RELIABILITY AND MAINTAINABILITY
OF MACHINERY AND EQUIPMENT,
PART 1: ACCESSIBILITY AND ASSESSING
MACHINE TOOL R&M PERFORMANCE

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Abstract

This article is the first of two that review some of the practical machinery reliability and maintainability (R&M) activities. Adhering to these R&M activities can help the builders and users of capital-intensive machineries improve their uptime and reduce their maintenance costs. The articles are collections of some of the published work of the author, based on 15 years of consulting work with the automotive industry. The topics to be covered in the first part include accessibility of machinery and assessing machine tool builders' R&M practices; those to be covered in the second part include benchmarking best maintainability practices, cost-effectiveness of predictive maintenance, and equipment life-cycle cost analysis. These articles review the contemporary subjects on R&M. In addition, a case study is presented that offers a road map to purchasing more reliable machinery and means of maintaining it more efficiently.

Key Words

Reliability and maintainability, machine-tool builder, accessibility, R&M assessment

1. Introduction

Manufacturing companies often struggle with the availability of their machinery and the equipment needed for meeting their production quotas. Many of these complex machines are unreliable and require extensive maintenance to continue running. Some of the primary consequences of these machine downtimes are higher production cost, low operator morale, higher WIP, and decreased customer satisfaction.

The concept of upfront engineering and continuous improvements in the design and development of machinery and equipment is becoming more and more important in today’s competitive world. Reliability and maintainability (R&M) are vital characteristics of manufacturing machinery and equipment that enable any manufacturer to be a world-class competitor. Successful R&M implementation does not happen by chance: it requires an understanding of the performance of the existing equipment, identification of the root causes of failures, elimination of those causes from the future designs, continuous communication between the builder and the user, and above all, planning and coordination.

The notion of reliability and maintainability (R&M) as applied to processes, machinery and equipment has not been well understood by the builders and users of those systems. Unfortunately, the same corporations who are known for their reliable products are not doing a good job of procuring reliable machinery and equipment and/or maintaining their existing machinery. Nor are the machine-tool builders who are responsible for design and development of the same machinery and equipment used to produce those reliable products scoring any better. This article is based on the author’s consulting work with capital-extensive machine-tool builders and users, and focuses on several R&M issues that have some bearing on the performance of capital-intensive machinery and equipment [1, 2].

The next section is an introductory one describing the significance of R&M activities in the profitability of any manufacturing system, and the disastrous impacts of ignoring the notion of reliability and maintainability in any production system [3].

Section 3 focuses on a better understanding of equipment accessibility and its role in improved maintainability. Every machine-tool builder’s intent is to design equipment that is reliable and maintainable. One means of improving the machine maintainability is designing it to be more accessible for maintenance. To effectively discuss the topic of accessibility in machine design, the concepts of maintainability, safety and ergonomics, and the adverse effects of hard-to-reach parts should be understood. Also, the impact of accessibility on the required time to repair, and the relevance of good documentation of the findings, should be noted. This section presents a set of guidelines to improve
the accessibility of existing machinery and, more importantly, to make sure that future machines are designed with accessibility in mind [4].

Section 4 discusses the process of assessing machine-tool builder’s R&M practices. Assessing machinery and equipment builders’ compliance with reliability and maintainability follows a systematic approach of assessing the degree to which a builder applies the tools and techniques of R&M to its design and manufacturing processes. In assessing a builder, one needs to critically review that builder’s performance in using failure mode and effects analysis (FMEA) procedures, design review procedures, derating techniques, apportionment techniques, and documentation procedures. This section presents a set of guidelines to evaluate machinery builder’s conformance with R&M practices [5].

In Part 2, following the introductory section, Section 2 discusses benchmarking techniques for identifying the best maintainability practices. Most companies wishing to instigate R&M practices face the question of how to select a corporation to assist them in setting up a top-of-the-line production system. This process can be eased through benchmarking, which can be internal and/or external. In an internal benchmarking, past performance of a company is reviewed and its future capabilities are determined. The key concept of an external benchmarking is to compare the performance of a corporation with that of others known to be the-best-in-the-business and to judge their future performance accordingly. This section presents evaluation guidelines for benchmarking machine-tool manufacturers past performance [6].

In Section 3 the concept of predictive maintenance will be discussed. Modern manufacturing systems and process plants are complex, highly optimized systems, for which seemingly small changes in the operating conditions of a component can have significant impact on the overall performance of the system. In these environments, even though any component breakdown could interrupt the whole process, the cost associated with unnecessary component replacement would lessen the plant’s profitability, and should be prevented as well. Therefore, the past maintenance strategies of corrective and/or preventive maintenance may prove to be costly, presenting the opportunity for the predictive maintenance techniques to be utilized. A clear understanding of predictive maintenance can help design and manufacture components with preventive maintenance features in mind. This section reviews the state-of-the-art on predictive maintenance and describes the relevance of the recent concept of reliability-centred maintenance in reducing operational cost [7].

In Section 4 the concept of life-cycle cost for machinery and equipment will be discussed. Life-cycle cost (LCC) is the sum of all cost factors over the expected life of production machinery. Appropriate discount factors may be applied for present-worth cost analysis. In LCC analysis, the cost breakdown structure showing numerous categories that are combined to provide the total cost is needed. The analyst, manager, customer, and supplier must all have the same understanding of what is and what is not included in a given category. Lack of adequate definition causes inconsistencies in the evaluation process, and could lead to a wrong decision. This section reviews the relevant cost factors and offers mathematical models for deterministic and probabilistic life-cycle cost analysis [2, 8–10].

Finally, a case study will be presented that portrays the steps taken by machine-tool builders to move from a trial-and-error approach to R&M to a more systematic stance that allowed them to be efficient and proactive in their R&M practices.

2. Significance of Maintainability in Design and Development

2.1 Introduction

Two of the most important factors that demonstrate the capability of any manufacturing system to deliver its uninterrupted and on-time service are the reliability and maintainability of its machinery and equipment. The former measures the frequency of failures, interruptions, or needed adjustments and corrections, whereas the later measures the duration of those events. A piece of equipment that fails less often, and when it fails takes less time to be brought back up to its operable conditions, is considered to be more reliable and maintainable than a machine that fails more frequently and requires a longer repair time. Reliability and maintainability of any machinery or equipment are functions of the reliability and maintainability of its components, subsystems, and systems. Therefore, to avoid any delays in service delivery, special attention should be given to designing more reliable components and to their optimum maintenance.

Reliability of a piece of equipment can be improved throughout the concept, design and development, and build and install stages by:
1. adopting a robust, yet simple design;
2. conducting rigorous design review sessions;
3. going through the practice of failure mode and effect analysis (FMEA) to:
   - identify each mode of failure
   - study the effect of that failure on the system performance
   - perform root cause analysis to identify and eliminate the unwanted cause(s).

Maintainability can be improved by implementing such maintainability strategies as accessibility, use of common building practices, diagnostics devices, captive hardware and quick attach/detach, modularity, visual management techniques, management of the spare parts, and colour-coding. In addition, developing a systematic maintenance procedure is conducive to a well-maintained system.

Attainment of reasonable levels of R&M seldom occurs by chance. It requires planning, goal definition, design philosophy, analysis, assessment, and feedback for continuous improvement. Program implementation entails management recognition of the value of R&M and commitment of human and other resources necessary to attain the goal. Without such a commitment, the probability of attaining R&M goals is low. A team effort involving all functions of
the business is needed to assure successful attainment of the R&M quantitative and qualitative objectives.

The whole process of procurement seems to fail to concentrate on the significance of R&M as a measure of overall performance of a piece of machinery and equipment. The result is installation of a machine that is not reliable (fails frequently) and is not maintainable (takes more time to be restored). Lack of attention to application of simplicity in design, practice of reliability appportionment, compliance to accessibility and serviceability guidelines, use of diagnostic devices and visual management tools, and so on cost the builder and the user community billions of dollars and will adversely affect the purchasing power of consumers. It is believed that builders/users in other countries are battling with lack of appreciation for the notions of R&M and LCC, as well. In consulting work with European, Canadian, and South American countries, the author noted the same pattern of unfamiliarity with the R&M concepts at the operational level.

2.2 Developing an R&M Program

Reliability and maintainability are vital characteristics of manufacturing machinery and equipment that enable U.S. manufacturers to be world-class competitors. Reliability consideration plays an increasing role in virtually all engineering disciplines. As demand for systems that perform better and cost less increases, there is great need to minimize the probability of failures, whether the failures simply increase costs and inconvenience or gravely threaten public safety.

In the broad sense, reliability is associated with dependability, with successful operation, and with the absence of breakdowns or failures. Efficient production planning depends on a process that yields high-quality parts at a specific rate without interruption. Predictable reliability and maintainability of manufacturing machinery and equipment is a key ingredient in maintaining production efficiency and the effective deployment of Just-in-Time (JIT) principles. Improved reliability and maintainability leads to lower total life-cycle costs that are necessary to maintain the competitive edge.

Implementation of the R&M concepts helps increase equipment availability and reduce overall operational and maintenance costs. Highly reliable and maintainable production machinery offers the means for producing consistently high-quality products at lower costs and at higher output levels. Successful application of R&M techniques has a very positive effect on employee morale and pride, as the reduction in downtime also results in significant reduction in employee stress and frustration.

Equipment reliability can be quantified by a measure of Mean Time Between Failures (MTBF), which is the average time between failure occurrences. Equipment maintainability can be quantified by Mean Time To Repair (MTTR), which is the average time it takes to fix a failure. Together, MTBF and MTTR make up the equipment’s availability (A), which is the percentage of time the equipment is available for production, A = MTBF / (MTBF + MTTR).

More formally, reliability is the probability that machinery/equipment can perform continuously without failure, for a specified interval of time when operating under stated conditions. Increased reliability implies less failure and consequently less downtime and loss of production. And maintainability is a characteristic of design, installation, and operation, usually expressed as the probability that a machine can be restored to specified operable condition (returned to a serviceable state) within a specified interval of time when maintenance action is performed in accordance with prescribed procedures and resources.

Machinery and equipment development programs can be managed using a five-phase program management process. The process starts in phase 1 with concept and proceeds through development and design (phase 2), build and install (phase 3), operation and maintenance (phase 4), and onto decommissioning and/or conversion in phase 5. This process is appropriate for any hardware development program for machinery and equipment. The reliability activities taking place during each of these phases of the product’s life may be quite different. In addition, the environment in which the system is to function must be determined. Finally, the service life to which the system is to be designed must be specified.

From such requirements, a conceptual design is formulated that in broad form outlines how the system is to function and provides the general plan for its construction. From the functional requirements comes the definition of failure and thus of reliability. Reliability requirements may then be set, and the trade-off between reliability, cost, and functional requirements may be examined as the design proceeds into the detailed phase.

The conceptual design must be converted into a detailed set of drawings and specifications from which the system can be built. During this phase, maintenance requirements and procedures are also likely to take place. As the design proceeds, experiments, testing, and analysis are required to choose between alternatives, to solve problems, and to predict the performance of subsystems or components.

Reliability considerations should permeate this stage of design in setting safety factors and design margins, eliminating unnecessary complexities, translating system reliability criteria into reliability requirements for subsystems, and setting time intervals for inspection, maintenance, and replacement of parts subject to wear. In this stage, the detailed examination of potential failure mechanisms and models is most beneficial, for often they may be eliminated or mitigated without too much expense. In the later stages of the design of the process, prototypes are built and the first reliability tests may be performed.

2.3 Ignoring Scheduled Maintenance: A Recipe for Disaster

Even though the automotive industry has performed beyond everyone’s expectation in designing and manufacturing reliable and maintainable cars and trucks, it has failed to procure and maintain reliable and maintainable machinery and equipment needed to manufacture those
cars and trucks. The result of operating faulty equipment and inadequate attention to builders’ recommended maintenance actions is underutilization of capital-intensive equipment, production delays, more frequent breakdowns, and increased production and maintenance costs. When multimillion dollar equipment used in manufacturing different components of a car that is sold for a profit of tens of thousands of dollars has low availability, the company is losing millions of dollars a day to unscheduled downtimes. The builder community is in no better shape. They generally ignore the existence of valuable data on the machinery performance, and do not maintain a central database, the result of which is reappearance of the same failures again and again.

From the tragic Challenger accident in 1986, to the explosion of TWA Flight 800 in the air in 1996, to the numerous distressing losses of lives due to the use of unreliable machinery and equipment, one thing is certain: we should not allow unreliable equipment to be designed, manufactured, and used. Working with a variety of manufacturing companies throughout North America and Europe, the author has seen a general lack of appreciation in the machine-tool builder and user community for the use of statistical tools and techniques in predicting and improving machinery performance. It seems that the industry has failed to fully utilize the importance of data analysis in designing, building, operating, and maintaining reliable and maintainable machinery and equipment.

From an industrial point of view, the root of the problem can be traced to a lack of understanding and appreciation of the role of statistical tools and techniques in predicting equipment’s performance. There is an urgent need to find answers to the following three basic questions:

- Industry-wide, how reliable and maintainable are manufacturing machinery and equipment?
- How informed are the users of the performance of the equipment?
- Has anything been done to improve the performance of capital-intensive machinery and equipment?

The fact is that, industry wide, we have accepted that no design is perfect, therefore allowing ourselves to design equipment that is less than perfect. Furthermore, even if there is such a thing as a flawless design, it is not carried on by the shop floor personnel, resulting in inferior products. More importantly, any manufacturing equipment, even flawless equipment, will deteriorate with time, and if proper care is not exercised, it may fail to operate at an unanticipated moment during its operation, interrupting production and creating backlog.

We are wrong to conclude that everything that needs to be done has been done, thus permitting ourselves to continue with business as usual and manufacture machinery and equipment that are not as reliable, as accessible, as serviceable, as maintainable, and as ergonomically safe and sound as they could be. The general viewpoint is that the building community tends to forego the opportunity to collect data on the machinery’s performance as soon as its installation is complete. They seldom conduct a field audit to collect data on the equipment performance during its early stages of production or during its useful life. The result is that they learn little from their previous mistakes, thus repeating the same mistakes again and again.

3. Identification and Integration of Accessibility and Maintainability in Design and Development

3.1 Background

Accessibility means having sufficient working space around a machine, piece of equipment, system, subsystem, or component to diagnose, troubleshoot, and complete maintenance activities safely and effectively. The impact of lack of accessibility on time to repair and the safety and ergonomics issues surrounding maintenance are well known to anybody who has been involved with maintaining a piece of equipment. But at issue is the fact that accessibility has never been well documented, resulting in the same mistakes being repeated over and over again. Although we have knowledge of the impact, there is no effective means of conveying these problems to the community that can have the greatest impact: machinery and equipment builders.

One of the areas of deficiency in supplier’s design is a good understanding of accessibility in design. The intent of this section is to reintroduce the concept of accessibility to the machinery and equipment builder community and initiate a documentation process that identifies the existing problems with the present design and the means of improving them.

Operators and maintenance and service personnel have the best knowledge of how the repair job should be done and should be involved in evaluating the design for accessibility. The early design stage is the most effective time to assess these problems in order to improve the performance of the machine. There are several maintainability techniques that, when used properly, can improve the machine’s uptime. A case in point is captive hardware and quick attach/detach, which provides for rapid and easy replacement of components, panels, brackets, and chassis. Modularity mandates design of components as removable and replaceable units for an enhanced design with minimum downtime. Diagnostic devices indicating the status of equipment should be built into manufacturing machinery to aid maintainability support processes. Colour coding should be used to ease the identification of components and parts and their replacement. Finally, through visual management, a system is created that enhances the equipment inspection process by allowing quick identification of safety, quality, environmental, equipment, and process abnormalities.

This section identifies and presents the means to:

- Encourage an active role in design reviews
- Help the user and supplier develop a clear understanding of accessibility usable
- Develop a better picture of different elements of machine downtime, and recognize means of reducing them
- Learn several techniques of cost reduction through improving mean time to repair
- Improve the safety of the skilled trade personnel and understand and follow ergonomics guidelines in repairing equipment.
The section begins with a brief description of safety and ergonomics of the workplace and reviews the significance of designing ergonomics features into the design. Different elements of maintenance time are next introduced, and means of decreasing them are identified. Later on, the significance of conducting a thorough design review procedure will be brought to light, and its role in improving accessibility in machine design will be discussed.

3.2 Safety

The machinery or equipment builder should make sure that the design meets all applicable national and federal legislation such as the Health and Safety at Work Act, O.S.H.A., and any local safety regulations. In addition, the machine or equipment should comply with all the user’s specified safety requirements. It is important to note that safety must be introduced at the design stage, not after the equipment is built. Therefore, safety personnel must be consulted up front to fully utilize the best technology available in a safe and ergonomically efficient manner.

Properly designed, the operator’s environment will not only reduce the risk of injury, but also avoid exposure to health risks or activities likely to cause repetitive motion disorders. Pinch points guarding, safety labels, personnel guards, warning devices, lockouts, and other appropriate safety measures must be integrated into the design, and safety requirements must be included in the specifications. In addition, in performing design reviews and FMEA, special attention should be paid to modes of failure that are safety related. The common practice is to focus on identifying and eliminating safety-related failures prior to working on any other mode of failure.

A few safety recommendations are:

- The equipment should be equipped with a single main electrical disconnect that can be padlocked in the open (off) position.
- Control circuit voltage should not exceed a nominal 115 volts.
- Start buttons should be of the fully guarded type to prevent accidental starting of equipment.

3.3 Environmental Controls

Any designed or purchased equipment will be installed in a location having some preestablished environmental conditions. A clear understanding of those conditions and clear communication to the supplier will help design a machine that is compatible with its environment. One means of assuring a better understanding of the environmental controls is through the practice of R&M. The R&M process must address the plant environment when considering the design criteria for any process or piece of equipment.

In addition to those environmental conditions that could affect the process or equipment, consideration must be given to the effects that the process or equipment will have on the operators, maintenance crew, plant, work place, and the earth’s environment. One such environmental consideration is the anticipation of all possible interactions between the machine and the operator. This topic, called ergonomics, is of prime importance in designing an accessible machine that, from the maintenance point of view, is ergonomically sound.

3.3.1 Ergonomics

Ergonomics is an applied science that deals with the interface between people and their work place. It takes into consideration the characteristics and capabilities of people in the design and arrangement of equipment, work place, tools, work methods, and facilities, so that people and things will interact most effectively and safely.

Some of the major considerations are maintainability, operability, ease of inspection (to detect abnormalities), and access points. To assure an “ergonomically sound design,” the user should look for the use of basic ergonomic principles in the builder’s design and development effort. In addition, the user should consult with the local ergonomics committee for advice on ergonomic principles to be applied to design and development.

The builder should demonstrate that the design has considered ergonomic principles such as the structure of human anatomy and the limits of such factors as reach, leverage, grasp, the pressure with which one squeezes, and agility (flexibility and speed of movements). In addition to the human capabilities and limitations, the working environment also has to be suitable. Among environmental factors to be considered in the ergonomic development of a machine or equipment design are:

- Dimensions and forces
- Temperature and humidity of the workplace
- Lighting, vibration, and noise
- Displays, controls, and panels.

3.3.2 Checklist for Ergonomically Sound Design

When evaluating a design for accessibility, safety, and ergonomics, follow a checklist that guides you through the basic requirements. The most common topics are related to the physical limitations of human being. For instance:

- Does the working space allow for a full range of work movements?
- Are mechanical aids and equipment provided when feasible?
- Is the work surface height proper and adjustable?
- Is the working area designed to minimize or eliminate:
  1. Twisting at the waist?
  2. Reaching above shoulder?
  3. Bending at waist?
  4. Static muscle loading?
  5. Extending the arms?
  6. Bending or twisting the wrist?
  7. Elevations of elbows?
  8. Lifting heavy weights?

A more detailed checklist directed to maintenance activities may require a critical review of the design to assure its compliance with ergonomics. The checklist includes:

- Has a tall man enough room, and can a petite woman reach everything?
3.4 Focusing on Maintainability

Reliability and maintainability are vital characteristics of manufacturing machinery and equipment that enable U.S. manufacturers to be competitive worldwide. Improved R&M leads to lower total life-cycle costs that are necessary to maintain the competitive edge. Efficient production planning depends on a process that yields high-quality parts at a specific rate without interruption. Predictable R&M of the manufacturing machinery and equipment is a key ingredient in maintaining production efficiency and the effective deployment of Just-in-Time principles. R&M of any equipment are characteristics of design, installation, and operation of that equipment, and their successful implementation requires a cooperative effort between the users and their machinery and equipment builders.

It is important to realize that maintainability is a characteristic of design, installation, and operation, and accessibility plays a major role in improving the maintainability of the equipment by reducing its MTTR. Therefore, the task of having a maintainable machine starts at the early stages of design and continues until the machine is decommissioned. For a successful design implementation, there must be a process for considering R&M activities at the start, coupled with a process for assuring that inherent R&M is achieved during the design/development, build/install, and operation phases of manufacturing machinery and equipment. To do so, machinery and equipment builders should develop an R&M plan.

An R&M plan determines how to achieve the R&M goals necessary to meet operational requirement for machinery and equipment. If necessary, the plan identifies what has to be performed, who should do it, and when it should be done. The plan should describe the quantitative R&M requirements that are imposed by the user. It should also explain how various R&M techniques, disciplines, and procedures will be applied to ensure attainment of the requirements.

The user must ensure that the equipment will be properly maintained and the builder will be made aware of its performance. The builder and the user should jointly develop a system for measuring equipment performance data. To assure concise planning and execution, the user and the equipment manufacturer can review the R&M program as each phase of the design and development program is completed.

3.5 A Close Look at Different Elements of Time

To stress the importance of accessibility as one of the tools of reducing the nonproductive machine time, equipment nonoperating time will be classified as:

- The time that the machine is down for scheduled activities, such as lunches, breaks, scheduled preventive maintenance (PM), and meetings, which will cause the machine to be unstaffed
- The time that the equipment is down due to stoppage such as breakdowns, setups, adjustments, and minor stoppages (unjamming/clearing of parts)
- The times that, even though a machine is up and ready to process parts, due to the problems associated with other machines it cannot process parts. These elements of time are known as blocked time and starved time.

In particular, the repair time consists of five basic elements:

- **Administrative time:** The period between failure and onset of diagnosis, which includes time to become aware of the failure and preparation of service, orders, assignment of people, and so on
- **Diagnostic time:** The portion of repair time between administrative and active repair time used to determine cause of failure and correction method
- **Logistic time:** The time to acquire replacement parts
- **Active repair time:** The time required to physically perform a repair, including getting tools, gaining access, and repairing, assuming replacement part availability
• **Start-up time:** The time required from completion of active repair to begin producing satisfactory parts at design cycle time, which includes warm-up and adjustment times.

Not all of the time allocated for machine repair time is used up by the skilled-trade personnel for active repair time. In fact, of all the listed elements of repair time, the active repair time is the only time that is essential; the rest of the time should be minimized or completely eliminated.

This section identifies the means for improving the design so as to eliminate and/or reduce the time required to access the system/subsystem, component, or part; to decrease the time required to remove the failed component; and to lessen the time required to replace the failed component. In many cases, machinery and equipment builders use only active repair time as a substitute for the actual machine downtime. Actual downtime consists of many more elements that should be investigated during design for savings.

The machinery builder should design the machine with automatic diagnostic features in mind, and specify the required spare parts inventory. The user should develop a maintenance protocol as well. The protocol must describe in detail the adjustments, replacements, and repair of machine, system, subsystem, and component parts. In addition, the user must:

- Stock sufficient units of spare parts
- Create an efficient communication system for immediate notification of the skilled trade personnel of any problem
- Eliminate all nonessential downtime activities
- Train the skilled trade personnel to identify means of improving the access time of the existing machines on the floor.

### 3.6 Design Review

Design review activities are carried out to ensure that the design has gone through a complete scrutiny prior to its manufacturing. Review activities include a formalized, documented, and systematic management process through which both the builder and user review all technical aspects of the evolving design, including R&M. They should be an integral part of the design and development process, and involvement of operators and maintenance personnel in this process is highly recommended. This process involves the review of drawings, sketches, engineers’ notebooks, test results, mockups, process documentation, assemblies, and other hardware/software depiction of the evolving design.

For a design review to be effective, in addition to covering all aspects related to its operation, the review should focus on assessing the risks associated with routine as well as crisis maintenance of the new design.

From the accessibility point of view, any new design should go through a systematic and rigorous risk assessment process. During the process those issues associated with frequency of maintenance, ease of identifying the cause of the problem, ease of reaching the faulty components and parts and removing them, and safety and ergonomics of repair crew should be reviewed. Owing to the significance of establishing good maintenance practice, participation of maintenance personnel is recommended. Their active participation can help identify some of the unforeseen accessibility, safety, and ergonomics problems that may go undetected with the current design. This is especially important because this preliminary review is held prior to commitment to a final design approach, and it is followed by an intermediate design review when more details of the design become available.

As previously stated, the review is expected to include maintainability design features that make the machine accessible to the skilled trade personnel, reduce the time required to repair a faulty machine, and increase the time period between preventive maintenance. Involvement of the operators and maintenance personnel help discussion on such design techniques as testability, accessibility, standardization, modularity, repairability, and interchangeability to be deliberated.

### 3.7 Maintainability Improvement Strategies

During the design review sessions, the operators and maintenance personnel should consider the characteristics of design for maintainability. They should examine the design to ensure that:

- equipment is designed for repair with standard tools and test equipment;
- maintenance manuals are developed that are consistent with the skill levels of those performing the maintenance;
- maintenance manuals address the most difficult aspects of the design;
- preventive maintenance requirements are developed to be compatible with existing schedules and inventories;
- easily identifiable location points for predictive maintenance analysis are used (e.g., vibration analysis sensors); and
- spare parts lists are based on equipment reliability characteristics.

To review the performance of a machinery and equipment builder, the auditor must look for documentation on maintenance procedures early in the design phase. These documents must describe in detail the adjustments, replacement, and repair of machine systems, subsystems, and component parts. In addition, the builder should provide recommended preventive maintenance procedures at intervals based on time and/or machine cycle count. These maintenance requirements should be prioritized to enable the user to prioritize maintenance scheduling related to the criticality of the activity. Exploded view illustrations, photographs, simplified assembly drawings, and/or parts lists relating to the required maintenance activities and procedures should be included wherever applicable. In addition, points of access, required tools, sequence of operations, testing procedures, and the like should be discussed.

### 3.8 Visual Management Techniques

Use of visual management techniques by the machinery and equipment builder is considered an important means
for alleviating maintenance activities. Visual management techniques are used on machinery and equipment to bring the workplace awareness to a level that allows problems and abnormal conditions to be quickly recognized at a single glance.

Through visual management, a system is created that enhances the equipment inspection process by allowing quick identification of accessibility, safety, quality, environmental, equipment, and process abnormalities. Typical visual management techniques include:

- Match marking of all fasteners (nuts, bolts, screws) fixed, adjustable or critical
- Match marking of all control adjustments (pressure, flow, temperature, speed, level, voltage, etc.)
- Direction of flow and product colour coding on piping and hoses, and direction of rotation on (drives, belts, chains, motors, etc.)
- Function labels on (switches, valves, buttons, lights, etc.), identification labels on (cabinets, panels, etc.)
- Belt and chain drives with guarding that permit quick visual inspection and access, and replacement belt or chain number labels on guarding
- Equipment layout with all electrical control panel safety lockout points indicated.

The best time for improving the accessibility of equipment is while the equipment is at its design stages and formalized design review sessions are in progress.

### 3.8.1 Maintenance Load

The most effective time to measure MTTR is during design. A machine can fail in different modes, some of which require more effort to be maintained and therefore are more crucial. Maintenance load is a tool that can be used during design to measure the relevance of each mode of failure. The information needed for this analysis is mostly embodied in Failure Mode & Effect Analysis (FMEA), which has to be completed anyhow. During design, when very little data exist, the procedure for measuring MTTR is:

1. List different modes of failure of the equipment, using your judgement and maintenance experience with similar equipment.
2. For each mode of failure, estimate its failure rate or frequency of failure.
3. Based on the way the equipment is to be designed, estimate its time to repair for each mode of failure.
4. By multiplying the failure rate (item 2 above) by the time to repair (item 3 above), calculate the maintenance load for each mode of failure.
5. Calculate MTTR as: MTTR = (Maintenance Load) / (System Failure Rate), in which system failure rate is the sum of failure rate for different modes.
6. Compare the maintenance load for different modes of failure; suggest design changes for failure modes that create a high load on the maintenance function.

Maintenance load is a useful tool for identifying the high-maintenance components and can be used to improve their performance. To improve the maintenance load, either the failure rate or time to repair has to be reduced.

### 3.9 Conclusion

Every machine-tool builder’s intent is to design equipment that is reliable and maintainable. One means of improving the machine maintainability is to design it to be more accessible for maintenance. The impact of lack of accessibility on time to repair and the safety and ergonomics issues surrounding maintenance are well known to anybody who has been involved with maintaining a piece of equipment. But accessibility has never been well documented, resulting in the same mistakes being repeated over and over again. One of the areas of deficiency in supplier’s design is a good understanding of accessibility.

This section reintroduced the concept of accessibility to the machinery and equipment builder community and presented a documentation process that displays the existing problems with the design and the means of improving it. A set of guidelines was offered to improve the accessibility of existing machinery and, more importantly, to make sure that future machines are designed with accessibility in mind. To effectively discuss the topic of accessibility in machine design, the concepts of maintainability, safety, and ergonomics and the adverse effects of hard-to-reach parts were discussed. Furthermore, the impact of accessibility on the required time to repair, and the relevance of good documentation of the findings were pointed out.

### 4. Process of Assessing Machine-Tool Builders

Assessing a machinery and equipment builder’s compliance with reliability and maintainability (R&M) involves using a systematic approach to assess the degree to which a builder applies the tools and techniques of R&M to its design and manufacturing processes. In assessing a builder, one should critically review the builder’s performance in using failure mode and effects analysis procedures, design review procedures, derating techniques, apportionment techniques, and documentation procedures.

One of the most important activities associated with a supplier’s commitment to improving product reliability and maintainability (R&M) involves analysis and documentation is willingness to regularly monitor the performance of the installed equipment. Every engineering organization believes it designs the most reliable and maintainable equipment it can within the project constraints, and every engineering organization knows how its product fails. The practice of R&M demands a more intimate knowledge of failure, the development of root cause, and an understanding of how the failure is managed by the user.
Even though reliability monitoring should start before shipment of machinery and equipment, it should also continue as an integral part of the manufacturing process throughout the machine life. This includes an often-neglected aspect of reliability monitoring, known as field audit or field performance monitoring. The neglect stems from two primary considerations:

1. It is a costly, slow, and difficult operation to get accurate data from a customer’s plant.
2. There is a widespread feeling that, once machinery and equipment is in the hands of the customer, it is too late to take any meaningful or cost-effective actions to improve reliability.

While these claims have some truths, it is crucial to realize that a good field audit provides an opportunity to:

- detect unexpected failure mechanisms (by type or by magnitude of occurrence),
- acquire input to improve the design of future generations of the equipment,
- provide feedback information on root cause of failure,
- validate and correct the failure rates used for reliability estimation, and
- verify that corrective actions worked as anticipated.

This section:

- Offers the tools to be used by the technical staff of the purchasing departments to effectively assess their potential machinery and equipment builders
- Introduces a series of guidelines for benchmarking a builder’s past performance
- Assesses a builder’s benchmarking performance by examining internal sources, as well as external sources via other vendors
- Proposes a procedure for analyzing the documentation of actions taken by the builder to achieve a preset reliability target.

To analyze the accuracy of the documentation of actions taken by the builder to achieve a preset reliability target, a series of guidelines will be offered that includes:

- A verification of the data and method used for establishing the baseline reliability forecast
- A review of design review procedures, apportionment techniques, and derating procedures routinely used by the builder
- A review of reliability improvement design actions, and their substantiating analysis and forecasted effect on baseline
- A review of computer simulation studies, comparing the new design features to baseline design and operating practices
- A review of durability test results for machine components and subsystems
- A review of plan for preventive and predictive maintenance.

Builders are expected to have a strong field audit program in place. Every builder is expected to participate in the reliability growth and continuous improvement process, observing the equipment in operation and assisting in the root cause analysis of all failures that occur.

The section pointed out the significance of evaluating the builder’s field audit by looking for:

- Signs of the builder’s voluntary participation in field audits and reliability growth process when it is not contractually required
- Presence of a failure reporting, analysis, and corrective action system, known as FRACAS. These systems provide orderly recording and transmission of failure data from the supplier’s plant and user sites into a unitary database. This database allows identification of pattern failures and rapid resolution of problems through rigorous failure analysis
- Existence of a system for summarizing and analyzing failure data obtained at both supplier and user plants as a means of promoting R&M improvement activities
- The builder’s eagerness to share its findings with the suppliers and users.

5. Recommendations

Any builder’s implementation of R&M should be a basic part of its engineering division. R&M is largely quality assurance, particularly as regards its origins, but it is inherently an engineering function, as are machine function, fit, material selection, and so on, and it involves trade-offs within itself and other engineering activities as a part of the overall engineering process. It does not benefit from a separation from the engineering and production efforts and controls, but rather benefits most from a tight integration with them. Additionally, R&M concerns like MTBF and MTTR will soon be negotiated contractual matters, further indicating that R&M is a basic and natural part of engineering.

Human resources for R&M are a leading concern. There should be an R&M leader who is dedicated to the R&M effort and who is a part of the engineering structure. Other R&M personnel could be drawn from various disciplines while working in their other functions. Newly hired personnel, even those hired specifically for R&M work, should begin with regular assignments in their own departments. These other disciplines should not be limited to engineering but should also include such fields as sales, marketing, service, and production, among others. Having experienced personnel on the team is highly desirable. As implementation of R&M progresses, additional personnel should be introduced into the R&M team. The size of the team will depend on the needs of ongoing project activity. A team that grows and shrinks in dynamic response to these needs may be more suitable.

Ideally, at least one member of the R&M team being formed should be drawn from current engineering operations, but if this is not feasible, it should not have a crippling effect on R&M implementation. Involvement of mechanical, electrical, and computer engineering departments is essential. R&M activities will initially include failure modes and effects analyses (FMEAs), design reviews, delay studies, development of MTBF and MTTR data for major components, and so on. Other activities, such as apportioning subsystem/component reliabilities for future designs and assisting customers with reliability growth programs, will follow later.
Delay studies should be initiated to develop “short-time” MTBF and MTTR data. Builders everywhere are feeling pressure from their customers for these data. MTBF and MTTR data for major and long-lasting subsystems/components are necessary and are particularly hard to obtain. These subsystems can outlast the system, but when they fail, they take a rather long time to repair or replace. Service reports should be reviewed and inquiries at customers’ plants should be made about failures, particularly where failures are not the result of misapplication, defective maintenance, or other operational problems.

Formal design reviews constitute a fundamental requirement of R&M work. A methodology is needed that involves development of checklists. It has become apparent that an overall checklist for a feasibility design review (FDR) should be held prior to submission of a bid. Developing these checklists should have a high priority, and their refinement will need to be ongoing.

The principal benefits of R&M are better understanding of the performance of the designed equipment and a better relationship with the user. Builders can also expect improved communications to result from the cross-discipline functioning inherent in R&M. And the cross-disciplinary nature of R&M activity will engender a sense of “ownership” of products in everybody involved, which will be an ever-increasing percentage of the technical staff. These benefits will in turn work towards improving overall morale. Further into the future, once R&M has become fully integrated into the operations, it will provide excellent training for a large percentage of new hires, which eventually results in a cultural change in the way machine reliability and maintainability is perceived.

References


Biography

Azim Houshyar earned his Ph.D. in industrial and systems engineering from the University of Florida in 1978. He is currently Professor of Industrial and Manufacturing Engineering at Western Michigan University. His interests include simulation methodology, reliability engineering, application of operations research to manufacturing processes, and production control. Since 1987, Dr. Houshyar has been actively involved with consultation to local, national, and international manufacturing corporations. A few examples are: Whirlpool Corp., Humphrey Products, Eaton Corp., Checker Motors Inc., Steelcase, Ford Motor Company, Verson, Automatic Feed, Pratt & Whitney, and ABB Olofström. He has assisted corporations in the United States, Germany, the Czech Republic, Iran, Portugal, Canada, and Mexico. Dr. Houshyar has published over 30 journal articles and 100 articles in conference proceedings. For the past five years Dr. Houshyar has been the Editor-in-Chief of the International Journal of Modelling and Simulation. His professional affiliations include ORSA, TIMS, APICS, SME, and IIE.