# Using the Monte Carlo Stochastic Method to Determine the Optimal Maintenance Frequency of Medical Devices in Real Contexts

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**Abstract**

The purpose of this study was to implement and validate a Monte Carlo Algorithm (MCA) to determine the best T value (the time between two preventative maintenances) that optimizes the achieved availability of equipment types. In doing so, we (1) collected 796 maintenance works orders from 16 medical devices installed in a 900-bed hospital; (2) we fitted the probability distributions for each of the inputs of the achieved availability mathematical model (the mean preventative and corrective service time (in hours)); (3) we generated a set of random inputs following a Weibull distribution of the achieved availability mathematical model; (4) we calculated the achieved availability for every random input generated; this process was repeated for "m" iterations (an accuracy of 1%, 95% CI, alpha = 0.05); (5) the trends of the mean achieved availability for the different maintenance T intervals versus mean time to failure (MTTF) for all the equipment types were plotted; finally, (6) the best T value with the maximum value of the achieved availability of a medical device type for a specific MTTF was the optimal target. The mean simulation time for all the cases was 12 min. The MCA was able to determine the best T value, optimizing the achieved availability in 81.25% of cases. In conclusion, the results showed that, on average, the T maintenance intervals determined by the MCA were statistically significantly different from the original T values suggested either by the clinical engineering department or third-party maintenance providers ($MCA_{Tmean} = 1.68$ times/yr, $Actual_{Tmean} = 2.56$ times/yr, $p = 0.008$).

**Keywords**

Monte carlo simulation • Maintenance optimization
Preventative maintenance frequency • Biomedical engineering • Clinical engineering

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## 1 Introduction

The aim of this study was to implement and validate a Monte Carlo algorithm (MCA) as a method of determining the optimal maintenance intervals, i.e. T (or maintenance frequency, $F_{pm} = 1/T$), of medical devices. The motivation for conducting this research to provide additional evidence for the clinical engineering community when determining whether the maintenance frequency should be established *"periodically in accordance with the manufacturers' recommendations"* [1], or whether they can use their own maintenance records. In doing so, the authors believe they are contributing to filling the gap in the existing knowledge for implementing maintenance optimization models, specifically the optimal maintenance intervals of medical devices [2], thus adding another point of view to the current debate (named following the *manufacturers' recommendations* or not) about how to establish the maintenance frequencies of medical devices.

### 1.1 Maintenance Policies and Analysis

A maintenance policy is the implementation of a certain maintenance model to improve the reliability of a system [1]. According to the authors' experience, the most commonly



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used maintenance policy for the maintenance of medical devices is the periodic preventative maintenance (PM) policy [3]. In this policy, the parts of a medical device are preventively maintained at fixed time intervals k*T (k = 1, 2,…*n*, and T is constant) independently of the failure history of the medical device (frequency of failures, λ), and repaired at intervening failures. The cornerstone of this policy is determining the T value (or the maintenance frequency, $f_{pm}$ = 1/T). Ideally, if the T value is adequate (i.e. $f_{pm} \approx \lambda$) the device will never fail because the PM is always performed first, after which the availability of the device is maximized. Therefore, the next problem to be solved is: what is the best T value that "optimizes" the availability of a certain device, knowing that maintenance tasks have a cost? The mathematical model of the achieved availability to be optimized is shown in Eq. 1 [2]

$$A_a = \frac{1}{1 + \lambda * (\mathrm{MCMT} + \mathrm{MCVT}) + f_{pm} * (MPMT + MPVT)} \quad (1)$$

where:

| | |
|---|---|
| $A_a$: | Achieved availability |
| λ: | Failure rate (MTBF = 1/λ) |
| MCMT: | Mean time to perform a corrective maintenance (in hours) |
| MCVT: | Mean time to perform a verification or quality inspection of corrective maintenance (in hours) |
| $f_{pm}$: | PM frequency (times/year, 1/T) |
| MPMT: | Mean time to perform a PM (in hours) |
| MPVT: | Mean time to perform a verification or quality inspection of PM (in hours) |

To solve this problem, the authors implemented and validated an algorithm using a Monte Carlo simulation [4]. To implement and run the Monte Carlo algorithm it is necessary to generate random variables that follow a statistical distribution. In this research, the Weibull distribution (see Fig. 1) was used to generate the random numbers of MCMT, MPMT, and λ

## 2 Materials and Methods

### 2.1 Materials

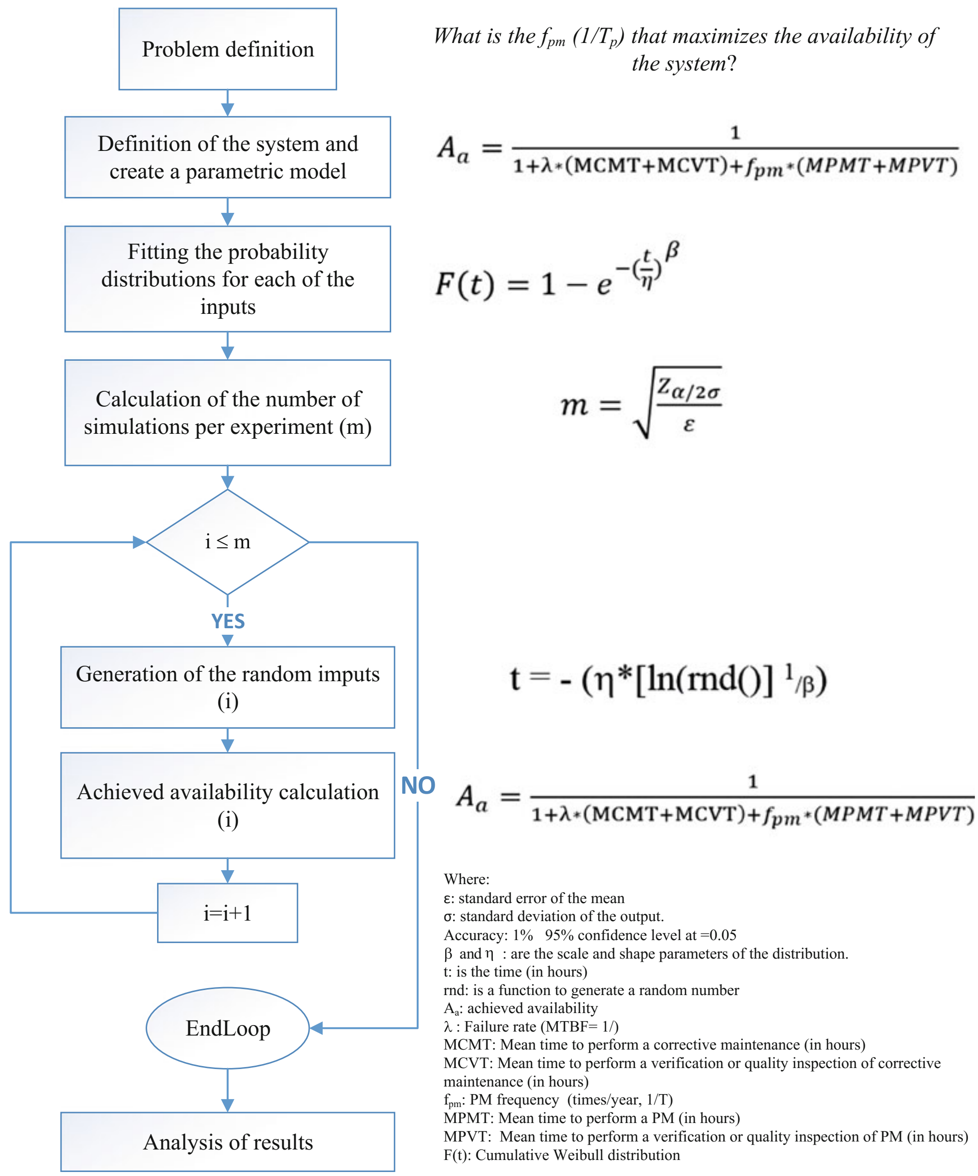
The MCA was implemented using the Scilab v.5.5.2 software package licensed by GPL [1]. The SPSS® V 22.0 statistics package was used to generate descriptive, univariate, and bivariate statistics. The programming and validation of the simulation were conducted on an Inter Core i7 personal computer, 3,40 Ghz, 6 Gb RAM, with the Windows 7, 64 bits operative system.

### 2.2 Methods

In this study, we followed the methodology proposed by [2]. The data were extracted from a primary source of maintenance records from the clinical engineering department. The maintenance records corresponded to the medical devices located in the Intensive Care Units (ICUs) and imaging services. Two research assistants extracted from a secondary information source the preventative and corrective maintenance data records from 2009–2017 including the mean time to failure (MTTF) (or frequency of failures λ, times/yr), the actual maintenance frequencies ($f_{pm}$, times/yr) established by either an in-house or external service provider, and the corrective and preventative service time (in hours). In addition, whether or not the maintenance task was conducted by an in-house or an external service provider was determined. With the extracted maintenance data, the Weibull probability distributions for the MCMT, MPMT, and λ variables were fitted. We selected the Weibull probability distribution because it has the great advantage in reliability work that by adjusting the distribution parameters it can be made to fit many life distributions [5, p. 78]. Next, the MCA was implemented using Scilab (see the MCA implementation for more detail). Then, the MCA was validated. To validate the implemented MCA, the authors first ran one experiment per device type (i.e. electrocardiographs, infusion pumps, ECG monitors, etc.); next they verified that for each availability curve obtained from the different scenarios of $f_{pm}$, a typical parabolic curve was obtained (side-opening parabola, see Eq. 1); finally they verified that for a specific λ value, if $f_{pm} \approx \lambda$ (i.e. ±5%) the achieved availability curve at this point was maximum (i.e. the $f_{pm}$ was optimum or "tuned" with failures). Descriptive statistics to summarize the demographic data of the medical device population and a test for differences between the groups were conducted. The Mann–Whitney U test for differences between the groups was conducted with the aim of determining whether the preventative maintenance frequency of the medical devices as determined by the implementation of the MCA was statistically significantly different from the actual preventative maintenance frequency established by either an in-house or external service provider. The alpha level of significance was set at $p \leq 0.05$.

**Monte Carlo algorithm implementation**. Monte Carlo simulation is a method for iteratively evaluating a deterministic model using sets of random numbers as inputs. It is a simple mathematical procedure, with random inputs and random outputs [5, p. 108]. To run a Monte Carlo simulation the generation of random variables that follow an arbitrary statistical distribution is needed. The inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population. Therefore a

**Fig. 1** Diagram flow of the implemented MCA




distribution for each input that best represents the current state of knowledge is chosen. Figure 1 shows the diagram flow of the MCA implemented in this study.

## 3 Results

Table 1 shows the results obtained from the simulations and the maintenance data per equipment type, including the mean MPMT (SD), MCMT (SD) (in hours), the equipment type brand name, the actual failure frequency (λ, in times/yr), the maintenance frequency ($f_{pm}$, times/yr) at which the optimum achieved availability ($A_v$) was found using the implemented MCA, and the actual maintenance frequency ($f_{pma}$, times/yr) established by either an in-house or external service provider. Table 1 also shows, highlighted in italic, the types of medical device where the optimum achieved availability was determined by the implemented MCA. The mean simulation time for all the cases was 12 min.

The results obtained from the data analyses showed that the actual average failure frequency (λ, times/yr) for every type of device (5.56 times/yr SD 3.99) was higher than either

**Table 1** Achieved availability versus mean time to failure (in months) for each medical device type

| Equipment type | Brand name | MPMT | | MCMT | | Actual λ (t/yr) | | Monte Carlo $f_{pm}$ (t/yr) | | Actual $f_{pma}$ (t/yr) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | MTTF | $f_{pm}$ | $A_v$ | $f_{pm}$ | $A_v$ |
| Angiography U | Siemens | 7.33 | 2.03 | 5.32 | 3.51 | 15.63 | 0.77 | *4* | *0.940* | 4 | 0.935 |
| Angiography U | Toshiba | 7.34 | 2.51 | 4.68 | 2.88 | 7.83 | 1.53 | *2* | *0.974* | 3 | 0.973 |
| Mobile C-arm | Siemens | 2.75 | 0.96 | 2.69 | 1.53 | 4.38 | 2.74 | *2* | *0.989* | 2 | 0.980 |
| Fluoroscopic U | Siemens | 4.86 | 2.60 | 4.01 | 2.83 | 2.88 | 4.17 | *1* | *0.985* | 4 | 0.983 |
| Gamma Camera | Siemens | 7.93 | 2.82 | 4.23 | 3.11 | 5.5 | 2.18 | *2* | *0.969* | 4 | 0.967 |
| Mammography | Siemens | 4.00 | 1.81 | 2.16 | 1.53 | 1.83 | 6.56 | *1* | *0.965* | 2 | 0.955 |
| ECG monitor | Nihon K | 0.52 | 0.06 | 0.21 | 0.06 | 6 | 2.00 | 2 | 0.998 | 2 | 0.998 |
| TAC | Toshiba | 6.72 | 1.79 | 3.95 | 3.02 | 10.13 | 1.18 | *2* | *0.976* | 3 | 0.977 |
| Mobile X Ray | Siemens | 2.23 | 0.62 | 2.84 | 2.09 | 6.38 | 1.88 | *3* | *0.987* | 2 | 0.986 |
| Mobile X Ray | Toshiba | 2.5 | 0.68 | 3.03 | 1.88 | 2 | 6.00 | 1 | 0.995 | 2 | 0.996 |
| MRI | Siemens | 7.15 | 1.65 | 4.32 | 3.3 | 10.75 | 1.12 | *2* | *0.963* | 4 | 0.961 |
| X Ray U | Siemens | 4.00 | 1.58 | 2.99 | 2.27 | 6.75 | 1.78 | *1* | *0.985* | 2 | 0.984 |
| X Ray U | Toshiba | 2.86 | 0.83 | 2.08 | 0.82 | 1 | 12.0 | *1* | *0.999* | 2 | 0.998 |
| X Ray U | Universal | 4.31 | 2.05 | 2.04 | 1.16 | 2.5 | 4.80 | *1* | *0.995* | 2 | 0.994 |
| Tourniquet | Pangas | 2.67 | 1.30 | 2.00 | 1.06 | 1.43 | 9.60 | 1 | 0.994 | 1 | 0.994 |
| Surgical lamp | Drager | 2.27 | 1.42 | 1.16 | 0.85 | 5.5 | 2.18 | *1* | *0.987* | 2 | 0.986 |

the average of the optimal maintenance frequencies determined by the MCA ($MCA_{Tmean}$ = 1.68 times/yr SD 0.87) or the actual maintenance frequencies suggested either by the clinical engineering department or third-party maintenance providers ($Actual_{Tmean}$ = 2.56 times/yr SD 0.96). The latter result indicates that the optimal maintenance frequencies determined by the MCA are not always well-tuned with the failure frequencies (times/yr) for every type of device. On average, the actual maintenance frequencies suggested either by the clinical engineering department or third-party maintenance providers was 1.5 times/yr compared with the optimal maintenance frequencies determined by the MCA. The results also showed that, on average, the optimal maintenance frequencies determined by the MCA were statistically significantly different from the actual maintenance frequencies suggested either by the clinical engineering department or third-party maintenance providers (Mann–Whitney U test two-tailed $p = 0.008$, power of the test = 62%). The results also showed that the average achieved availability obtained from the MCA ($MCA_{av}$ = 98.13% SD 1.60) was higher compared with the actual average achieved availability ($Actual_{av}$ = 96.98% SD 1.76) for all the medical devices, although these differences were not statistically significantly different (Mann–Whitney U test two-tailed $p = 0.694$, power of the test = = 39%). The MCA was able to determine the best T value (or the maintenance frequency), optimizing the achieved availability in 81.25% of cases (Pearson-Chi-Square = 16.0, df = 1, $p = 0.000$).

## 4 Discussion

This study aimed to implement and validate an MCA to determine the optimal maintenance intervals (or the maintenance frequency) of types of medical device. In doing so, we extracted a set of maintenance records data from a 900-bed hospital.

Although the MCA was able to determine in most cases the optimal maintenance frequency, some opportunities for improving this study existed. One is to improve the power of the statistical tests. The powers of all the tests were below 80%, an unacceptable value that increases the risk of Type II error [3]. This can be solved by increasing the data sample of the types of medical device involved in future studies. The standard deviation of the failure frequencies mean was too high (i.e. 71.76% on average), with such a high variation in the failure frequencies that generating the random number of failure frequencies in the implemented MCA was problematic. Future research should focus on collecting data with less standard deviation.

## 5 Conclusions

On average, the T maintenance intervals (or the maintenance frequency) determined by the MCA were statistically significantly different from the original T values suggested either by the clinical engineering department or external maintenance providers.

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