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ORIGINAL ARTICLE

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System health monitoring and prognostics – a review of current paradigms and practices

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Abstract System health monitoring is a set of activities performed on a system to maintain it in operable condition. Monitoring may be limited to the observation of current system states, with maintenance and repair actions prompted by these observations. Alternatively, monitoring of current system states is being augmented with prediction of future operating states and predictive diagnosis of future failure states.

Such predictive diagnosis or prognosis is motivated by the need for manufacturers and other operators of complex systems to optimize equipment performance and reduce costs and unscheduled downtime. Prognosis is a difficult task requiring precise, adaptive and intuitive models to predict future machine health states. Numerous modeling techniques have been proposed in the literature and implemented in practice. This paper reviews the philosophies and techniques that focus on improving reliability and reducing unscheduled downtime by monitoring and predicting machine health.

Keywords Condition-based maintenance · Health monitoring · Model-based diagnosis · OSA-CBM · Preventive maintenance · Reliability-centered maintenance

1 Maintenance strategies and motivations for health monitoring

The oldest and most common maintenance and repair strategy is "fix it when it breaks." The appeal of this approach is that no analysis or planning is required. The problems with this approach include the occurrence of unscheduled downtime at times that may be inconvenient, perhaps preventing accomplishment of committed production schedules. Unscheduled downtime has more serious consequences in applications such as aircraft engines.

These problems provide motivation to perform maintenance and repair before the problem arises. The simplest approach is to perform maintenance and repair at pre-established intervals, defined in terms of elapsed or operating hours. This strategy can provide relatively high equipment reliability, but it tends to do so at excessive cost (higher scheduled downtimes). A further problem with time-based approaches is that failures are assumed to occur at specific intervals.

Figure 1 illustrates the typical incidence of failure over the life of equipment. At the left, so-called "infant mortality" failures are plotted. Failure rates are low throughout the useful life of a piece of equipment, and rise toward the end of life.

This curve however doesn't capture the complex interactions between the components of a system and is loosely based on the

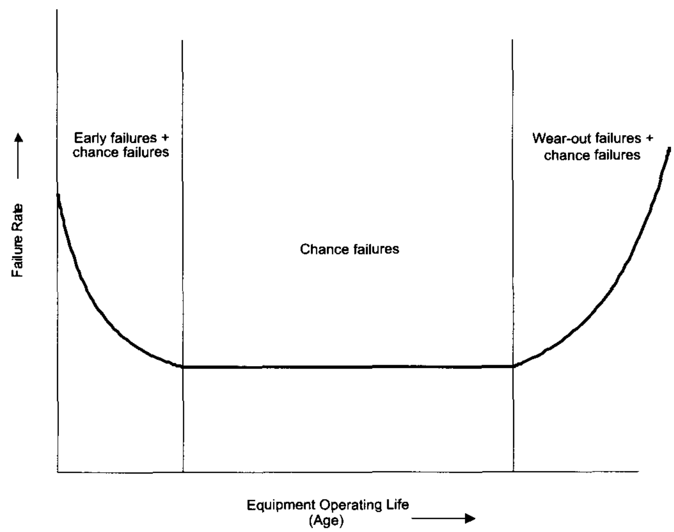

Fig. 1. Bathtub curve depicting reliability in terms of failure rate of equipment [1]

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assumption that the system progresses (or deteriorates) deterministically through a well defined sequence of states (however, the curve might in some cases be valid even if the sequence is not well defined). This assumption is not true especially in the case of discrete manufacturing systems and other complex environments where seemingly random failure behavior is a function of the changes in the work content, schedule and environment effects, as well as unknowable variations between nominally identical components or systems.

The only way to minimize both maintenance and repair costs and probability of failure is to perform ongoing assessment of machine health and ongoing prediction of future failures based on current health and operating and maintenance history. This is the motivation for prognostics: minimize repair and maintenance costs and associated operational disruptions, while also minimizing the risk of unscheduled downtime.

The connection between effective maintenance management techniques and significant improvements in efficiency and profitability has been well documented [2]. Though the return on investment is highly dependent on the specific industry and the equipment involved, a survey states that an investment in monitoring of between \$10, 000 and \$20, 000 dollars results in savings of \$500, 000 a year [3]. Across many industries, 15%–40% of manufacturing costs are typically attributable to maintenance activities. In the current competitive marketplace, maintenance management and machine health monitoring play an increasingly important role in combating competition by reducing equipment downtime and associated costs and scheduling disruptions [4].

Another important motivation for improved maintenance management is its inherent objective to increase machine availability, which has a direct impact on organizational agility. Due to ever increasing customer demands and changes in technology, management strategies such as just-in-time (JIT) and material resource planning (MRP) become essential. These activities improve organizational efficiency by eliminating wasteful production activities. Unscheduled or frequent breakdowns pose a major hindrance to the implementation of such techniques [5]. They also result in high variance in production activities thus increasing the onus on the other business functions such as scheduling. A detailed study of the effects of the maintenance policies on the manufacturing systems is reported in [6–10].

Another compelling but less addressed justification of maintenance is safety and environmental preservation. With the increase in stringency of safety and environmental laws, proactive maintenance assumes an increasingly important role. Since operational hazards and accidents lead to enormous legal expenses, inattention to these issues is no longer affordable [3].

Quality is increasingly seen as a motivation for improved maintenance management. Since the relation is not immediately apparent it is not surprising that it has not received enough research attention. Since quality improvement is becoming proactive by merging it with techniques like process control and productivity improvement, the effect of equipment maintenance on quality is being exposed [11]. A similar analysis can be found in [12–15].

Manufacturing and quality present interesting perspectives to maintenance in the form of objectives to maximize availability and minimize defective outputs (or in some cases maximize process capability). These however are the conjoined objectives of total productive maintenance [16], which aims at maximizing equipment effectiveness. Terotechnology comes with the same objective but in a much broader sense including the supplier (of the system) and all the involved engineering implementers and users [17].

Due to these insights there has been a considerable shift in perspectives governing maintenance practices in industry. Equally important, new theoretical advances and computer-based technologies have provided critical new maintenance management capabilities. These techniques are often interdisciplinary, originating in quite disparate fields. The objective of this paper is to survey current theories and practices in system health maintenance and to identify relevant references.

The following Section 2 elaborates health monitoring paradigms and Section 3 gives a brief description of the tools and techniques involved. Section 4 contains a survey of recent case studies that use state of the art techniques in data modeling for machine monitoring, failure prediction and control in industrial applications while Section 5 surveys the academic and industrial institutions focusing on the maintenance cause.

2 Health monitoring paradigms

Health monitoring and its associated functions have been the focus of research and implementation for quite a few years. Through these years they have significantly evolved in terms of governing philosophy, implementation, and enabling advances in technology, modeling techniques, and emerging or redefined necessities. The evolution of system health monitoring has an interesting chronological perspective as elaborated by Kinclaid [18]. A brief taxonomy of the various philosophies is given in Fig. 2.

Maintenance philosophies can be broadly classified as reactive and proactive. Reactive or unplanned maintenance is a legacy practice: maintenance only after the manifestation of the defect, breakdown, or stoppage. It is appropriate in facilities where the installed machinery is minimal and the plant is not totally dependent on the reliability of any individual machine [19]. It might also be appropriate when the failure rate is minimal and failure does not result in serious cost setbacks or safety consequence. Breakdown or corrective maintenance and emergency maintenance belongs to this category.

a) Corrective maintenance is defined as the activity carried out after a failure has occurred and is intended to restore an item to a state in which it can perform its required function [20–22].
b) Emergency maintenance is defined as the maintenance activity that is necessary to accomplish immediately to avoid serious consequences. Constraints are applied on the frequency of maintenance with the object of cost-wise optimization. These constraints are defined in terms of the immediacy of