Maintenance: Changing Role in Life Cycle Management

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Abstract
As attention to environmental problems grows, product life cycle management is becoming a crucial issue in realizing a sustainable society. Our objective is to provide the functions necessary for such a society while minimizing material and energy consumption. From this viewpoint, we should redefine the role of maintenance as a prime method for life cycle management. In this paper, we first discuss the changing role of maintenance from the perspective of life cycle management. Then, we present a maintenance framework that shows management cycles of maintenance activities during the product life cycle. According to this framework, we identify technical issues of maintenance and discuss the advances of technologies supporting the change in the role of maintenance.

Keywords:
Maintenance, Life Cycle Management

1 INTRODUCTION

Everyone agrees that maintenance is a necessity. Nevertheless, maintenance has a negative image and is sometimes regarded as a necessary evil. But as the paradigm of manufacturing shift towards realizing a sustainable society, we should also begin to recognize the changing role of maintenance. The goal of manufacturing is no longer to produce products in an efficient way, but rather to provide the functions needed by society while minimizing material and energy consumption. Product life cycle management is becoming a crucial issue in order to achieve this goal. In this context, the role of maintenance should be redefined as an essential means for life cycle management. Maintenance is the most efficient way to keep the functional level of a product above the level required from the viewpoint of environmental impact.

Traditionally, the scope of maintenance activities has been limited to the operation phase. In considering the role of maintenance in life cycle management, however, we should be aware that there are close relationships between maintenance activities and those in other phases of product life cycle, such as the design, production, and end of life phases. These relations create the necessity for integration in terms of technologies as well as information throughout the product's life cycle so as to perform effective maintenance. Hence, we should investigate maintenance technologies more extensively in connection with, for example, design technologies such as product modeling and digital engineering.

Changing the role of maintenance could also affect the business models of manufacturing companies. Attention to maintenance could facilitate the transformation of businesses from product providers to service providers, with maintenance being a major service.

In this paper, we first discuss life cycle management for closed-loop manufacturing, which could be an essential means for realizing a sustainable society, and the changing role of maintenance from the perspective of life cycle management. Then, we present a maintenance framework that shows management cycles of maintenance in the product life cycle. According to this framework, we identify technical issues regarding maintenance activities ranging over the entire product life cycle, and we discuss advances in technologies supporting the changing role of maintenance.

2 THE ROLE OF MAINTENANCE FROM THE PERSPECTIVE OF LIFE CYCLE MANAGEMENT

2.1 The need for life cycle management in realizing a sustainable society

Since the Industrial Revolution, people have been improving the quality of human life by increasing manufacturing capability. Mass production, however, has also brought about mass consumption of natural resources and energy, as well as mass disposal. The scale of our industrial activities has already extended beyond the limit. We cannot continue to consume resources and energy, and to dispose of waste without considering the impact of these activities on the environment. We therefore need to change the paradigm of manufacturing from "how to produce products most efficiently" into "how to avoid producing products while still maintaining customer satisfaction and corporate profits." Closed-loop manufacturing has been proposed as a solution to this question [1].

The concept of closed-loop manufacturing can be expressed as "renewing functions while circulating material." There are, however, many ways to circulate material, as shown in Figure 1, otherwise known as the comet circle™ [2]. Each orbit in the figure corresponds to a life cycle option, such as prolonged use by means of maintenance, product reuse, part reuse, recycling, and energy recovery. To realize closed-loop manufacturing, the product life cycle should be managed by selecting proper life cycle options.

In selecting life cycle options, we need to consider their environmental performance or eco-efficiency, which is

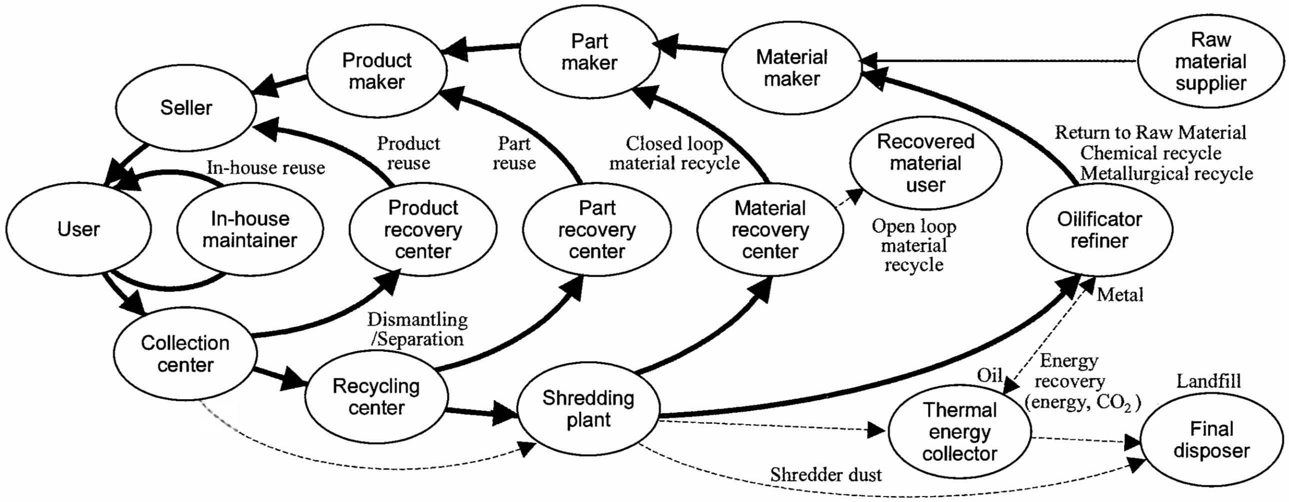

Figure 1: Comet circle™. (Comet circle is a trademark of Ricoh, Co., Ltd.).

defined as the ratio of provided value to environmental load. Therefore, we cannot always select the options with the lowest environmental load, because we need to consider the balance between environmental friendliness and customer satisfaction, as well as corporate profits. Nevertheless, the more the orbit is inner, the smaller is the load applied on the environment. In this sense, maintenance is the most important means for life cycle management.

2.2 The changing role of maintenance

In the past, maintenance was regarded as repair work. Machines were operated until they broke down, and there was no way to predict failures. With the development of reliability engineering in the 1950s, the concept of preventive maintenance was advocated, and time-based maintenance (TBM) was introduced. TBM was based on the so-called bathtub curve, which represents the increase in the failure rate of products after a certain period of operations. However, in many cases, product condition cannot be identified from the extent of the operational period, since the rate of deterioration depends not only on elapsed time but also on various other factors, including operational and environmental conditions. Therefore, TBM sometimes imposes unnecessary treatments, which often disrupt normal operations and induce malfunctions due to missed operations.

After the limitations of TBM as a means of preventive maintenance were recognized, the concept of condition-based maintenance (CBM) was proposed based on the development of machine diagnostic techniques in the 1970s. In the case of CBM, preventive actions are taken when symptoms of failures are recognized through monitoring or diagnosis. Therefore, CBM enables taking the proper actions at the right timing to prevent failures, if there is a proper diagnostic technique.

However, CBM is not always the best method of maintenance, especially from the perspective of cost effectiveness. When failures of machines or components are not critical, we can allow breakdown maintenance (BM), in which actions are taken after failures are detected. When the lives of machines or components can be estimated precisely, TBM is the most effective means of maintenance. Therefore, from the latter half of the 1980s, the importance of selecting proper maintenance strategies has been acknowledged in various areas. Reliability Centered Maintenance (RCM) [3] and Risk Based Inspection (RBI) or Risk Based Maintenance (RBM) [4] are the most well known methodologies for this purpose.

Although maintenance concepts and methodologies have advanced significantly over the past several decades, as explained above, maintenance still has a negative image because it is regarded as merely a measure against troubles. A maintenance department is usually regarded as a cost-centre, which does not create profits.

If we look at the role of maintenance from the perspective of life cycle management, however, we realize that the picture is completely different. The purpose of product life cycle management is to control the conditions of products so as to provide the functionality required by customers or by society, while keeping the environmental load at a minimum and maintaining appropriate corporate profits. There are two reasons why it is necessary to control the conditions of products. One is the change in product conditions due to deterioration. Another is the changing needs of customers or of society. The former is referred to as the product's physical life and the latter as its functional life. In both cases, the measure that should be considered first is maintenance including upgrade, because maintenance generates a lesser environmental load. If maintenance does not work well, other measures should then be considered, such as remanufacturing. Production of new products should be the last measure taken. In this context, the priority relationship between production and maintenance has been completely reversed. What we need to consider from the perspective of life cycle management is the notion of "production free" rather than "maintenance free."

The perspective of life cycle management for closed-loop manufacturing has brought about transformation of business models of the manufacturing companies from product providers to service providers [5]. Maintenance could be one of the major services associated with product life cycle management. If this business transformation goes further, companies will sell utilization and customers will pay only for utilization. In this context, achieving effective maintenance could be of benefit to companies, which can increase their profits by reducing maintenance costs, as well as to customers who can enjoy improved service quality [6].

3 A FRAMEWORK FOR LIFE CYCLE MAINTENANCE

3.1 Life cycle maintenance activities

The objective of maintenance is to preserve the condition of products so as to fulfill their required functions throughout their life cycle. Maintenance is an important part of life cycle management, whose main purpose is to

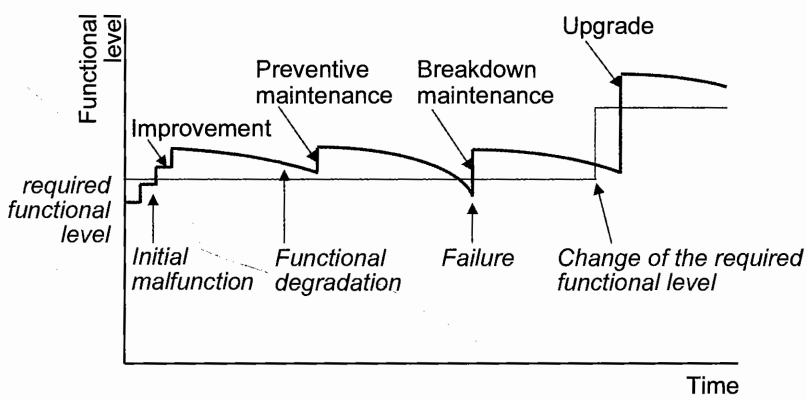

Figure 2: Maintenance activities.

enhance the eco-efficiency [7] of the product life cycle as explained above. We, therefore, use the term "life cycle maintenance" to stress its role from the perspective of life cycle management.

As previously mentioned, there are two reasons why it is necessary to control the conditions of products: changes in the condition of products due to deterioration, and the changing needs of customers or of society. These changes generate gaps between the required function and the realized function. Maintenance is executed to compensate these gaps by means of treatment or upgrading, as shown in Figure 2. For this purpose, maintenance should involve the following activities.

1. Maintainability design:

   Improving design based on evaluating maintainability in the product development phase and providing the design data for maintenance strategy planning and maintenance task control.

2. Maintenance strategy planning:

   Selecting a maintenance strategy appropriate to each part of the product.

3. Maintenance task control:

   Planning and executing the maintenance tasks based on the selected strategy.

4. Evaluation of maintenance results:

   Evaluating the results of maintenance to determine whether the maintenance strategy planning and maintenance task control are appropriate.

5. Improvement of maintenance and products:

   Improving maintenance task control, maintenance strategy planning, and even product design based on the evaluation of maintenance results.

6. Dismantling planning and execution:

   Planning and execution of dismantling at the end of the product life cycle.

In life cycle maintenance, we have to manage the activities listed above in an effective way throughout the life cycle of the product. For this purpose, the following issues should be considered.

1. Adaptation to various changes during life cycle:

   During the product life cycle, there could be various changes in the required functions, in the operating environment, in the operating conditions and in the product itself. Maintenance management should be flexible enough to adapt to these changes, because maintenance methods depend on these factors.

2. Continuous improvement of products:

   In general, it is impossible to design a product perfectly. Therefore, maintenance should include a mechanism for continuous improvement of products based on experience and knowledge acquired during their life cycle. This mechanism is also effective for functional upgrade of products to cope with shortening the product life cycle because of rapid changes in users' needs and technology development.

3. Integration of maintenance information:

   For effective maintenance management, all information associated with maintenance should be integrated in such a way that it is available from any phase of the life cycle. In the development phase, for example, it is essential to know the real operating situations and the problems encountered during past operations. On the other hand, it is necessary to have exact design data for maintenance strategy planning and maintenance task control.

3.2 A framework for life cycle maintenance

Three feedback loops for maintenance management

For fulfilling the requirements of life cycle maintenance described above, effective execution of a P-D-C-A (plan-do-check-action) cycle is essential. For this purpose, the

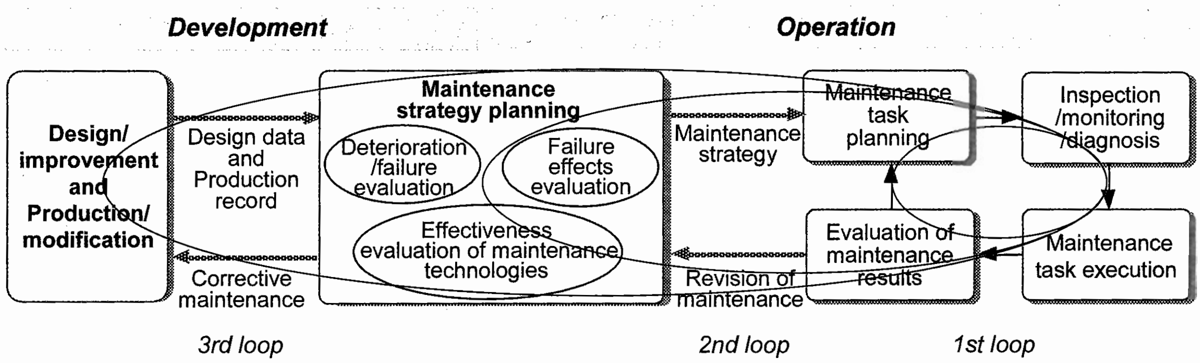

Figure 3: Framework for life cycle maintenance.

- criteria for providing treatment
  - time
  - condition
    - detection of breakdown
    - detection of symptom
    - analysis of trend
- opportunity of maintenance task execution (inspection/monitoring diagnosis/treatment)
  - during operation
  - during stoppage
  - when disassembled
- type of treatment
  - servicing
  - repair
  - replacement
  - design improvement

Figure 4: Categorizations of maintenance strategies.

framework for life cycle maintenance shown in Figure 3 has been proposed [8]. In this framework, maintenance strategy planning plays a key role. This planning involves selecting the strategy of maintenance among various options, such as BM, TBM, and CBM, based on the evaluation of potential problems that could occur during operation, as well as evaluation of failure effects and effectiveness of maintenance technologies. Maintenance strategy planning serves as a bridge between the product development phase and the operation phase. It obtains design data and production records from the development phase, and determines the maintenance strategy for each component of the product. These strategies are passed on to the operation phase, where maintenance tasks are planned in terms of procedures and schedules based on them. After maintenance tasks, such as inspection, monitoring, diagnosis and treatment, are executed, the results are evaluated by comparing the actual condition of the product to what is anticipated when the maintenance strategy was selected. If there are discrepancies, the information is fed back to the maintenance strategy planning, where the maintenance strategies are revised based on re-evaluation of potential problems, taking the actual data into account. If corrective maintenance, i.e., design improvement, is needed, the information is further fed back to the development phase, where improvements and modifications of product design are performed.

As seen in Figure 3, there are three feedback loops. The first is the loop of operational phase maintenance task management, which consists of maintenance task planning, task execution and assessment of maintenance results. This is the loop for controlling routine maintenance work. The second loop includes maintenance strategy planning. By means of this loop, the maintenance strategies can be improved based on the observation of actual phenomena and knowledge accumulated during the product life cycle. The third loop includes product development. This loop is essential for continuous improvement of the product during its life cycle.

These three loops provide effective mechanisms for adapting maintenance strategies to various changes, such as changes in operation conditions and environment, and also for continuously improving products.

Maintenance strategy planning

As pointed out above, maintenance strategy planning plays a key role in life cycle maintenance management. Maintenance strategies are categorized in terms of three factors: criteria for providing treatment, opportunity of maintenance task executions, and type of treatment, as shown in Figure 4. Among these options, a maintenance strategy is selected for each component based on two kinds of evaluations: technological evaluation and managerial evaluation, as shown in Figure 5.

Two major factors should be considered in the technological evaluation. The first factor involves the characteristics of deterioration and the resultant functional failures, which should be considered in the deterioration and failure analysis. The other factor is the applicability of maintenance technologies. (In this paper, deterioration refers to physical and/or chemical processes, such as wear, fatigue and corrosion that change the conditions of product components. Deterioration may induce changes in the behavior of the product. If these behavioral changes are related to functions required of the product, they are recognized as functional degradation or failures.)

A progressive pattern of deterioration and functional degradation is one of the most important characteristics of deterioration and failures. Figure 6 schematically illustrates this progressive pattern. The pattern can be attributed to the predictability of the period of the normal state τ_N and the time length of the symptomatic state τ_D in comparison with the cycles of monitoring, diagnosis, or treatment. If τ_N is unpredictable, for example, time-based maintenance cannot be applied. If τ_D is very short, on the other hand, condition-based maintenance cannot be adopted.

It should be noted, however, that the pattern could change

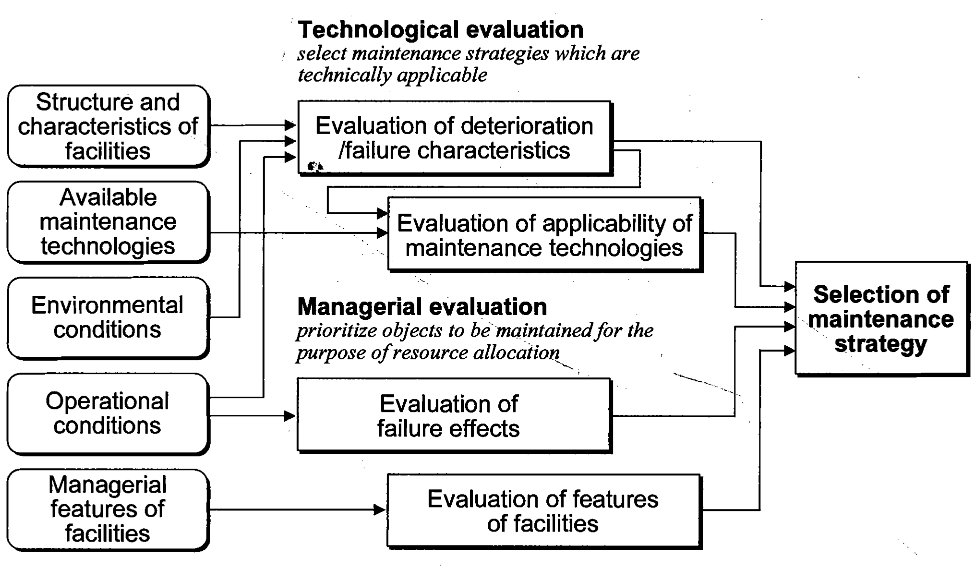

Figure 5: Factors for determining maintenance strategies.

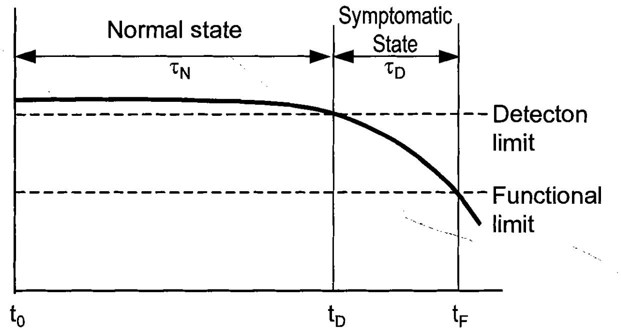

Figure 6: Progressive pattern of deterioration or functional degradation.

depending on what parameter is observed by what kind of sensing technology. Even though the occurrence of a failure is recognized as sudden, the deterioration that induces the failure may progress gradually and be detectable by a certain sensing technique. In such a case, application of the proper sensing technique enables the application of condition-based maintenance, which seems to be inapplicable from the failure characteristics. In this sense, the second factor, applicability of maintenance technologies should be taken into account in the technological evaluation.

In the managerial evaluation, the severity of the failure is evaluated in terms of its effects outside of the system concerned and in terms of its likelihood. The effects should be assessed from various perspectives. Typical examples are safety, operational, and economic factors. It is often difficult to make a quantitative evaluation of failure severity. In many practical cases, this severity is estimated qualitatively from various perspectives, and the results are combined to provide an overall rating.

While technological evaluation and managerial evaluation are independent of one another, they must be integrated to obtain maintenance strategies that are consistent and effective for the system as a whole. Figure 7 shows the general procedure for this purpose. The principle underlying the procedure is to allocate maintenance resources to minimize the expectation of total loss due to potential failures of the system. First, the goal of the maintenance level of the system to be achieved is determined. Then, technically feasible strategies and effects of the failure of each component are evaluated for each component. (If there are multiple failure modes for one component, evaluation should be performed for each failure mode.) Since the expectation of loss due to a failure depends on the likelihood of the failure, which further depends on the maintenance strategy, we have to assume a certain maintenance strategy beforehand for estimating the expected loss due to the failure. This assumption-evaluation loop is repeated until a proper maintenance strategy for the whole system is obtained, based upon which the expectation of the total loss can be kept below the acceptable level with affordable cost.

4 TECHNOLOGIES AND RESEARCH SUBJECTS

4.1 Technology map in maintenance

As described in the previous section, maintenance activities extend over the entire product life cycle and are supported by a wide variety of technologies. The technological subjects associated with maintenance are organized in Table 1, where the columns represent the product life cycle phases and the rows represent technologies. In the following sections, we describe technological issues and research subjects corresponding to each of the life cycle phases.

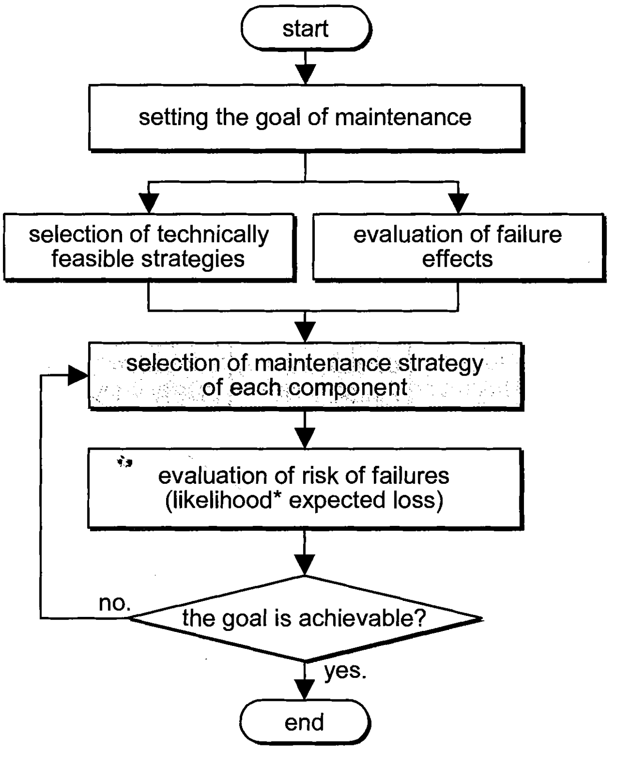

Figure 7: Procedure of maintenance strategy planning.

4.2 Design for maintenance

Prediction of potential deterioration and failures

Since the main purpose of maintenance is to manage the condition of products, it is essential to identify potential deterioration and failures, which are primal causes of changes in product condition. Without being aware of problems, you cannot take any action. Weak points in the product design, which are indicated by deterioration and failure analysis, should be countered by design improvement or maintenance. The former is called reliability design. In the latter case, the results of deterioration and failure analysis are provided as base data for maintenance activities such as maintenance strategy planning, monitoring and diagnosis.

Although deterioration and failure analysis is very important, it is a time-consuming task and requires expertise. Even FMEA (Failure Mode and Effects Analysis), which is the most popular method for deterioration and failure analysis, is not used extensively in the industry. To solve this problem, computer support systems have been considered. FMEA supported by computers is called Computer-Aided FMEA [9, 10].

Design to ease maintenance operations

Disassembly and assembly operations are often required for maintenance. Thus, it is important to enhance assemblability and disassemblability of products by means of DfX (Design for X) in order to increase the efficiency of maintenance operations [11, 12].

Serviceability is a more sophisticated concept for evaluating the ability of a product to be maintained. It combines concepts of accessibility, assemblability, and component reliability in order to evaluate life cycle service costs. Methodologies and computer tools for evaluating serviceability have been proposed. They are called Service Mode Analysis or Service Modes and Effects Analysis [13, 14].

Table 1: Technology map of maintenance.

issues / technologies	design for maintenance	maintenance planning	inspection/ monitoring/ diagnosis	middle of life treatment	end of life treatment	life cycle management
sensor, signal processing, chemical analysis			inspection/ monitoring/ diagnosis		condition diagnosis	
failure analysis failure physics	deterioration evaluation, life span evaluation, FMEA, FTA	deterioration evaluation, residual life evaluation, FMEA, FTA	trend analysis		deterioration evaluation, residual life evaluation	
artificial intelligence, knowledge management			monitoring/ diagnosis/ prognosis	self-maintenance operation support system (ES)		malfunction data collection system
model-based technologies	deterioration and failure simulation	deterioration and failure simulation	model-based monitoring/ diagnosis	operation support system (VR)	operation support system (VR)	
reliability engineering,	reliability design	RCM			residual life evaluation	
risk management		RBM	RBI			
network, database.	deterioration and failure mechanism database	deterioration and failure mechanism database	remote monitoring, remote diagnosis	tele-service		MP data management life cycle maintenance data management
design methodologies	DfX (accessibility, assemblability, disassemblability), tolerancing			maintainability/ serviceability	upgrade	
automation, robotics				maintenance robot	automated disassembly	
organizational and human factors, method engineering			TPM	TPM operation support system	operation support system	
environmental management						LCA
costing						LCC

4.3 Maintenance planning

Maintenance planning is divided into maintenance strategy planning and maintenance task planning. The former involves selecting a proper maintenance strategy for each component of the product. The latter consists of process planning, capacity planning, and scheduling of maintenance task execution [15]. Maintenance task planning is performed based on the strategy determined by the maintenance strategy planning, as shown in Figure 3. Efficiency of maintenance depends more on the appropriateness of the maintenance strategy planning than on maintenance task planning. Therefore, establishment of a systematic methodology for maintenance strategy planning is an important issue for life cycle maintenance.

The study of systematic approaches to maintenance strategy planning is, however, a relatively new area of research. The most well known methodology for this purpose is RCM. It was developed in the field of aircraft maintenance in the late 1970s. Recently it has been applied to other areas, such as nuclear power plants and various manufacturing plants. RCM provides a systematic procedure for maintenance strategy planning based on a logic tree analysis, in which effects of failure are first categorized and then effectiveness of maintenance actions are evaluated based on the procedures given according to the categories of effects.

In addition to RCM, Risk-Based Inspection (RBI) or Risk-Based Maintenance (RBM) has attracted attention in recent years as a systematic method for maintenance strategy planning, especially in the area of nuclear power

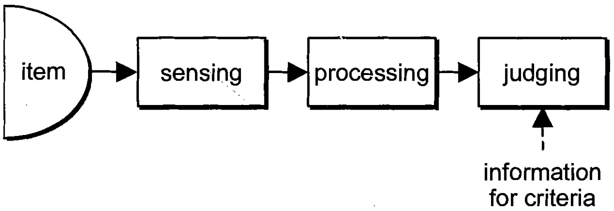

Figure 8: Three phases of inspection/monitoring/diagnosis.

plants. While RCM selects the maintenance strategy based on qualitative evaluation of failures, RBI/RBM uses risk for prioritizing potential failures. Risk is defined as the product of a failure probability for each item and its respective consequence. The basic concept of RBI/RBM is to focus inspection and/or maintenance efforts on items with higher risks. Recently API (American Petroleum Institute) established a procedure for applying RBI to the hydrocarbon and chemical process industries. The procedure is now widely referred to in applying RBI to process plants [16, 17].

4.4 Maintenance task execution

Maintenance tasks are divided into three categories: identification of conditions of products, including inspection, monitoring and diagnosis; middle-of-life treatment; and end-of-life treatment.

Identification of states of products

Identification of the product condition is one of the major maintenance tasks, not only for condition-based maintenance but also for diagnosis in the case of breakdown maintenance. The purposes of the task are:

- to check product integrity
- to detect symptoms or failures
- to analyze cause of failures or symptoms
- to predict the future trend of the condition

Terms such as inspection, monitoring, diagnosis and prognosis are used to represent these activities. While inspection implies observation and understanding of the product's current status, diagnosis and prognosis involve analysis of causality and anticipation of the progress of deterioration and functional degradation. On the other hand, monitoring implies continuous or periodic observation of the product condition for detecting symptoms or failures. In any case, the activity consists of three phases: sensing, processing, and judging, as shown in Figure 8.

Various techniques are applied to each phase. In the sensing phase, numerous physical and chemical parameters are observed by means of a wide range of sensing technologies. In the processing phase, when the sensory data is obtained as time series data, various signal-processing techniques are applied for extracting features indicating the status of the product conditions [18]. Chemical analysis techniques, such as lubrication analysis and wear particle analysis, are also used in the processing phase.

In the judging phase, the features extracted from the signal are interpreted to determine whether they indicate deterioration and/or functional degradation. For this purpose, we need information about the judgment criteria in addition to sensed information. In many cases, difficulties of monitoring and diagnosis come from a lack of such information. To cope with this problem, various technologies have been applied. In particular, knowledge engineering technologies are extensively applied as promising methods, such as rule-based reasoning, model-based reasoning, case-based reasoning, and neural networks. Many diagnostic expert systems have so far been developed based on these technologies [19-36]. However, there are still various issues to be resolved in order to achieve reliable monitoring, diagnosis and prognosis under practical conditions.

Middle-of-life treatment and end-of-life treatment

Since methods of maintenance treatment depend on differing product conditions, execution of this treatment requires skills and knowledge. Therefore, maintenance personnel should be provided with operation guidance to improve operation efficiency. For this purpose, virtual reality and tele-service technologies are considered, as will be discussed in the next section.

Another means for improving the efficiency of executing maintenance tasks is to automate the operations. For this purpose, various types of maintenance robots have been developed [37, 38, 39]. Furthermore, development of process technologies is also important for efficient execution of treatment [40].

4.5 Life cycle maintenance management

In addition to the technologies supporting each phase of the product life cycle, we need technologies to evaluate and manage the total life cycle. LCC (Life Cycle Costing) and LCA (Life Cycle Assessment) are the primary methods for evaluating the entire product life cycle. In many cases, a maintenance-centered life cycle in which product functions are maintained for a longer period through maintenance has an advantage in life cycle cost and also in environmental impact [41, 42, 43]. Recently, experimental economics have attracted attention for considering the economic aspect of life cycle management [44].

Another important issue in life cycle maintenance management is providing an information infrastructure in order to share product and maintenance data throughout the life cycle. This infrastructure includes product life cycle data management, malfunction data collection and MP (Maintenance Prevention) data management [45, 46].

5 RECENT ADVANCES AND EMERGING TECHNOLOGIES IN MAINTENANCE

5.1 Enabling technologies for maintenance

Since maintenance covers a wide range of activities in which various technologies are applied, the recent rapid advancement of technologies has impacted maintenance in diverse ways. These technologies include 3-D modeling, knowledge management, simulation, and web technologies. In the following sections, we describe how these technologies serve the transition of the maintenance paradigm in light of life cycle management.

5.2 Model-based maintenance

Recent advancements in digital product modeling technology enable us to use the product model as a core for product life cycle management and to utilize it for various evaluations needed in each life cycle phase. It can also be effectively applied in maintenance in a number of ways, for example in deterioration analysis, failure mode and effects analysis (FMEA), monitoring and diagnosis, and disassemblability analysis for repair works [47, 48].

Requirements of the models for maintenance

Whether used for failure analysis in the planning stage or diagnosis in the operation phase, the product model for maintenance should represent not only geometrical information but also behavioral information of the product. Maintenance essentially deals with cause-consequence relations between deterioration and failures. The former could be represented by changes in attributes of part models, and the latter could be represented by changes in

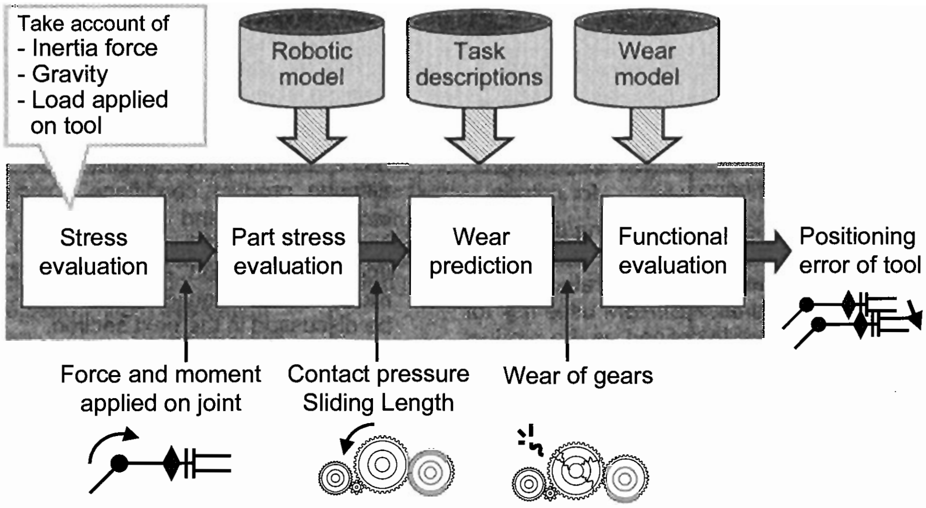

Figure 9: Procedure of deterioration simulation applied to joint gears of industrial robots.

behavior of the product model. Model-based failure analysis, for example, could be performed by evaluating the behavioral changes of the product model induced by changes in attributes of part models. Model-based monitoring and diagnosis can also be executed by comparing observed behavioral changes with those predicted by the models.

In general, intensive computation is required for computing precise behavioral change based on quantitative models. To avoid this problem, use of qualitative models has been proposed [49]. Behavioral changes are evaluated by means of qualitative physics. The method has been applied to self-diagnosis of photocopiers [50] and to fault-tree analysis of nuclear power plants [47]. As a basis for qualitative models, function modeling plays a crucial role. An example is the Function-Behaviour-State (FBS) model [51].

Model-based simulation for deterioration evaluation

Evaluation of deterioration is a key element in rational maintenance. It is necessary at every phase of the product life cycle. While FMEA involves qualitative analysis, simulation of deterioration and failure enables quantitative analysis. Deterioration processes such as wear are simulated, and their effect on product behavior is evaluated based on the product model. Deterioration is induced by operational and environmental stresses. Since conditions of operation and environment are different from machine to machine and changeable over time, the progress of deterioration is not the same even in the case of the same type of machines. Therefore, we need to use a physical model in which specific conditions can be considered rather than a statistical model by which only average values can be discussed.

For evaluating deterioration under non-steady operating conditions, model-based deterioration simulation is effective [47, 48, 52, 53]. Figure 9 shows a procedure of deterioration simulation applied to joint gears of industrial robots. The system evaluates the stress acting on each part of the joints using a robot model. Then, deterioration of joint gears is evaluated by using a wear model. This deterioration simulation system is applied to optimize the operating conditions under which the estimated amounts of joint wear can be reduced by about 50%, still maintaining the same cycle time.

Application of augmented reality to maintenance

Augmented Reality (AR) is another important technology for maintenance that has been made possible by the existence of product models [54-58]. It is effective in educating and training maintenance personnel, and also in online guidance of maintenance operations. Since unlike production operations, many maintenance operations are not repetitive, online guidance could significantly enhance the efficiency and quality of operations. Such functions as skill and know-how transfer could also be useful for transferring knowledge from the manufacturer of the product to the users, who have to maintain the machine by themselves at the site. Figure 10 shows an example of augmented reality applied to PC maintenance.

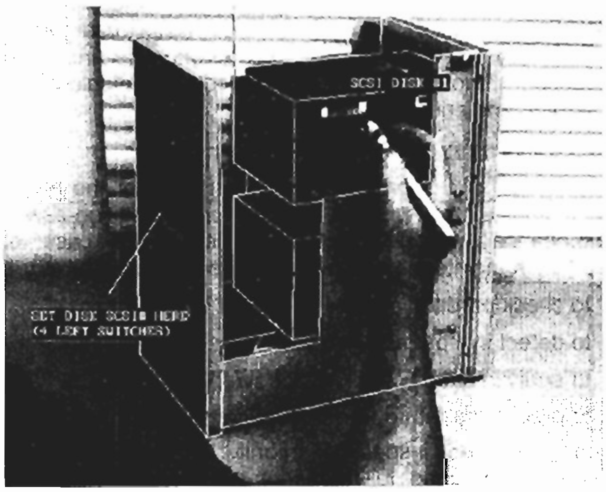

Figure 10: Application of augmented reality to PC maintenance.

5.3 Life cycle simulation for maintenance strategy planning

Proper selection of maintenance strategies is important to achieve effective maintenance. In selecting a maintenance strategy for each component, we need to optimize the maintenance strategy plan from the perspective of the entire system, according to the procedure shown in Figure 7. In addition, maintenance strategies should be evaluated from the viewpoint of life cycle management, since they are regarded as part of life cycle planning [59]. However, it is not easy to perform such evaluation, because we need to consider a number of factors associated with maintenance. The use of simulation has been proposed to cope with this problem [60]. Figure 11 depicts simulation models for evaluating elevator

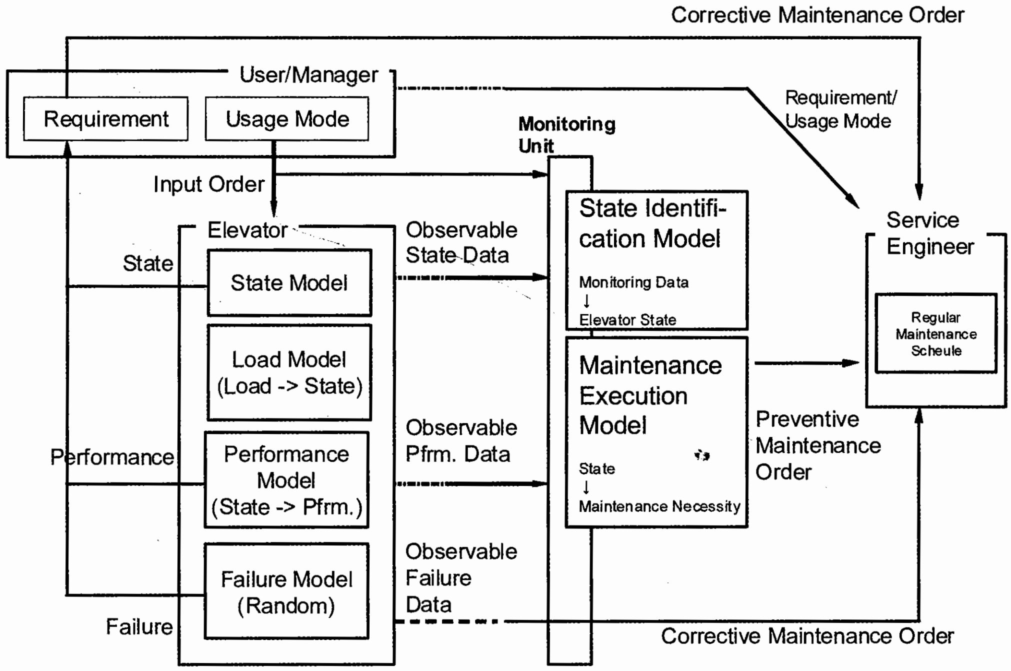

Figure 11: Simulation model for evaluating elevator maintenance strategies.

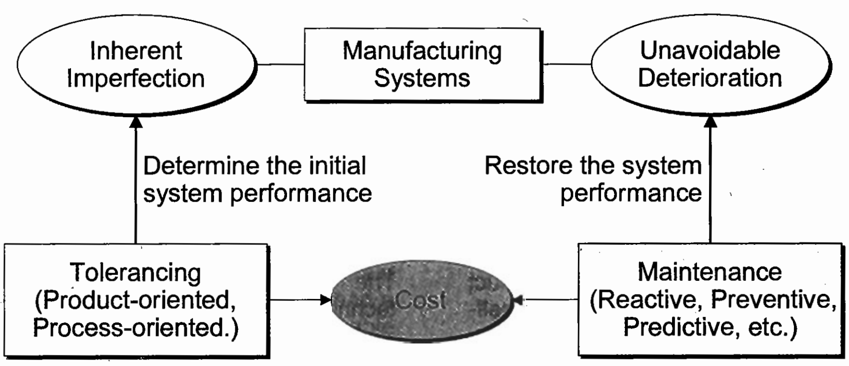

Figure 12: Integration of tolerance design and maintenance.

maintenance strategies. The simulation shows that the performance of maintenance is, in this case, quite sensitive to monitoring accuracy and dispatch rules of service personnel.

5.4 Integration of product and maintenance design

While design tolerance allocates an acceptable range of product parameter variation and determines initial product performance, maintenance is carried out to restore the increased parameter variation due to deterioration. Therefore, tolerance design and maintenance planning are closely interconnected, because there are two options for preserving product performance: tightening the tolerance or intensifying maintenance. In the past, however, tolerance design and maintenance planning were carried out separately.

In the course of recent advancements in the stream-of-variation modelling approach for multi-station manufacturing processes [61-65], and tolerance design [63, 66, 67], integration of tolerance design and maintenance scheduling has been proposed [63]. The methodology offers the understanding of system response to variation inputs and system performance changes over time, thus facilitating an integrated design procedure. Figure 12 illustrates a concept of the proposed methodology, which is applied to manufacturing process design in automotive assembly.

5.5 Proactive maintenance based on intelligent units

Although early failure detection and prognosis has been a basic concept of condition-based maintenance since the 1970s, its successful applications have been restricted by availability of proper sensors and information processing capabilities. The development of ubiquitous computing technologies, however, enables installation of an intelligent unit on a machine or component to be maintained. The unit, in which sensors and processors as well as communication devices are integrated, can monitor the conditions of machines and carry out prognosis while storing usage data effective for residual life evaluation.

An example of such a unit is the so-called Watchdog Agent™ shown in Figure 13. It can assess performance degradation of an observed product by means of embedded sensors, forecast future performance degradation and diagnose the reasons for degradation through trending and statistical modeling of the observed process signatures [68-72].

Another example is the so-called Life Cycle Unit (LCU), which acquires and stores usage data about components through integrated sensors over the entire life span. Thus, it provides the data for end-of-life services in addition to middle-of-life services. The prototype of the unit has been experimentally implemented in a shock absorber, a

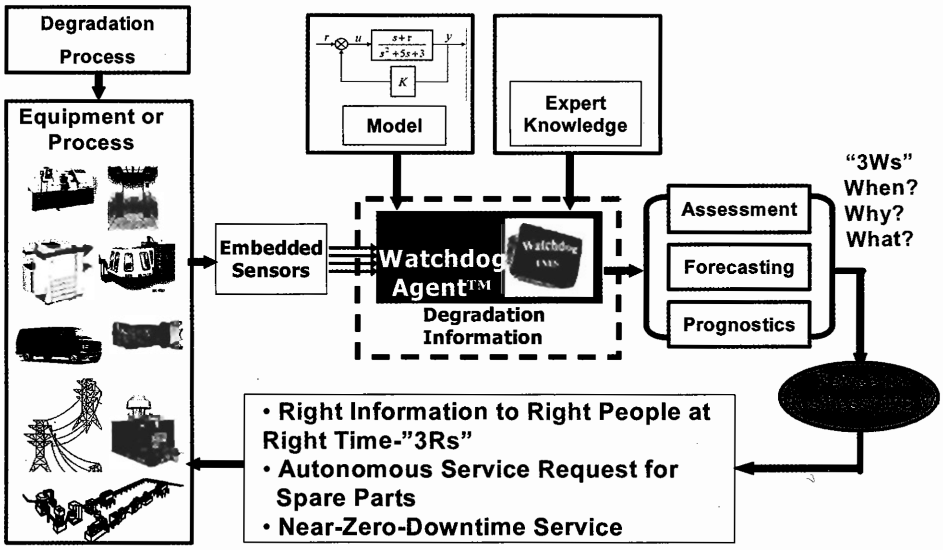

Figure 13: Watchdog Agent™.

washing machine, and the buggy of a rail freight wagon [73-75].

5.6 Self-maintenance

Nowadays, most products have self-diagnostic functions executable by a build-in microprocessor. Although these functions are regarded as a kind of self-maintenance, the concept of self-maintenance discussed in this section includes not only self-diagnosis but also self-repair and self-evolution. A self-maintenance machine should be equipped with a control and reasoning processor, sensors, and actuators to perform these tasks. In contrast to biological systems, however, it is difficult for a mechanical system to repair itself physically. Instead, the repair is carried out functionally. If a failure occurs, the product autonomously recognizes the failure through its self-diagnostic function, and tries to reconfigure its state, behavior, or function to maintain the lost function. Three types of self-maintenance technologies have been proposed: control [50], function redundancy [76], and network/group intelligence [77]. The control type self-maintenance photocopier has been commercialized. In order for these types of repair mechanism to be realized, the product should be designed to have functional redundancies. The design methodology for this purpose is also effective for upgradeable design, which enables evolution of the product during the life cycle, and thus extension of its life.

5.7 Web-based maintenance

The rapid advancement of communication and network technologies has had a significant impact upon

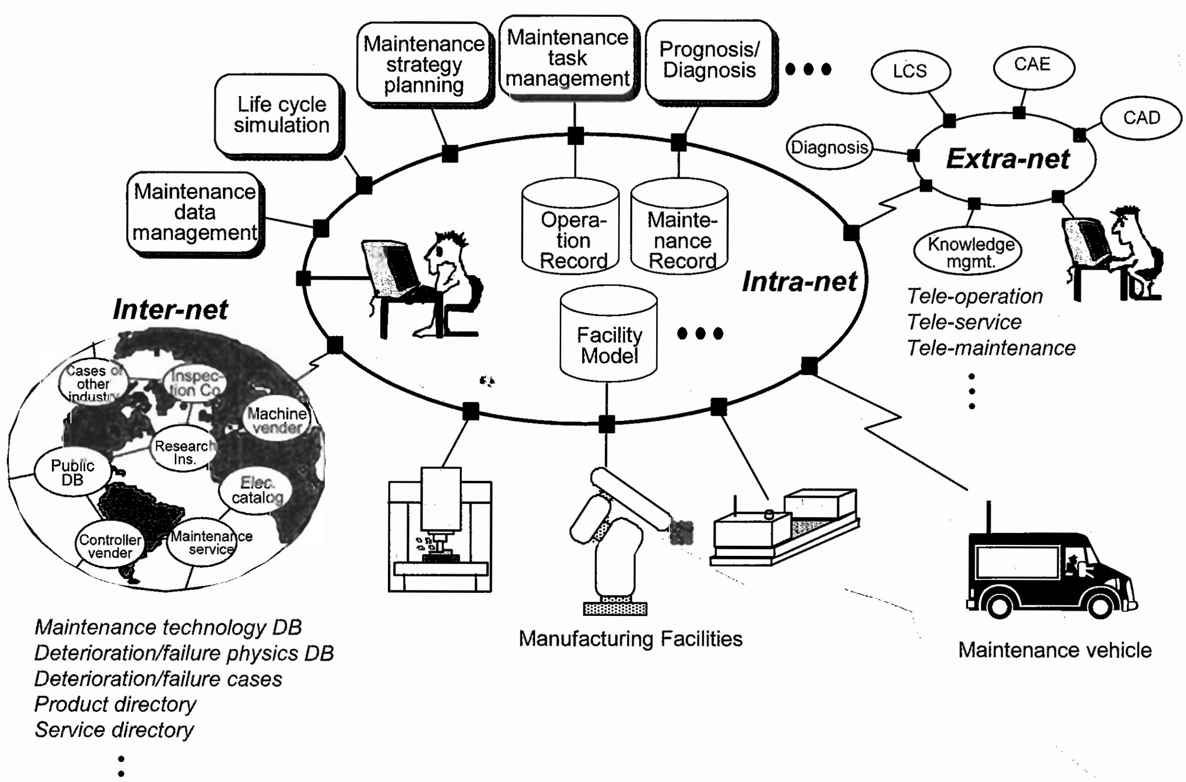

Figure 14: Concept of a web-based maintenance system.

maintenance technology, as well as on other engineering areas. The impact can be broadly divided into two categories: remote maintenance and web-based maintenance service.

Remote maintenance

Remote monitoring and diagnosis was discussed considerably in the 1970s, when the technology for data transmission via telephone line was first developed. Although many machine tool manufacturers offered remote maintenance service at that time, this type of service did not become popular due to the immaturity of the technology. Recent developments in Internet and wireless communication technologies, however, have enabled remote maintenance to be put to practical use.

Web-based maintenance service

Internet technology makes it possible to provide various maintenance services other than remote monitoring and diagnosis via networks. Emphasis is placed on providing entire services for life cycle management via a network, such as deterioration and failure analysis, residual life estimation, maintenance strategy planning, maintenance task management, end-of-life treatment and life cycle data management [78-81]. Figure 14 illustrates the concept of a network-based maintenance system. An intelligent maintenance service platform is proposed to enable easy implementation of a web-based maintenance service system. The platform consists of five layers: interface layer, data transformation layer, data transfer layer, intelligent informatics tools, and synchronization module [82].

6 SUMMARY

In this paper, we have discussed the changing role of maintenance from the perspective of life cycle management. Although the critical role of maintenance within automated factories was pointed out by Yoshikawa a quarter of a century ago [83], maintenance has long had a negative image. However, in view of sustainable manufacturing, we should redefine the role of maintenance as a prime method for life cycle management whose objective is to provide society with required functions through products while minimizing material and energy consumption.

Though an enormous number of works have focused upon maintenance as a whole, they are dispersed across various areas and are not yet systematized. We, therefore, have proposed a maintenance framework that could help us discuss maintenance technologies from various areas on the same table.

Recent advancements in information and communication technologies could also facilitate the integration of maintenance activities. There are many possibilities for making use of technologies such as digital modeling and web-based technologies to improve maintenance effectiveness.

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