation for a strategy that minimizes TCO (as measured by impact on gross margin) and delivers on customer expectations.

Scenario 1: High Reliability

A special environmentally-controlled enclosure is designed and built to house the 20 test systems. Including procurement, installation, operating and energy costs, the total cost of the enclosure is $180,000. The residual value of the enclosure at the end of its useful life is $40,000. The enclosure results in improved reliability of the test systems with these reliability characteristics:

Subsystem A′: 2-parameter Weibull distribution with shape paraeter (β) = 0.95 and scale parameter (η) = 4000

Subsystem B′: lognormal distribution with logmean (μ) = 7.7 and logstdev (σ) = 1.0

Subsystem C′: 2-parameter Weibull distribution with shape parameter (β) = 0.85 and scale parameter (η) = 12000

Cost to have a failed system repaired is $20,000 and repair TAT is 10 days.

Scenario 2: Spare Test System

A complete spare test system is purchased and held in reserve. Cost is $320,000 and residual value after the end of its useful life is $60,000. When a system goes down, the spare system is deployed by technicians. The time required to deploy the spare system, verify performance characteristics and route production units to it is six hours. Cost to have a failed system repaired is $20,000 and repair TAT does not impact system availability.

Scenario 3: Offsite Annual Repair Contract

A third party service company is utilized. An annual repair contract is arranged whereby the failed system is shipped offsite for expedited repair. Cost of the annual contract is $180,000 per year to service the fleet of 20 test systems, and the downtime experienced during repair is five days.

Scenario 4: Onsite Repair

An arrangement is made with the equipment supplier to provide rapid response onsite repair of a downed test system. This is handled on a Per Incident basis and repair cost is $35,000 per event. The downtime in this scenario is 24 hours.

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A summary of Investment (capital) expenses and Contract repair expenses for the four downtime mitigation strategies is shown in Table 1.

Reliability and Availability Analyses

Using the reliability characteristics of the subsystem components, the Test System reliability was calculated and charted over time as shown in Figure 5. One can see that the environmentally-controlled enclosure in Scenario #1 provides improved reliability as compared with the system reliability observed in the three other scenarios.

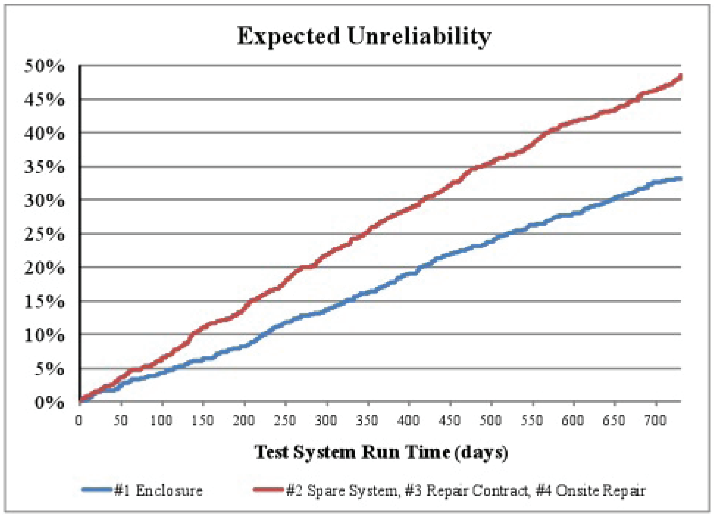

Figure 5. Unreliability curves generated from modeling system reliability of the four downtime mitigation strategies.

The reliability engineer then performed Availability analyses using the reliability and maintainability information provided in the four downtime mitigation strategies. Test system availability was modeled and expected outcomes were calculated using Monte Carlo simulation as shown in Figure 6.

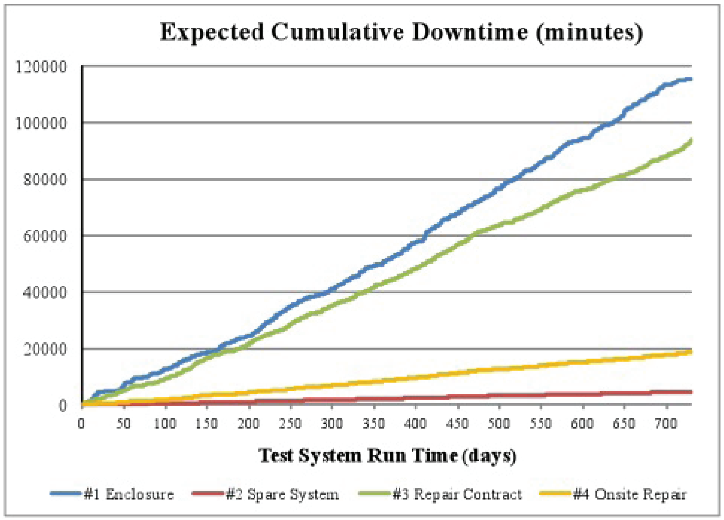

Figure 6. Expected total downtime of the 20 test systems under four different downtime mitigation strategies.

Based on the Availability analysis, the engineer calculates the expected number of failures and expected total downtime over a two year manufacturing lifecycle. Total repair costs were calculated by multiplying the expected number of failures times the Per Incident Repair costs listed earlier. The repair cost for Scenario #3 is zero because all repairs are covered under a service contract. Downtime costs were calculated by multiplying total expected downtime minutes times the impact on gross margin ($4.00 per downtime minute). Impact of operating costs on gross margins is then calculated by summing repairs costs and downtime costs as shown in Table 2.

Note: For each minute of lost test time due to corrective maintenance, the enterprise loses $4.00 of gross margin. This loss is reflected as Expected Downtime Costs and is calculated by multiplying Expected Downtime x $4.00.

By combining investment costs, repair contract costs and operating costs, we have the total impact on gross margins expected over the

Table 1. Investment and Contract expenses to implement downtime mitigation strategies.

Scenario	Downtime Mitigation Strategy	Investment Costs	Residual Value	Annual Contracted Repair Cost x 2	Total Invest. + Contract Costs
1	Enclosure	$180,000	$40,000	$ -	$140,000
2	Spare System	$320,000	$60,000	$ -	$260,000
3	Repair Contract	$ -	$ -	$360,000	$360,000
4	Onsite Repair	$ -	$ -	$ -	$ -

Table 2. Operational Availability, operating costs and impact on Gross Margins for the fleet of 20 test systems over the two year manufacturing lifecycle.

Scenario	Expected Op. Availability	Expected # of Failures	Expected Downtime (minutes)	Expected Repair Costs	Expected Downtime Costs	Impact of Op. Costs on Gross Margins
1	99.45%	8	115134	$160,000	$460,536	$620,536
2	99.98%	13	4677	$260,000	$18,708	$278,708
3	99.56%	13	92768	$ -	$371,072	$371,072
4	99.91%	13	18662	$455,000	$74,648	$529,648

two year manufacturing lifecycle of the new microwave component as shown in Table 3.

Table 3. Total impact on gross margin from the four downtime mitigation scenarios.

Scenario	Downtime Mitigation Strategy	Total Impact on Gross Margins
1	Enclosure	$760,536
2	Spare System	$538,708
3	Repair Contract	$731,072
4	Onsite Repair	$529,648

Through the incorporation of availability analysis with an understanding of TCO, we are able to develop a downtime mitigation strategy that minimizes costs to the organization and enables it to deliver on its customer commitments. In this hypothetical example, we see that purchasing a Spare Test System or establishing an Onsite Repair Agreement will provide the business with optimized results.

Conclusions

The costs to operate equipment over its useful life can easily exceed the capital expense used to acquire the equipment. Selecting an effective downtime mitigation strategy will help reduce the impact of unreliability on the business' bottom line. Performing availability analysis can be an essential step in selecting an optimal downtime mitigation strategy for reducing total cost of ownership.

Further Reading

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About the Author

Bill Lycette is a Quality Manager at Agilent Technologies in Santa Rosa, California. He has 29 years of experience in management, quality and reliability engineering, manufacturing engineering and NPI positions with Hewlett-Packard and Agilent Technologies. He is ASQ certified in Manager of Quality/Organizational Excellence and in Reliability Engineering. Mr. Lycette's undergraduate engineering study was in the field of materials science at the University of Washington and he holds an M.S. in Engineering Management from Stanford University.