Preventive Maintenance Optimization in Healthcare Domain: Status of Research and Perspective

H. Mahfoud, A. El Barkany, and A. El Biyaali

Faculty of Sciences and Techniques, Mechanical Engineering Laboratory, Sidi Mohammed Ben Abdellah University, 2202 Fes, Morocco

Correspondence should be addressed to H. Mahfoud; hassana.mahfoud@usmba.ac.ma

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Although medical equipment maintenance has been carefully managed for years, very few in-depth studies have been conducted to evaluate the effectiveness and efficiency of these implemented preventive maintenance strategies, especially after the debate about the credibility of manufacturer’s recommendations has increased in the clinical engineering community. Facing the dilemma of merely following manufactures maintenance manual or establishing an evidence-based maintenance, medical equipment maintenance could have exploited an advanced area in operations research which is maintenance optimization research. In this paper, we review and examine carefully the status of application oriented research on preventive maintenance optimization of medical devices. This study addresses preventive healthcare maintenance with a focus on factors influencing the maintenance decision making. The analysis is structured by defining different aspects necessary to construct a maintenance optimization model. We conclusively propose directions to develop suitable tools for better healthcare maintenance management.

1. Introduction

In the present competitive market, where companies worldwide are tightening their economical belts to diminish costs while assuring high services quality and safety, plant dependability key performance indicators have become an area in which to center initiatives [1]. Recently, companies realize that their competitiveness, performance, and thus their future are sturdily linked to the effectiveness and efficiency of maintenance management [2, 3]. Therefore, this recognition brings about a radical change of maintenance perception from a “necessary evil” to an “investment opportunity” to be optimized. Maintenance excellence can be achieved by making the rational maintenance decision balancing costs and industrial performance [4]. It is worth mentioning that the amount, multiplicity, sophistication, and costs of medical equipment are abruptly rising, which make that their maintenance complexity and costs also escalate sharply in the last few years [5]. In addition to maintenance expenditure, medical devices (MD) are frequently involved in patient incidents (death or injury) [6]. Therefore, a legal obligation is imposed upon healthcare organizations and clinical engineering to ensure high-level safety and reliability of their medical devices as well as checking maintenance strategies efficiency. In this paper, we address a better part of existing publications on preventive maintenance optimization, particularly applied and validated models in healthcare domain. This study reviews various important aspects of medical equipment maintenance, analyses different research insufficiencies found in healthcare maintenance optimization modeling literature, and proposes directions to develop suitable tools for better medical devices management.

In the interest of drafting a general bibliography on healthcare maintenance optimization problems, we consulted a range of academic databases, mainly Scopus database. And then, we extracted 35 sources related to medical equipment maintenance, based on several combinations of these keywords: Healthcare maintenance, Medical equipment, maintenance optimization, medical strategy effectiveness, and clinical maintenance efficiency. The extracted collection includes articles published between 2000 and 2015, which spans various aspects: maintenance optimization modeling, empirical studies, and risk-based prioritization of medical equipment; see Figure I and the Appendix. “Journal of clinical
engineering” was singled out, as providing the most coverage on the topic investigated in this study (20% of the journal papers). According to the study, only 11% of researches concern medical equipment maintenance optimization modeling compared with 60% empirical and 29% prioritization publications. We deduce that preventive maintenance optimization modeling in healthcare domain is still in its infancy stage and it is an underexplored area in which to focus initiatives to address optimal maintenance strategies.

2. Maintenance Evolution

Due to the increasing consciousness of the importance of maintenance management, this process has undergone successive changes over recent years, Figure 2. Until 1960s, run to failure maintenance had been the widespread policy; then, preventive maintenance (PM) concepts appeared and became well known. Time-based maintenance is the first aspect of PM, which consists of scheduled activities of maintaining and parts replacement to avoid unpredicted failures [7–10]. In the second half of 1980s, condition monitoring technologies were developed and condition-based maintenance (CBM) came out. This policy triggers maintenance activities no more than when there is evidence of deterioration to reduce unnecessary scheduled actions [11–14]. Recently, maintenance management community introduced “prognostics” concept which deals with fault prediction before it happens [15, 16]. In this context, predictive maintenance (PdM) is a CBM policy that includes prognostics in its decision process. Thus, PdM incorporates more information on assets degradation, in the form of their remaining useful life (RUL) [17, 18].

Despite the exponential rising of information technologies supporting these advanced maintenance policies, there are still some issues unaddressed in the literature. According to [19], many optimization models have been developed to choose the optimal policy; however, they are inappropriate for business context. Many researchers arrived at the same conclusion: It is necessary to handle the gap between academic models and real environment applications [18, 20]. In this context, [21] it is pointed out that the application of maintenance optimization models to medical devices is rather scarce and new. Most of the healthcare organizations merely follow manufacturer’s recommendations and do not profit from maintenance excellence in so far as other industries. The majority of researches in this domain just put forward how to evaluate and improve devices reliability in their design or manufacturing phase without considering reliability assessments and maintenance strategies of these pieces of equipment in their operating context. The paper [22] assigned specific failure codes to measure maintenance effectiveness for numerous kinds of medical devices. They concluded that current maintenance strategies are effective but it is not evident whether they are efficient.

3. Overview of Medical Devices

Maintenance Optimization

Even though many equipment management programs (MEMPs) have been well planned and executed in healthcare organizations for more than 30 years, very few studies investigate the effectiveness of these programs in providing an optimized PM considering reliability, cost, and safety for service delivery.

Several risk-based MEMPs have been already proposed in the literature and are currently in use. The paper [23] implemented a risk-based prioritization tool for preventive maintenance inspections. The PM intervals are assigned according to a risk level of critical devices. The paper [24] drew attention to the necessity of providing a logical basis for determining reasonable and appropriate PM interval tests, taking into account partial failures. Ridgway proposed a risk-based approach to prioritize devices that meet maintenance sensitivity criteria. The paper [25] highlights that one of the most criticized problems of clinical maintenance management is the obsolescence of medical devices. They stressed the inadequacy of life cycle costs mathematical models for critical devices replacement and proposed a fuzzy inference model to include both quantitative and qualitative parameters affecting replacement decisions. The paper [26] developed for the same goal a multicriteria decision model using Macbeth sociotechnical approach based on decision maker’s preferences. The proposed model provides not only raking risk levels but also cost benefits analysis. Nevertheless, the decision conference duration and difficulties to concentrate in the criteria assessments are the main weaknesses. The paper [27] presents a multicriteria prioritization technique derived from an analytical hierarchy process using crisp scales that do not handle uncertainty. The paper [28, 29] proposes a fuzzy risk-based framework to prioritize MD and decide the optimal maintenance strategy. The paper [28] tried to overcome the previous works shortcoming that neglected other criteria like economic loss and the uncertainties in expert’s judgment issues.

Nevertheless, the single risks assessment used to guide safety and PM activities is a common theme in these methods that are inconsistent aggregation processes and so unable to provide appropriately optimized solutions for stochastic maintenance problems [30].
A staid debate has been raised recently among clinical engineers (CE) professionals and researchers about the credibility of manufacturer-recommended PM intervals and whether it is founded on meaningful test data. Ridgway [31] debates the question and stresses the importance of streamlining the current maintenance policies by analyzing the operational reliability of MD. The paper [32] evaluated and analyzed maintenance strategies effect on the survival probability of some MD using exponential distribution approach. The foremost finding of this study is that the equipment flowing strictly the manufacturer’s recommended interval for PM is less reliable than the one of the same model with less preventive interventions. That authenticates [31] debate.

This paper focuses on aspects related to preventive maintenance optimization of medical devices. The analysis is structured by defining different classes necessary to construct a maintenance optimization model using the framework in Figure 3.

3.1. Maintenance Concepts. Reliability centered maintenance (RCM) [33, 34] and total productive maintenance (TPM) [35, 36] are the eminent maintenance concepts in the literature. They set out the general decision support structure in which maintenance actions and policies are planned. The review has shown that a little has been done to prove the performance of those empirical approaches in the healthcare domain. The paper [37] indicated that keeping track of reasons which trigger repair calls in hospitals would be useful to provide remedial measures. Based on statistics of 9 major causes’ categories, the author found that user-related causes represent 10% of the total and he drew attention to the necessity of adopting RCM methodology in hospitals. Furthermore, [38] studied the relationship between availability of high risk MD and patient outcomes and suggested new maintenance approaches for critical equipment such as TPM to improve the MMS (medical management system). The paper [39] implemented Six Sigma methodology on corrective maintenance process in Jordanian hospitals. It was mentioned in the model that check time, decision time, and delivery time are the key factor influencing the downtime, not maintenance time. The author proposed new CM procedure to organize the maintenance staff. Even if these approaches are heuristic and time consuming and founded on expert’s judgments and experience, they represent a significant step in “getting the most out” of assets such as aeronautics and military applications [40]. The paper [41] asserts that empirical studies may help medical maintenance services elaborate evidence-based strategies for the betterment of their performance levels.

3.2. Maintenance Policies and Actions. Maintenance policies can be usually classified into three categories: preventive, corrective, and condition-based maintenance. As indicated in [42] PM including block and time-based maintenance is the most investigated policy in the literature compared to CBM. PM is also the widely established policy for medical devices. The paper [24] distinguishes between three different kinds of MD preventive maintenance: scheduled maintenance (SM), performance verification (PV), and testing safety (TS). Likewise, [22] recapped several types of MD maintenance activities consisting of repair, replacement, or inspections. The paper [5] dispelled a misunderstanding related to MD maintenance which is “the more maintenance the better” and introduced the analogous concept “evidence-based maintenance.” A high completion rate of scheduled maintenance is not a good indicator of maintenance effectiveness (reliability-availability-safety) and efficiency (overall costs), to the extent that evidence-based maintenance would be a continual improvement process that analyzes the effectiveness and efficiency of maintenance policy deployed in comparison to outcomes attained.

Although maintenance modeling trend is shifting to CBM and predictive maintenance strategies, this remains an unexplored area in the healthcare domain. In fact, [43] makes evident the efficiency of condition-based maintenance in medical devices through a case study which demonstrates a large cost-benefit of CBM compared with previous policy consisting of reactive and time-based PM.
3.3. Optimization Objectives. Maintenance optimization is achieved by maximizing or minimizing one or multiple criteria, called objective function. The paper [44] indicates that these objectives can be classified under four captions. The first significant one is ensuring system function, synonym to dependability (reliability, availability, and maintainability) and capability and the second one is ensuring system life and minimizing costs to meet the norms of asset management. Further, guarantying safety is vital, especially in the case of dramatic consequences. Finally, performing maintenance personal management and human well-being is rarely investigated.

Many maintenance objectives have been cited in the literature; however, very few of them have been taken into account in optimization models [42]. The majority of researches in this area seek to optimize one criterion (single-objective optimization), which is typically maintenance costs [45]. In a large amount of these studies, maintainability is not considered because of the common assumption of neglected repair times. Maintenance action duration exclusion sometimes leads to suboptimal solutions. Then again, a limited number of publications that appeared in the literature deal with multiobjective optimization problems adding reliability or availability criterion [8, 11, 46].

In the healthcare domain, optimization models limited scope by considering a single objective (mainly the overall cost) is another limitation perceived in this review [47–49], which is often not the case of real industrial environment. The paper [5] confirms that, in addition to reliability, safety, and maintenance efficiency measure, availability is an important indicator of maintenance effectiveness. This statement is argued in [38, 50] study. Accordingly, multobjective optimization models remain an underexplored subject for medical equipment. And less attention was paid to determine the key objective criteria to avoid incorrect maintenance model leading to suboptimal solutions.

3.4. Maintenance Effectiveness. It is the degree to which a component’s operation condition is restored after a maintenance action is performed. The paper [51] presents a review of different possible reinstatement degree: perfect repair or as good as new (AGAN) maintenance where the failure rate becomes the same as a new component. Minimal repair or as bad as old (ABAO) for that the degradation level is restored to the situation before the maintenance action is executed. These assumptions are the main shortcoming of a wide range of maintenance optimization models in the literature [42, 51, 52]. We find also worse repair which is the maintenance action that causes failure rate decreasing while the worst repair leads to the breakdown of the maintained system. Imperfect maintenance is considered the appropriate maintenance effectiveness representation in real industrial context [7, 45, 53], where system’s operating condition is returned to somewhere between AGAN and ABAO. Brown-and Porchan model, \((p, q)\) rule, improvement factor, and virtual age are some methods among the multitude ones developed to model this kind of maintenance [51].

For medical devices, few works were developed to assess maintenance effectiveness. In [48] mathematical optimization model of periodic inspections was founded on the same simple assumption of perfect maintenance (AGAN). Later, [32] presented an age-dependent model to evaluate and analyze maintenance strategies (PM, CM) effect on the survival probability of some MD using exponential distribution approach. The purpose of this study is to counter the credibility of manufacturer’s recommended interval. Minimal and perfect repair assumptions are the main shortcoming of a wide range of maintenance optimization models in the literature and imperfect maintenance is less addressed to assess MEMP s effectiveness.

3.5. Modeling Deterioration. It is the central part of maintenance optimization models. Maintenance excellence is measured by its ability to address the most significant failure mechanisms [44]. Deterioration modeling should match up as close as possible the system’s real time to failure. Therefore, many tools were developed in the literature to model deteriorations behaviors that are classified into three categories: black, white, and grey box [42].

Statistical distributions are the easiest and widespread used models among black box category [69] (e.g., normal, exponential, and Weibull) which do not provide any physic
interpretation of the studied system. Additionally, they
depend strongly on failure data availability which is usually
not the case of high reliable systems [67, 70]. Then, white
box method is an attractive tool to model component fail-
ure behavior with focus on physical properties details of
maintained systems (e.g., corrosion, crack) [14]. Nevertheless,
the failure mechanism is lacking for several cases and the
reliability analytical expression derived usually increases the
complexity of the model. Thus, researchers use intermediate
stochastic methods (grey box). Referring to [70, 71] works,
Markov process is a common approach employed to model
either discrete or continuous time stochastic degradations.
However, with more complex systems, this model has a
disadvantage of state explosion which makes the optimization
too complex to solve.

In the same way, numerous other models have been pro-
posed in the literature to overcome modeling deterioration
problems. The paper [72] evaluated a multicomponent system
performance drawing on Petri net network. The paper [73]
assessed a system’s dependability in a dynamic hybrid context
employing hybrid stochastic automaton (ASH). The paper
[74] exploited the Bayesian dynamic network (RBD) to model
rail deteriorations reliability. The emergence of condition-
based maintenance instigates the deployment of other tools
such as proportional hazard model (PHM) to investigate the
influence of covariates on system’s degradation [13]. Main-
tenance strategies shift to predictive making decision using
prognostic information has brought about new publications.
The paper [16, 17] used gamma process and [75] evaluated
modeling approaches for remaining useful life (URL) of
deteriorated system.

Even though failure mechanism modeling has been
widely used and applied in many industries, its application to
the healthcare devices operating context is fairly new. Most
of the researches in this area are limited to the reliability
assessment of MD early design stages. The paper [54, 68] enu-
erates some well-known reliability models in the concept,
design, prototype, and manufacturing phase of MD to attain
a high level of safety satisfaction. Yet, [6, 66] reported that
several facts and figures in relation to patient outcomes are
directly or indirectly associated with medical devices reliabil-
ity and operators errors. The paper [6] provides useful guide-
lines to improve MD reliability. Thus, Dhillon [6] insisted
on using classical methods like general approach, parts
counts method, Markov chain, failure mode and effect anal-
ysis (FMEA), and fault tree analysis (FTA). Dhillon as well
addresses the problem of human error and resumed that reli-
ability engineering has successfully improved systems in the
aerospace area and its application to the healthcare domain
would generate similar dividends [55].

Work in [56] was the first step to assess the applicability
and usefulness of some commonly used age-dependent and
repair effect models to repairable MD systems. He concluded
that the power-law process is the most convenient for
the survival models and the best fitted for repairable devices.
Likewise, [32] evaluated and analyzed maintenance strategies
effect on the survival probability of some MD using
exponential distribution approach. Later, [67] proposes a
statistical analysis of MD soft and hard failure data flowing
Nonhomogenous Poisson process (NHPP) with a power-law
intensity function.

The results of the above studies contradict the common
belief that medical device’s failures follow an exponential
distribution and that their times between failures (TBF) are
independent. Black box models including survival distribu-
tions are the most applied methods to evaluate degradation
mechanism for medical equipment. Then, other stochastic
methods are supposed to be investigated in this domain.

3.6. System Information and Data Sources. Normally, all sys-
tem information including technical description, its function,
and importance is the first aspect covered by maintenance
optimization models. The paper [44] stresses that analyzing
failure data with system’s incomplete information makes
possible wrong model and decision. The paper [76] sum-
marizes multicomponent maintenance models based on eco-
nomic, structural, and stochastic dependencies. These models
are also available for different configurations given series,
parallel, K-out-of-N, and standby [77]. The paper [65] applied
a simple method of decomposition to evaluate medical
devices reliability on series-parallel-systems. The paper [67]
states that complex repairable MD can be classified into
two categories: hard and soft failure components, those are
stochastically and economically independent.

There is always an obvious requirement of a reliable and
available data to shift from theoretical to applied research
[44]. In general, maintenance optimization application calls
for three kinds of data: failure, operating, and cost data.
Maintenance information system unavailability is often seen
the biggest obstacle to overcome the lack of failure data.
Moreover, cost data is quite difficult to count, especially indi-
rect maintenance costs. Therefore, many publications have
appeared to tackle data uncertainty [78, 79]. The paper [67]
proposes a statistical analysis of MD soft and hard failure data
presenting a lot of censoring events. In medical environment,
equipment tends to be highly reliable which makes scarce and
censored failure data the key problem of this domain.

3.7. Optimization Techniques. Once objectives are well iden-
tified and all necessary information is collected, useful
maintenance optimization algorithms vary according to their
ability to find an optimal solution in a minimum time and
money. Analytical and numerical methods are the prevalent
used methods in the literature [80]. However, they are only
applied to simple systems with reduced constraints number.
In the case of more complex models, these exact methods are
time consuming or sometimes impossible to implement [42].
Indeed, maintenance optimization in real industrial context
is usually subjected to several constraints and very complex
to resolve. Therefore, many simulation methods were used
to overcome this problem. For example, [72] evaluated a
multicomponent system performance drawing on Petri net
network combined with Monte Carlo simulation. The paper
[81] gives an overview of simulation-based optimization and
remarks that discrete event simulation (DES) dominates the
literature. Although this method gives a solution in a reason-
able time, there is no guarantee if this solution is accurate and
reliable [42]. Recently, researches are oriented toward a new
trend of maintenance optimization techniques, called meta-
heuristics [81]. These evolutionary methods are based on
mechanism observed in nature and give an intelligent explo-
ration and exploitation of the optimization problem search
space [46, 53, 82]. It is worth mentioning that population-
based heuristics, especially genetic algorithm (GA), are the
well-known class of metaheuristics applied in maintenance
optimization problems [42, 81].

As mentioned before, maintenance optimization models
for medical equipment are still an underexplored area. Based
on a mapping review, [41] states that applying mathematical
models to optimize maintenance strategies in the healthcare
domain is scarce and still in its infancy stage. Besides,
the few models proposed in the literature are founded on
critical assumptions such as constant failure rate regardless of
equipment age, neglected maintenance time, complete mainte-
nance history, and information.

Further, the few publications that appeared in the litera-
ture are founded on several simpler assumptions and employ
classical optimization methods. The paper [48] proposed sev-
eral mathematical models to find the optimal periodic inspec-
tion interval for MD repairable systems based on minimal
maintenance hypothesis. The author used a recursive algo-
rithm to find the solution, which makes the model computa-
tionally hard and time consuming. The paper [32] suggested
a mixed-integer linear programming to solve an MD mainte-
nance scheduling problem using greedy algorithms.

Premature convergence to local optima is seen the biggest
delimitation of the local search algorithms employed in
optimization models already presented. These mathemat-
cal models are also limited to the assessment of failure
rate excluding maintenance effectiveness. Then, taking into
account the other assumptions makes the optimization model
more complex to solve by a classical exact approach.

3.8. Outputs. Maintenance optimization models yield an
assortment of aspects, described in [44, 80]. The first usual
output of these models is a determination of timing decisions
(when and how often to inspect, replace, or maintain) [9, 12,
14, 83]. Secondly, they can serve as a tool to evaluate and
compare different maintenance strategies [11, 72, 84]. Opti-
mization models can also provide an optimum maintenance
scheduling and planning and help to specify maintenance
resources requirements (crew size and composition, spare
parts, and outsourcing) [11, 46, 53]. Maintenance optimi-
ization models for medical equipment results are princi-
pally the determination of an optimal maintenance inspec-
tion/replacement interval [47, 48, 56]. The paper [47] evalu-
ates and compares PM to CM strategy and [43] studies the
implementation of CBM in healthcare domain compared
with the existing (PM and CM) policy. Even so, the assump-
tion of promptly available maintenance resources is regular
in the literature and the authors in this research area do not
consider logistics in maintenance optimization models.

4. Discussion and Conclusions

This work has set sights on assessing the status of research
tackling preventive maintenance optimization problems of
medical devices. Since not much has been presented in this
field, the study was broadened to take account of other
research papers which have demonstrated to a large extent
the success of advanced maintenance optimization models on
other industries. We deeply analyzed ten aspects determining
a model of maintenance optimization problem: maintenance
policies and actions, maintenance objectives, maintenance
effectiveness, modeling deterioration, system information
and configuration, data sources, and optimization tech-
niques. The foremost finding of this study is the necessity
of further research in maintenance optimization modeling
in the healthcare domain, as highlighted by literature gaps
detailed above. Our proposal for future effort in this research
field is along these lines:

(i) Instead of merely following standards, regulations,
and manufacturer's recommendations, healthcare
professionals should deploy evidence-based mainte-
nance to learn from comparative maintenance effi-
ciency studies and make required adjustments to
maintenance policies and actions, especially, when
many manuscripts have showed how maintenance
strategies for medical equipment are extensive and
counterproductive.

(ii) Reliability centered maintenance and total productive
maintenance concepts represent a significant step in
“getting the most out” of medical equipment com-
pared with other industries applications and may
help medical maintenance service elaborate evidence-
based strategies for the betterment of their perfor-
ance levels.

(iii) Risk-based prioritization methods are widely used
only to identify the critical medical devices subject to
stringent maintenance program and not for true PM
optimization issues. Evidence in the literature points
that mathematical modeling is much more flexible
than empirical approaches, and medical maintenance
would benefit from optimization modeling.

(iv) Hardly any study in medical equipment maintenance
has addressed condition based maintenance policy
compared with preventive and corrective ones. Fur-
ther research in this field should measure outcomes
of predictive maintenance including prognostics.

(v) Regarding previous few works in medical devices
optimization modeling, multiobjective optimization
models remain an underexplored area. And less atten-
tion was paid to determine the key objective criteria
to avoid inappropriate maintenance model leading to
suboptimal solutions.

(vi) Minimal and perfect repair assumptions are the main
shortcoming of a wide range of maintenance optimi-
zation models in the literature. Imperfect mainte-
nance is less addressed to assess MEMP effectiveness.

(vii) Black box models including survival distributions are
the most applied methods to evaluate degradation
mechanism for medical equipment. Other stochastic
methods are supposed to be investigated in this
domain.
### Table 1

| Ref | Theme | Description |
|-----|-------|-------------|
| [54] | Empirical | Reliability in the medical device industry |
| [55] | Empirical | Medical device reliability |
| [23] | Prioritization | Smart-IPM tool for the MD PM |
| [56] | Optimization | Data-based modeling of the failure rate of repairable equipment |
| [24] | Prioritization | A practical, risk-based approach to PM program management |
| [57] | Prioritization | JCAHO's equipment inclusion criteria revisited |
| [58] | Prioritization | Analyzing (PM) inspection data by FTA analysis methodology |
| [59] | Empirical | The theory and practice of preventive maintenance |
| [60] | Empirical | Interview with Larry Fennigkoh |
| [61] | Prioritization | MD risk-based evaluation and maintenance using FTA |
| [25] | Prioritization | A fuzzy approach for medical equipment replacement planning |
| [62] | Empirical | A practicum for biomedical engineering |
| [63] | Empirical | Decoding the PM puzzle |
| [64] | Empirical | Medical equipment management manual |
| [31] | Empirical | Manufacturer-recommended PM intervals |
| [37] | Empirical | Reducing equipment downtime a new line of attack |
| [26] | Prioritization | Multicriteria model to support the MD replacement |
| [22] | Empirical | Measuring maintenance effectiveness with failure codes |
| [65] | Empirical | Measuring the efficiency of medical equipment |
| [49] | Prioritization | Comparing maintenance strategies using failure codes |
| [6] | Empirical | Medical equipment reliability: a review |
| [66] | Empirical | Enhancing patient safety using failure code analysis |
| [67] | Empirical | Reliability analysis of maintenance data for complex MD |
| [48] | Optimization | Reliability and maintenance of medical devices |
| [47] | Optimization | Evidence-based mathematical maintenance model for MD |
| [39] | Empirical | Implementation of Six Sigma on corrective maintenance |
| [68] | Empirical | Reliable design of medical devices |
| [41] | Empirical | Medical device maintenance outsourcing: A mapping review |
| [5] | Empirical | Medical equipment maintenance: management and oversight |
| [32] | Empirical | The effect of maintenance on the survival of medical equipment |
| [38] | Empirical | A study of current maintenance strategies and the reliability |
| [43] | Optimization | Case study of cost benefits of condition based maintenance |
| [29] | Prioritization | A fuzzy logic model for medical equipment risk classification |
| [21] | Empirical | Medical devices inspection and maintenance, a review |
| [28] | Prioritization | A fuzzy risk-based maintenance framework for MD prioritization |

(viii) Different kind of configurations and system’s components dependencies are ought to be considered to make optimization models much more realistic.

(ix) Maintenance resources requirements (crew size and composition, spare parts, outsourcing, and logistics issues) should be further included in optimization models for medical equipment to create more pragmatic decision-making structure.

(x) Metaheuristic algorithms found their success in many other industries. They can be useful for medical equipment maintenance optimization to overcome the weaknesses of classical methods already employed.

### Appendix

See Table 1.

### Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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