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# Imperfect Maintenance Models, from Theory to Practice

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## Abstract

The role of maintenance in the industrial environment changed a lot in recent years, and today, it is a key function for long-term profitability in an organization. Many contributions were recently written by researchers on this topic. A lot of models were proposed to optimize maintenance activities while ensuring availability and high-quality requirements. In addition to the well-known classification of maintenance activities—preventive and corrective—in the last decades, a new classification emerged in the literature regarding the degree of system restoration after maintenance actions. Among them, the imperfect maintenance is one of the most studied maintenance types: it is defined as an action after which the system lies in a state somewhere between an “as good as new” state and its pre-maintenance condition “as bad as old.” Most of the industrial companies usually operate with imperfect maintenance actions, even if the awareness in actual industrial context is limited. On the practical definition side, in particular, there are some real situations of imperfect maintenance: three main specific cases were identified, both from literature analysis and from experience. Considering these three implementations of imperfect maintenance actions and the main models proposed in the literature, we illustrate how to identify the most suitable model for each real case.

**Keywords:** imperfect maintenance, optimization model, reliability

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## 1. Introduction

Maintenance is defined as “the combination of all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in or restore it to, a state in which it can perform the required function” [1]. Maintenance is everywhere, when there are systems, machines, elements that we use every day, requiring specific actions for functioning correctly, since degradations and failures reduce the effectiveness in their use. The industrial

sector is perhaps one of the most interested in maintenance actions since companies need to guarantee their required productivity targets. Despite this, maintenance has not always had the attention it deserved and for many years it was a “Cinderella function” [2], but recently its role was revalued, and since the 1960s, it was considered as a specific organizational unit [3]. According to Sherwin [2], the reasons why maintenance was a “Cinderella function” for so many years are mostly historical and can be overcome by new information technology (IT). IT, in fact, simplifies data acquisition and analysis of systems requiring maintenance activities, whereas integrated IT allows mathematical optimization of many aspects related to maintenance, such as costs and availability [2].

One of the strategies to adopt in order to increase awareness of maintenance importance in industrial and productive contexts is to prove its effectiveness [4]. It is essential to measure maintenance performance, for the justification of investments in this function [5] and for strategic thinking for asset managers. However, in the existing literature, only the internal efficiency is measured even if the maintenance contribution toward a total business goal should be measured (both external effectiveness and internal efficiency). Life-cycle profit (LCP) could be a fair measure of overall effectiveness for highlighting both value and cost of maintenance [2]. Maintenance, in fact, consists of so many activities that it is difficult to quantify its benefits at an individual activity level, whereas at a macro level, it is difficult to find the best trade-off between costs and benefits for the company profit [6].

Despite all that, today it is accepted that maintenance is a key function for long-term profitability in an organization [7], and for this reason, organizations are treating maintenance as an important part of their business [8], in the same way as other functions like production, marketing, sales and so on. Effective maintenance management, in fact, requires a multidisciplinary approach where maintenance is viewed strategically from the overall business perspective [9]. Companies invest in early reliability estimation also in order to setup their on-field service [10].

The maintenance role evolution in industrial context could be summarized through **Figure 1**, proposed by Furlanetto and Mastriforti [11].

Corrective maintenance (CM) is certainly the approach with the lowest prevention and engineering contributions since it simply reacts to an occurred failure. Moving from CM to prevention maintenance, it goes from a defeatist and passive approach to a more “aggressive” one, where engineering principles and the aim of preventing future failures are the most important aspects in maintenance management.

Therefore, maintenance engineering is nowadays a very important function in industrial context. It is usually defined as “a staff function whose prime responsibility is to ensure that maintenance techniques are effective, equipment is designed and modified to improve maintainability, on-going maintenance technical problems are investigated, and appropriate corrective and improvement actions are taken” [12]. It is a very strategic resource essential for ensuring production capacity, product quality and best lifecycle cost. It is related to Business Continuity and to High-Reliability Organization (HRO) too: the choice of a specific maintenance policy, in fact, defines a more or less compliant maintenance approach to the HRO paradigm [13].

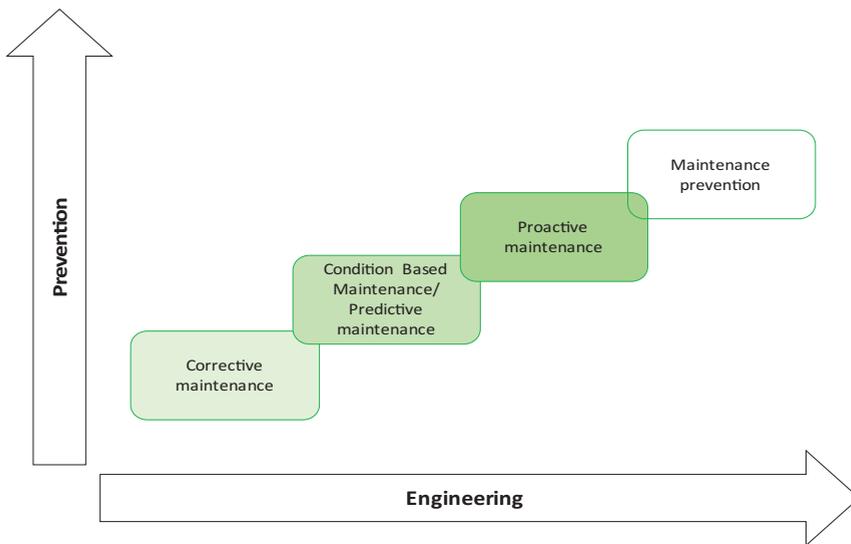


Figure 1. From failure to prevention [11].

Maintenance engineering is one of the three main maintenance organizational processes, as shown in **Figure 2**, adapted from Furlanetto et al. [16].

Maintenance has a unique role also in the latest 4th Generation Industrial Revolution (Industry 4.0), which focuses on intelligent products and production processes [14]. The new digital industrial technology defines a transformation where sensors, machines, workpieces and Information Systems are connected along the value chain: internet allows communication between humans and machines in cyber-physical systems (CPS). The interaction with surrounding systems is able to create self-aware and self-learning machines condition, with consequent improvement of overall performance and maintenance management [15]. It is clear that maintenance processes must be integrated in an effective way in the Industry 4.0 framework. Digitalization and networking, in particular, shall provide an increasing amount of actor and sensor data which can support the continuous monitoring of the process and of the machines conditions. Data, in fact, can be recorded and transmitted in real time to the cloud for predictive maintenance analysis.

Maintenance engineering is strictly connected to maintenance management and maintenance implementation. In fact, the maintenance implementation process gets orders from maintenance management, to which refer on their progress. Maintenance management sends information to maintenance engineering function for reliability and maintenance analysis. Then, maintenance engineering, through tools and specific software, defines maintenance plans to be transferred to maintenance management function and, finally, to maintenance implementation [16].

It is well recognized, however, that in many asset-intensive industries, maintenance costs are an important part of the operational cost [5], both for preventive and for corrective maintenance activities. Even if corrective and preventive maintenance is the most known maintenance

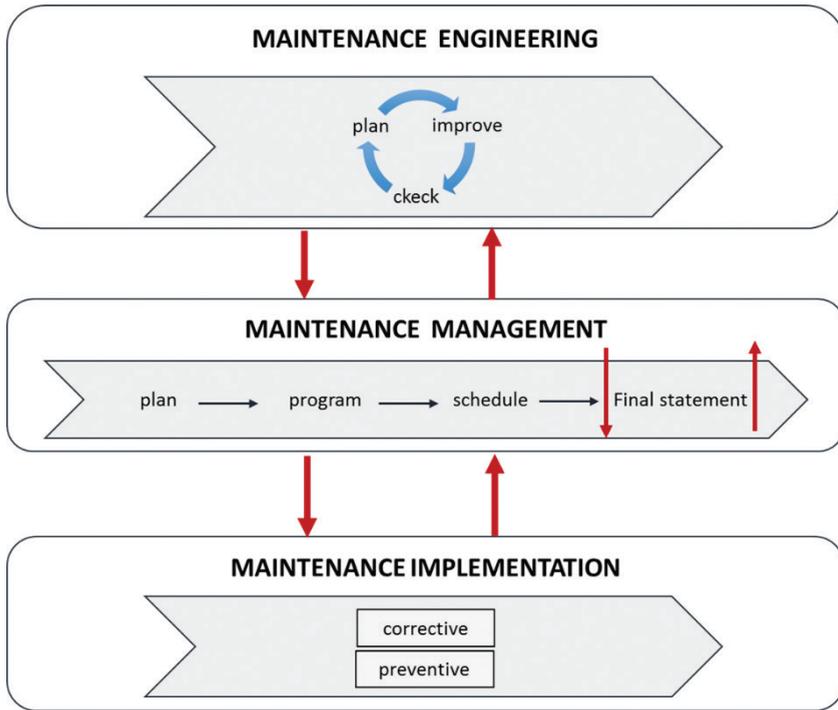


Figure 2. Role of maintenance engineering in maintenance organization process [16].

types, in the last decades, new kinds of maintenance were identified in the literature, as better explained in the following sections.

### 1.1. Maintenance and reliability

Reliability and maintenance are strictly connected: reliability models, in particular, define the main reliability properties of a system, which are essential for maintenance management.

Here, we show a brief summary of the most important reliability considerations useful in maintenance theory.

First of all, reliability is defined as the probability that a component (or an entire system) will perform its function for a specified period of time, when operating in its design environment [17]: reliability definition, therefore, requires an unambiguous criterion for distinguishing operation from non-functioning states and the exact definition of environmental conditions. In this way, reliability will depend only on time.

The most significant reliability parameters are:

- $f(t)$ : probability density function (pdf)
- $F(t)$ : cumulative distribution function (cdf), also known as failure function or unreliability function

- $R(t)$ : reliability function
- $\lambda(t)$ : hazard function, defined as the trend of the instantaneous failure rate at time  $t$  of an element that has survived up to that time  $t$ .

Hazard function is usually presented as a time depending curve, called the “bathtub” curve, which is useful for determining three main failure types corresponding to three different life stages of a component. The life of a device has a first part with a failure rate relatively high and a descending shape (decreasing failure rate DFR) because of the so-called early failures depending on potential manufacturing defects (design or installation defects, for example); the central part of its life corresponds to the useful life, in which it is usually assumed that the failure rate does not change over time (constant failure rate CFR); finally, the end of life corresponds to the wear-out phase with an increasing failure rate (IFR).

The reliability properties of a component might be represented with a specific probability distribution model in each one of the main phases (DFR, CFR, IFR): the early stage is modelled through the Weibull distribution, the random failure stage is defined by a negative exponential distribution and finally, for the wear-out failures, the normal distribution is the most suitable one, since its failure rate is always a monotonically increasing function of time (so the normal distribution is an IFR distribution) [18]. Obviously, the most suitable distribution has to be selected according to the real failure rate dependency on time.

The knowledge of the reliability features of a system is the starting point for the definition of the maintenance and replacement models to apply. Many models are shown in the literature [19]: all of them can fall into some categories, such as the age replacement policy, the block replacement policy, the periodic preventive maintenance policy, the failure limit policy, the opportunistic maintenance policy, the inspection policy [20], etc.

Reliability parameters are used in maintenance optimization models, too. For a long time, in fact, the cost was the only parameter considered for their optimization, in line with the old maintenance concept (maintenance as a necessary evil and the only maintenance is corrective). Today, however, both costs and reliability measures (such as availability) are present in maintenance optimization models. In literature, there are many contributions on maintenance optimization models, and the review papers on this topic are really interesting [21, 22]. Some models, for example, try to optimize maintenance activities according to risk management [23]: the main aim is the minimization of the effects of failures on the organization’s main objectives.

Maintenance models could be quite difficult to apply because of lack of data on maintenance actions and faults [24]. At the same time, cost data could be harder to have, especially with respect to indirect costs since, for example, it could be very difficult to quantify intangible aspects like the benefits of maintenance.

Furthermore, models are usually complex to apply since several constraints and several objectives usually affect the optimization of maintenance policies [22]: simulation approach could be a viable alternative to the analytical one.

In conclusion, we can say that maintenance optimization models could be very useful in a maintenance management process because they allow to consider all the main maintenance objectives (ensuring system function, ensuring system life, ensuring safety, ensuring human

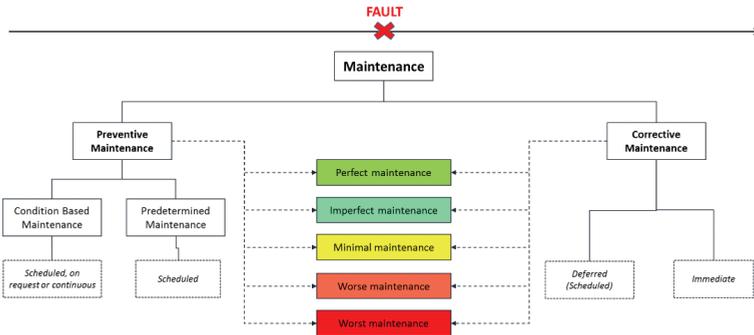
wee-being) [6]. At the same time, the input data must be corrected in accordance with the facts. The best suitable model could be identified among the several models proposed by literature.

## 2. The “new” maintenance classification and imperfect maintenance

Imperfect maintenance (I.M.) is a new kind of maintenance approach, which has spread in the last decades, as an alternative to the common classification of maintenance, proposed for example by the EN 13306:2010 [1]. This last one considers two main classes of maintenance approaches: corrective maintenance (CM) and preventive maintenance (PM). The distinguishing element in this classification is the time in which maintenance activity is performed and in particular the relationship between the occurrence of a fault and the maintenance activity. PM is an action done before the occurrence of the fault, while each maintenance action carried out after the fault is called CM. A CM action is performed at unpredictable time points (it is not known the failure time of a component), and its main function is to put the item into a state in which it can perform the required function. If CM is carried out immediately after the occurrence of the fault, we speak of *immediate* maintenance, while if it is postponed (scheduled with other maintenance actions or with down production period), we speak of *deferred* maintenance. Since CM costs are three or four times higher than the PM costs [25], it could make sense to delay CM activities waiting for a situation in which the time of repair has a negligible impact on the unavailability. On the other side, PM activities could be carried out at predetermined intervals of time or number of units of use (*predetermined maintenance*) or according to information on system degradation supplied by condition monitoring, inspection and test activities (*Condition Based Maintenance*).

In addition to this well-known classification, in the last decades, a new categorization emerged in the literature. It dates back to 70s and is based on the item restoration degree after maintenance actions. In Wang and Pham [34], an example of this classification is proposed. Both the “classic” and “new” classifications are summarized in **Figure 3**: it shows that both corrective and preventive maintenance could be:

- Perfect maintenance: Maintenance action that restores a system to an “As Good As New” (AGAN) condition. Considering the main parameters defining the reliability features of the system, we could say that after a perfect maintenance action, a system has the same lifetime distribution and the same failure rate function of a new one. For this reason, generally, the replacement of a system by a new one is a perfect repair.
- Imperfect maintenance: Maintenance action which makes a system not AGAN but younger: upon an imperfect maintenance action, the system lies in a state somewhere between AGAN and its pre-maintenance condition.
- Minimal maintenance: It restores a system to an “As Bad As Old” (ABAO) condition and, therefore, to the same failure rate as before the maintenance action. First of all, Barlow and Hunter [26] studied minimal repair proposing two preventive maintenance policies.



**Figure 3.** Classification of maintenance activities according to the time in which maintenance activity is performed (preventive maintenance vs. corrective maintenance) and to the system restoration degree (perfect, imperfect, minimal, worse, worst maintenance).

- **Worse maintenance:** It defines actions accidentally causing a worsening operating condition of the system. The system failure rate or the actual age increases after a worse maintenance action.
- **Worst maintenance:** It is similar to worse maintenance but, in addition, it causes fault or breaks of the system too.

This classification suggests that each “new” kind of maintenance action could be considered worse than the previous one. For example, imperfect maintenance causes a restoration degree lower than perfect maintenance but higher than minimal maintenance and so on.

The new maintenance activities classification is an accurate reflection of the reality since the maintained components are not always restored to an as good as new state [27]. At the same time, it has a huge impact on the reliability and maintenance theory, since maintenance has always been perfect or minimal, and therefore, reliability and optimization maintenance models were defined for these two extreme situations. The introduction of new maintenance ideas required new models, proposed in the literature in the last years.

In literature, there are many contributions on imperfect maintenance, and, at the same time, worse and worst maintenance were studied, for example, by Kay [28], Nakagawa and Yasui [29] and Chan and Downs [30], which considered a kind of preventive maintenance causing the failure of the maintained equipment.

Among the maintenance types considering the item restoration degree after maintenance actions, this chapter focuses on imperfect maintenance (IM).

### 2.1. Imperfect maintenance literature review

The first interest in imperfect maintenance dates back to the second part of 1970s thanks to researchers like Kay [28], Ingle and Siewiorek [31], Chaudhuri and Sahu [32], Chan and Downs [30] and Nakagawa [33]. In particular:

- Kay [28] dealt with the effectiveness of preventive maintenance concept [28].
- Ingle and Siewiorek [31] presented the imperfect recovery concept for multiprocessor systems: they suggested to use a factor  $C$  called coverage, that is, the condition probability that a system recovers successfully after a failure [31].
- Chaudhuri and Sahu [32] suggested a model to define the optimum preventive maintenance intervals both for perfect and imperfect PM [32].
- Chan and Downs [30] presented two criteria for preventive maintenance analysis (the maximization of the steady-state availability and the minimization of the expected maintenance cost per unit time under specific assumptions). The authors suggested a state transition diagram to represent preventive maintenance, considering a probability  $p$  of not restoring the component in an AGAN condition but in a failed state (worst preventive maintenance) [30].
- Nakagawa is one of the most interested researchers for this topic. He supposes that preventive maintenance is imperfect; then, he considers this kind of maintenance for defining optimum preventive maintenance policies [33].

These are only some examples, and many other researchers showed interest in imperfect maintenance topic.

Even if many works on imperfect maintenance regard the one-unit system [34], this concept could be also applied the multi-components system, which is the most common configuration in real problems.

Researchers show interest in imperfect maintenance even now, as highlighted by the number of publications of the more recent years (a systematic literature review was conducted on the web search engines Scopus, IEEE Xplore, Google Scholar and Web of Science). Analysing the last contributions, it is possible to underline a greater interest in IMpractical implications. Some more recently published papers were analysed in order to understand which are the more recent trends and interest in IM topic. Some of them are here shown:

- Sanchez et al. [35] consider the problem of testing and maintenance activities optimization with uncertainty in the imperfect maintenance modelling. The proposed methodology is applied to a stand by safety-related system of a nuclear power plant. It shows the importance of considering uncertainties in the modelling of imperfect maintenance since it impacts on system unavailability and cost [35].
- Mabrouk et al. [36] propose a model to determine the optimum PM scheduling strategy for a leased equipment, considering that both PM and CM are imperfect. Since a leasing agreement is considered, some penalty costs are in the model (when the total expected equipment downtime due to maintenance activities in the lease period are greater than a pre-specified value) [36].
- Pandey et al. [37] propose a mathematical model for decision-making on selective maintenance actions under imperfect repair, for binary systems (i.e. they are either working or failed). Since it is usually difficult to do all the required maintenance actions during the maintenance break, the focus is both on the optimal use of the available resources (budget, repairman and time) and on the maximization of the next mission reliability [37].

- Le and Tan [38] studied the optimal maintenance strategy of systems subject to a degradation condition, subject to imperfect maintenance. They suggest a combined approach including both inspection and continuous monitoring activities to improve system reliability [38].

IM is increasingly considered in maintenance optimization problem: researchers are more and more aware that this “new” kind of maintenance must be considered both in theoretical and in practical problems.

## 2.2. Imperfect maintenance models proposed in literature

As shown in Section 1.1, the definition of an optimal maintenance policy for a system requires that many factors have to be considered, like the maintenance policies, the system architectures (single-unit, series, parallel, k-out-of-n, complex), the shut-off rules for series systems (which is the dependence of a failed component on the others), the maintenance degree (perfect, imperfect, minimal, worse, worst) and the maintenance costs. It is clear that both reliability parameters and costs are essential to optimize maintenance activities management.

The first step, however, is the definition of the reliability parameters of the system after an imperfect maintenance action, since the system itself will be not AGAN.

In literature, many different models were proposed: most of them are summarized in Ref. [39]. In the following paragraphs, the main categories will be explained.

### 2.2.1. $(p, q)$ rule method and its variants

These methods use a probability parameter to model imperfect maintenance. According to the  $(p, q)$  rule method, a component, after a maintenance activity, could return to the AGAN state with probability  $p$  and to the ABAO state with probability  $q = 1 - p$ . It is clear that if  $p = 1$  maintenance is perfect, whereas if  $p = 0$  maintenance is minimal. This method was proposed by Nakagawa at the end of 1970s [33] and then resumed by other authors: Brown and Proschan [40], for example, under specific assumptions, obtained important results. They considered an item repaired each time it fails (with negligible repair time), in a perfect way with probability  $p$  or in a minimal way with probability  $1 - p$ . It is assumed that no perfect repairs occur in  $[0, t)$  so that the item, at  $t$ , behaves as an item of age  $t$ , with failure rate  $\lambda(t)$ . Let  $F$  be the life time distribution of the item and  $\lambda$  its failure rate. Under these assumptions, they proved that the time distribution function of the time between successive perfect maintenance actions is

$$F_p(t) = 1 - (1 - F(t))^p \tag{1}$$

and the corresponding failure rate is  $\lambda_p(t) = p\lambda(t)$ .

Furthermore, they proved that, since the original failure rate function is simply multiplied by  $p$ , then also  $F_p$  has this property for  $0 < p < 1$  [40].

This model was subsequently changed, and other methods were obtained:

- $[p(t), q(t)]$  rule method: It was proposed by Block et al. [41] and differs from the previous method only by time dependence: considering a one-unit system subjected to corrective

maintenance activities with negligible repair time, the item is restored to a AGAN state with probability  $p(t)$  while to an ABAO state with probability  $q(t) = 1 - p(t)$ , where  $t$  is the age of the item (the time since last perfect maintenance) [41].

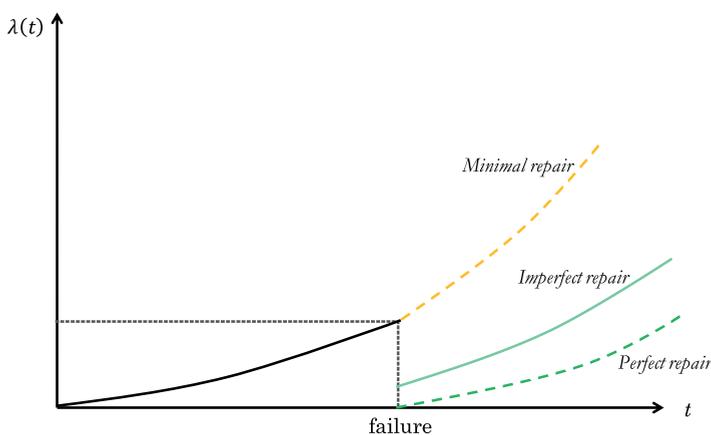
- $[p(n, t), q(n, t), s(n, t)]$  rule method: This model considers another parameter affecting on the effectiveness of maintenance activities, that is  $n$ , the number of failures since replacement. Therefore, according to this model, after a repair, a system will be in an AGAN state with probability  $p(n, t)$ , or in an ABAO state with probability  $q(n, t) = 1 - p(n, t)$ . A third possibility is considered: the repair could be unsuccessful with probability  $s(n, t) = 1 - p(n, t) - q(n, t)$  [42].

### 2.2.2. Improvement factor method

The improvement factor method considers that an imperfect maintenance PM activity can reduce the age of a system from  $t$  to  $t/\beta$ , with a new reliability of  $R(t/\beta)$ .

This method was proposed by Malik [43] in order to consider that the failure rate curve changes after preventive maintenance activities (in particular, the failure rate after PM lies between AGAN and ABAO) according to a parameter called improvement factor  $\beta$  [43]. In **Figure 4**, there is a representation of failure rate when minimal, perfect and imperfect repair are performed.

Over time, many improvement factors were proposed, since the restoration effect depends on several factors like the operating time of the system, the PM interval, the related costs, the number of PM carried out and so on. Lie and Chun [44], for example, considered an improvement factor to measure the restoration effect depending on PM cost and age of the system [44] considering the improvement factor as a variable of the model. Another example is represented by Chan and Shaw [45], which considered two types of failure rate reduction: the first one is fixed (so that we have always the same reduction of the failure rate), whereas the second one is proportional (all the reductions of failure rate are proportional) [45].



**Figure 4.** Minimal, perfect and imperfect repair according to the improvement factor method.

### 2.2.3. Virtual age method

Virtual age defines the restoration level achieved after a repair of a system. It depends on the operation time and on the number of maintenance activities performed. This method was proposed by Kijima et al. [46], which suggested that a system with virtual age  $V \geq 0$  behaves as if it was a new system which reached the age  $v$  without failure [46]. The main idea of the virtual age models, in fact, is to evaluate failure intensity considering virtual age instead of the real time [47].

According to Kijima, two main virtual age types could be identified: the first one assumes that the  $n$ th repair is able to remove the damage related to the time between the  $(n-1)$ th and the  $n$ th failures. The virtual age after the  $n$ th repair is:

$$v_n = v_{n-1} + q x_n \tag{2}$$

$v_n$  is the virtual age immediately after the  $n$ th repair,  $q$  is a parameter representing the effect of the  $n$ th repair (the quality of an intervention involving the component) and  $x_n$  is the time between the  $(n-1)$ th and the  $n$ th failures. Obviously, if  $q = 0 = 0$  the model explains a perfect maintenance, while if  $q = 1=1$ , we have a minimal maintenance.

With the second virtual age model, it is assumed that the  $n$ th repair is able to remove the cumulative damage of both current and previous failures, so that the virtual age after the  $n$ th repair is:

$$v_n = q(v_{n-1} + x_n) \tag{3}$$

Figure 5 shows a representation of the relationship between actual age and virtual age [48].

### 2.2.4. Shock model method

This model considers a unit that is subject to shocks randomly in time. At  $t = 0$  its damage level is equal to zero, while the damage level will increase over time upon occurrence of shock events. Obviously, each damage increases the current damage level of the unit: the unit fails when its cumulative damage is greater than a specified threshold value [49].

Kijima and Nakagawa [49] used this approach to model imperfect preventive maintenance, suggesting that each PM reduces the damage level by  $100(1 - b)\%$ ,  $0 \leq b \leq 1$ , of total damage.

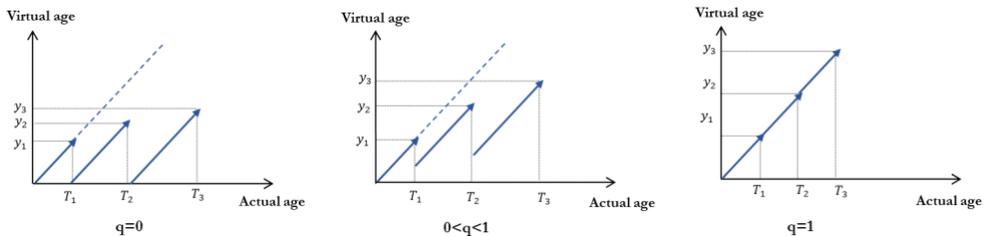


Figure 5. Virtual age vs. Actual age for  $q = 0, 0 < q < 1, q=1$ .

Even then, it is possible to trace back this situation to perfect and minimal repair: if  $b = 1$ , the PM is minimal, whereas if  $b = 0$ , the PM is perfect.

2.2.5.  $(\alpha, \beta)$  rule method

This IM treatment method was proposed by Wang and Pham [50]. According to this model, upon each repair, the lifetime of a system will be reduced to a fraction  $0 < \alpha < 1$  of its immediately previous one, and all lifetimes are independent (the lifetime decreases with the number of repairs) [50]. For the repair time, which is non-negligible and upon repair, the model supposes that the next restoration time becomes a multiple  $\beta > 1$  of its current one. Finally, all repair times are independent.

Figure 6 shows how, according to this model, when the number of repairs increases, the time to repair increases too, while the lifetimes decreases.

2.2.6. Hybrid model method

The hybrid model proposed by Lin et al. considers, in particular, the effects of PM activities in terms of how the hazard rate function and the effective age of the equipment are changed by the PMs [51]. The model is “hybrid” because it derives from two PM models proposed by Nakagawa [52]: the Hazard Rate PM model and the Age Reduction PM model.

The first one considers that the hazard rate function of a system is an increasing function of time when there are no PM activities, while each PM resets the  $\lambda(t)$  to zero and causes a faster growing of  $\lambda(t)$  itself after each additional PM action. The failure rate after the  $i$ th PM action becomes  $a_i \lambda(t)$ , given that  $\lambda(t)$  is the hazard rate in the previous period,  $a_i \geq 1$ .

On the other side, the Age Reduction PM model evaluates the effective age of a system after the  $i$ th PM action as a fraction of its effective age just prior to this PM. The effective age after the  $i$ th PM action is  $b_i E_i$ ;  $0 \leq b_i < 1$  is the improvement factor in the effective age due to the  $i$ th PM action, while  $E_i$  is the effective age of the system just prior to the  $i$ th PM action [52].

The hybrid model merges these two aspects, as better explained by Figure 7.

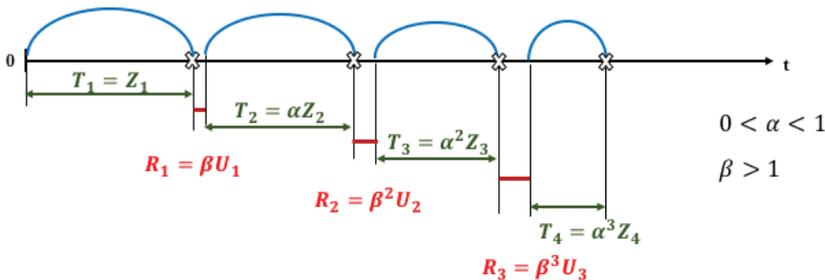


Figure 6.  $(\alpha, \beta)$  rule or quasi-renewal process method.

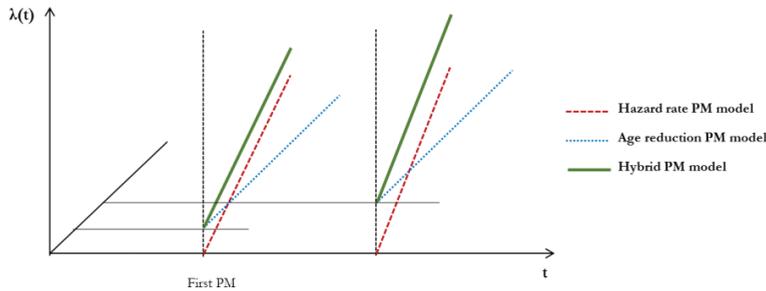


Figure 7. Comparison between the Hazard Rate PM model, the Age Reduction PM model [52] and the Hybrid PM model [51].

### 3. Imperfect maintenance in real cases

The theoretical definition of imperfect maintenance needs to be identified in real applications in an industrial setting. Literature analysis was the starting point, but the experience shared by reliability technicians was essential in order to identify some typical actual situations in which imperfect maintenance is indeed verified. Three main specific situations are proposed and summarized in Figure 8.

- “Conscious” imperfect maintenance: This is a case of an aware imperfect maintenance action. The reasons are various, and among them, it is possible to consider the use of unsuitable spare parts. When a fault occurs, for example, the required new component could not be available because of cost or time reasons. In this case, in order to reactivate the normal operation situation, it could be required to adopt alternative solutions like reconditioned part or “non-original” ones. Inventory management of spare parts, in fact, plays a key role in the maintenance management: their specific demand is usually unknown and random, even if it should be filled almost instantly or as soon as possible [53]. At the same time, for specific expensive components with a high risk of obsolescence, storage is not the best solution. Considering the issues related to the inventory management of spare parts, product recovery could be considered as a better option if compared to the acquisition of a new one. Since several remanufacturing options are possible, then several spare parts qualities could

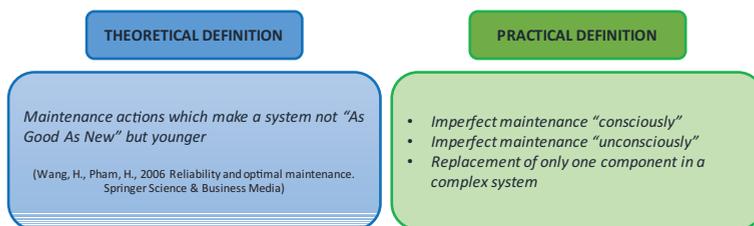
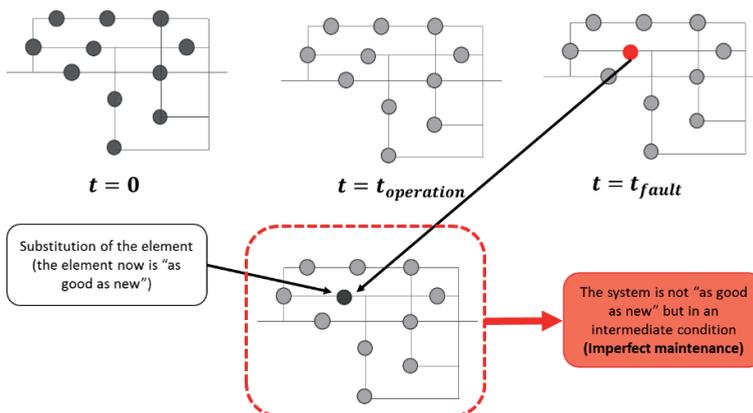


Figure 8. Imperfect maintenance theoretical vs. practical definition.

derive [54]. This quality level has a huge impact on the reliability of the system subject to maintenance, since the reconditioned part is not in the AGAN condition. The spare parts management just shown is very common in real contexts, and in literature, there are many papers on the topic. Just as examples, we can cite two contributions: Boudhar et al. [55] considered the problem of choosing the spare parts' quality to be used at each replacement minimizing the total cost; Boudhar et al. [54], an extension of the previous paper, proposed an optimal maintenance policy considering both the reliability and maintenance aspects and the quality of spare parts used for maintenance. Hence, it is possible to say that reliability and maintenance are strictly connected to reverse logistic and remanufacturing [54]. Another example of Imperfect maintenance done consciously, always related to spare parts, regards the use of "non-original" parts such as adapted part of the similar system (different brand, different technical features and so on). Both this last example and the others presented in this section could be related to maintenance expenditure problems like suggested by Helvic [56].

- "Unconscious" imperfect maintenance: This example is strictly connected to the maintenance operator skills. Contrary to the previous case, this one refers to an unknown "imperfect" action caused by incompetence, lack of attention and errors. According to some researches, in fact, some causes for imperfect, worse and worst maintenance could be ascribed to the skills of the maintenance technicians [29, 56], such as repairing the wrong part, only partially repairing the faulty part, repairing (partially or completely) the faulty part but damaging adjacent parts, incorrectly assessing the condition of the unit inspected and deferring maintenance actions.
- Replacement of only one component in a complex system: This situation is very common in real context; it refers to the case in which, after a practicality period, where all the components have a specific degradation state, if a component breaks, it is usually the only one replaced with a new one. The global system reliability must be defined with imperfect maintenance models since the whole system is not in an As Good As New condition. This is explained in **Figure 9**.



**Figure 9.** Representation of one of the real imperfect maintenance case (replacement of only one component in a complex system).

#### 4. Analysis of real imperfect maintenance cases through the most appropriate optimization model

The imperfect maintenance models proposed in the literature and shown in Section 2.2 are useful if used to describe the reliability features of real systems subject to imperfect maintenance actions. There are many models and many kinds of imperfect maintenance, so a question could be: “Which model should I apply for a correct evaluation of the reliability of a system subjected to imperfect maintenance?”

This section proposes the most suitable models for the three real cases of imperfect maintenance. These are summarized in **Table 1**.

We can see how the  $(p, q)$  rule method is suitable to model all the cases in which there is uncertainty on the maintenance action effectiveness. For this reason, it could be used in all the real situations of IM. This is also true for the Shock Model method.

The improvement factor method seems to be highly suitable for the “Conscious” IM, since this method considers some parameters that could be linked to a conscious decision of IM (the cost of maintenance activities, from which the improvement factor could be derived, is linked, for example, to the use of unsuitable spare parts).

The virtual age method fits better to the “Conscious” IM. This method, in fact, can model how much of the damage related to the time between the  $(n-1)$ th and the  $n$ th failures, the maintenance

Real cases of IM	IM model
“Conscious” imperfect maintenance	<ul style="list-style-type: none"> <li>• <math>(p, q)</math> rule method</li> <li>• Improvement factor method</li> <li>• Virtual age method</li> <li>• Shock model method</li> <li>• <math>(\alpha, \beta)</math> rule method</li> <li>• Hybrid model method</li> </ul>
“Unconscious” imperfect maintenance	<ul style="list-style-type: none"> <li>• <math>(p, q)</math> rule method</li> <li>• Improvement factor method</li> <li>• Virtual age method</li> <li>• Shock model method</li> <li>• <math>(\alpha, \beta)</math> rule method</li> <li>• Hybrid model method</li> </ul>
Replacement of only one component in a complex system	<ul style="list-style-type: none"> <li>• <math>(p, q)</math>rule method</li> <li>• Shock model method</li> </ul>

**Table 1.** Proposal of the most suitable methods to treat each real case of IM.

action is able to remove: using not a new spare part (but, for example, an already used component, with its own wear level) only a part of the damage of the system will be removed.

The  $(\alpha, \beta)$  rule method is highly appropriate both for the “Unconscious” and the “Conscious” IM: the reduction of lifetime of a system and the growth of time to repair with the number of repairs might refer both to human error in maintenance activities and to cumulative damages because of non-suitable spare parts. The same reasoning applies to the hybrid model method.

## 5. Conclusions

In the last years, a new maintenance classification was introduced: it suggests various maintenance types that are: perfect, minimal, imperfect, worse and worst [34]. Imperfect maintenance (IM), in particular, is defined as maintenance action that makes a system not “as good as new” but younger: upon an imperfect maintenance action, the system lies in a state somewhere between AGAN and its pre-maintenance condition.

In addition to the theoretical definition, some real cases for IM were identified, considering both literature analysis and maintenance technicians’ experience. Each one of them could be studied and optimized through appropriate maintenance models. Among the IM models in the literature, there is a proposal to find the most suitable one for describing each real situation. From this approach, a correct reliability and availability estimation can be developed in real cases.

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