A SIMULATION STUDY OF MILITARY LAND EQUIPMENT AVAILABILITY UNDER CORRECTIVE AND PREVENTIVE MAINTENANCE REGIMES

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KEYWORDS

Operational Availability, Simulation, Condition-based Maintenance, Corrective Maintenance.

ABSTRACT

This paper presents a simulation study for military land equipment operational availability (OA). A discrete event simulation model was developed within this study to support the analysis of the effect of several maintenance regimes on OA namely Corrective Maintenance (CM), Scheduled Preventive Maintenance (SPM), and Condition-Based Maintenance (CBM). The model was implemented using the ARENA environment and simulations were run with various probability distributions for the various process durations such as task duration, time between failure, repair time, supply delay and non-operating time. The maintenance "cost" metric has been considered in this model. The results indicate that the simulation model capture the important trends of an OA such as military land systems for the CM, SPM and CBM regimes. The simulations results showed that as time between repairs becomes larger, the SPM triggers less often, so CBM catches more failures. The results showed also that the way the three maintenance regimes (CM, CBM, and SPM) interact can be complex, particularly because parts can fail during a task. Many possible improvements were identified, at the design, implementation, and results levels.

INTRODUCTION

Maximizing military land equipment availability without increasing costs is a priority for Land Forces. Although operational availability (OA) is conceptually simple, measuring it using the available systems and data structure is very complex. It appears that the pursuit of accuracy and agreement in measurement of OA may at times distract operators from the real objective of meeting the user's training and operational requirements at an affordable cost. Indeed, the problem of land equipment availability is highly complex, with multiple interdependencies and external influencers (Boukhtouta et al. 2012). Best practices for managing land equipment availability could be applied at different levels of the chain of command to influence, monitor and optimise the availability of the equipment to meet the target operational availability and readiness imperatives. Many logistics and support factors contribute to achieving levels of equipment availability for both training fleets and those deployed to operations. Studies (simulations, theoretical, etc.) and analysis are required to identify and understand the relative contributions of these factors and activities, and how they can be employed within the supply chain and the logistics support network to achieve desired levels of OA within the limited Defence budgets (Commander Canadian Army 2013).

This paper examines OA of Canadian Armed Forces (CAF) land equipment and focuses on the impact of different maintenance regimes on OA when the maintenance cost is considered as an important metric in the simulation model. A high level generic framework, capturing the most important factors influencing the OA is presented (Boukhtouta and Ghanmi 2014). The framework considers several maintenance regimes, such as Corrective Maintenance (CM), Scheduled Preventive Maintenance (SPM), and Condition-Based Maintenance (CBM) and was implemented in discrete event simulation model using ARENA software. Simulations were run with various probability distributions for the various process durations such as task duration, time between failure, repair time, supply delay and non-operating time. The maintenance "cost" metric has also been implemented in this model. A literature review of the military operational availability simulation studies is given below.

Availability of military systems is of major concern for military forces to meet their operational commitments (See US DoD 2014 and Lie 1977). Different papers addressing the OA of military systems from different perspectives have been published in the literature. However and in our knowledge there is no discrete event simulation study of the OA of military systems under different maintenance regimes and including the maintenance costs. We discuss below the studies pertaining to the current paper.

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Gary (2008) proposed a methodology for estimating OA of military systems. The equations and methodologies given in this paper describe the most common techniques, to determine the OA, as well as their limitations and shortcomings. From another side, an investigation study on the effects of the prognostics capability on OA of military land systems has been conducted in Koehn et al. (2005). It is also shown in that paper that OA of military vehicles is significantly affected by Administrative Logistics Delay Time (ALDT) and repair times. Koehn et al. recommended in their paper to use prognostics approaches which allow the ALDT reduction and OA improvement by anticipating failure and preparing the necessary replacement parts. Mi (1998) compared system availability time interval measures of a single-unit system based on stochastic orderings and classifications of lifetime distributions. Murdock (1995) used the renewal theory to develop an availability model over a finite time horizon for a continuously demanded component. He showed that the optimal age replacement period in an infinite time horizon does not maximize average availability. The result of Murdock (1995) study is very useful for lifecycle maintenance planning. A discrete event simulation model using Monte Carlo methods is presented by Sadananda and Srinivasan (2012) to estimate the availability of military systems but not under different maintenance regimes. The probability of failure is approximated by a linear function in Schoenborn, et al. (2014) however this probability is implemented in our study as a sigmoid function of the tire thickness. The current study is an extension of the simulation study presented in Boukhtouta and Ghanmi (2014). We extended the latter study by allowing parts to fail during a task (to study CM, CBM, and SPM interactions) and we also implemented in the maintenance “cost” metric in the model presented in this paper. A system engineering approach is used in this paper and the availability results obtained may be used for long-term procurement decisions and strategic planning.

The paper is organized as follows. The next section describes Land Force’ OA conceptual model followed by the presentation of the simulation model and the impact of different maintenance regimes on OA. The maintenance cost impact is also presented and discussed. Possible improvements of the model and the simulation study are also discussed. Concluding remarks and are given in the last section.

LAND FORCE’ OPERATIONAL AVAILABILITY CONCEPTUAL MODEL

A high level OA conceptual model of a land system is presented in Figure 1. The CAF Land system consists, for the purpose of this study, of fleets of vehicles, which partake in missions (tasks). Between tasks, vehicles are non-operating and awaiting their next task. While non-operating, a vehicle could be down for maintenance (repair, upkeep, or checkup), on standby, or simply available and ready for their next task. There are three main categories of maintenance operations:

- **CM** : CM deals with repair of system faults and requires diagnostics for fault identification. CM is triggered by system failures and the vehicle remains down until repaired.
- **SPM**: is a preventive maintenance (PM) which includes upgrades and checkups to decrease likelihood of failure. SPM is triggered via a maintenance tracking system that follows the rules established by the manufacturer. The vehicle is down for SPM when required spares are available only.
- **CBM**: is a PM triggered by a decision-making system that uses health and usage monitoring system (HUMS) data to prognoses what is most likely to fail, based on current state, if not maintained within a certain time. Similar to SPM, the vehicle is down for CBM when required spares are available only.

All types of maintenance consume spare parts. If spares are not available at the maintenance site, they must be ordered from the Supply System. Demand Forecasting technologies can be used to reduce the Time to Supply Spares (TSS). The prefix M is used in this paper to designate the mean (eg. MTSS, is the Mean Time to Supply Spares).

A vehicle undergoing CM is considered unavailable (down) while spare parts are being shipped to maintenance site. This is referred as TSS. The time required for CM can be subdivided into Time for Failures diagnostics (TFD), TSS, and Time To Repair (TTR). The latter includes an operational checkout performed to ensure the vehicle is once more serviceable. If the check passes, the vehicle goes on standby (the acronym SBT – Standby Time is used for this time), otherwise the CM must restart with a new attempt at diagnostics. Repair times are typically much smaller than TSS. However, for CBM, TSS is eliminated, and there is no diagnostics time: down time is approximately equal to repair time.

As indicted above, Figure 1 depicts most important concepts (boxes) and relationships (lines). The system could be available (green), in-use (yellow), and unavailable (orange). The Fleet Vehicles box is the main component, representing the fleet of vehicles in standby. On average a vehicle is in a standby state for the mean standby time (MSBT). Vehicles undergo wear as a result of the Mission and Task Environment box, representing the usage of vehicles on mission tasks. Tasks last on average a time MTMT (the mean time for mission tasks). A vehicle may become non-serviceable as a result of wear-induced or combat induced failures, both experienced during mission tasks. Failures manifest on average every MTBF (mean time between failures) days. The Preventive Maintenance box is the actual maintenance activity resulting after either SPM or CBM has been triggered and spares are available (no TFD).

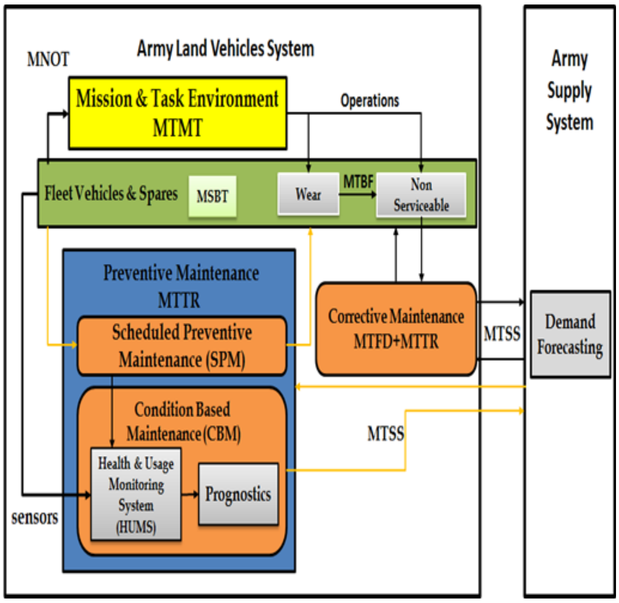

Figure 1: High level Conceptual model for Analysis of OA of Land Systems

Figure 2 depicts a graphical representation of a given Task Cycle Time (TCT) for a vehicle; each cycle has two times: Time on Missions Tasks (TMT) and Non-operating Time (NOT). The NOT can be decomposed into DWT (Downtime) and SBT (Time on Standby). The DWT is the sum of TFD, TSS, and TTR. Using these notations, the uptime of a vehicle is TMT + SBT whereas its downtime is DWT, which can be approximated by the sum of TSS and TTR (i.e. TFD is treated as negligible in comparison with TSS and TTR). The operational availability Ao (this symbol is usually used in formula to express the OA) of a vehicle is given by (see Gary 2008):

$$Ao = \text{uptime}/(\text{uptime}+\text{downtime}) \quad (1)$$
$$= (TMT + SBT) / (TMT + SBT + TSS + TTR)$$

Each of those time durations is treated as a stochastic variable.

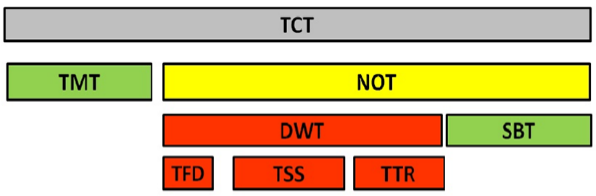

Figure 2: Time Subdivision Hierarchy for Vehicle OA Measurements

SIMULATION STUDY

Only one vehicle type is supported, with one spare part type, and one task type. The sensor variable for CBM is tire thickness. Tire thickness can be interpreted as a metaphor for any sort of "system wear". It was assumed to be a linear function of time spent on task. Once the tire thickness goes below Tcbm (thresholds of CBM which is represented by tire tread thickness expressed in mm, 25 mm for our study), the vehicle will finish its task and then go for repair, and the tire thickness is reset to NewTireThickness. Pf is implemented in the current study as a sigmoid function of the tire thickness with a mean Mf (the center of the profile).

All probability distributions are labelled Px where x is a suffix indicating which component it represents: x=t for tasks, n for non-operating, r for repair, and s for supply. Each distribution has a mean Mx and standard deviations Sx.

The task duration is discretized into durations of 0.1 days. That is, the Pf is updated, and the system is given an opportunity to break, every 0.1 days. The Pf function was scaled to give approximately the same probability of failure for each task as before, however the standard deviation of the "time to fail" will increase with the time resolution of this approximation.

If a vehicle breaks down during a task, it goes through CM, and then completes the remainder of the task duration. A design decision was made to not allow the system to undergo CBM or SPM while on task. As realistically, the vehicle would be far away from base and not be able to do this. In addition, in practice there should be a time penalty for system failure while on task, to represent the addition time to repair, but this was not implemented.

Among the variables used in the model we have Mt (mean duration of task), Mn (mean duration of non-operating), Mf (mean time between failures), Fspm (Period or frequency of SPM), and Wr (wear rate of tire per Km (mm/km)).

We also implement a "cost" metric in this model in a very simple way. Spares have a fixed unit cost in this simulation for simplicity. Each time a spare is used in a repair, the total cost of the simulation is incremented by one (the cost of the spare). Essentially, this method simply counts the number of *spares* needed to reach a given OA. In practice, vehicles have operating costs, the spare cost is not fixed, repairs have costs that sometimes outstrip the price of parts, and CBM is usually more expensive to implement. Nevertheless, this simple model gives a very clear picture of the "cost" of maintaining a certain OA with given repair regimes. The following is a sensitivity analysis of the operational availability in our model. We increment several parameters that we feel are illuminating over a range of both realistic values, and nonphysical (but interesting) boundary cases.

Sensitivity of SPM Operational Availability to Wear Rate, Replacement Frequency and Mt

The effect of the Time between Replacement (TBR) on OA evaluated with respect to mean task duration (Mt), and rate of tire wear (Wr), with CBM off is shown below in Figure 3, Figure 4 and Figure 5. Since CBM is off, Wr essentially corresponds to Mf. The title of the axis giving the values of the operational availability is represented by Ao on the different figures.

When Wr is very low, the system takes a long time to fail "naturally", so a low TBR results in many unnecessary replacements, which causes unnecessary repair time, lowering the OA. As the Wr rises, the system fails more often, so SPM repairs have a positive effect on the OA. SPM is only effective beyond a certain point. If the Wr and TBR are such that the vast majority of parts fail before the scheduled maintenance, SPM has little effect on OA.

Furthermore, the OA as a function of Fspm contains some "bumps" that seem counterintuitive. This phenomenon is caused by the way SPM is implemented with respect to Mt. That is, a part is replaced before a task if the scheduled repair time is expected (that is, the calculation uses Mt, the mean task duration) to coincide with a task.

Another result of the implementation is that extreme combinations of TBR, Mt, and Wr can cause odd situations where the part is replaced before the task even begins (when Mt>TBR for instance). However, parameters like these are nonsensical and would never occur in the real world. They are included as boundary cases for completeness and interest's sake.

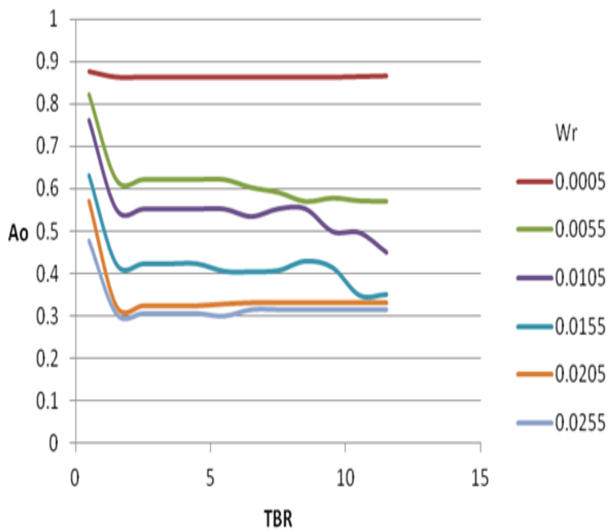

Figure 3: Sensitivity of Ao to TBR and Wr, for Mt = 1

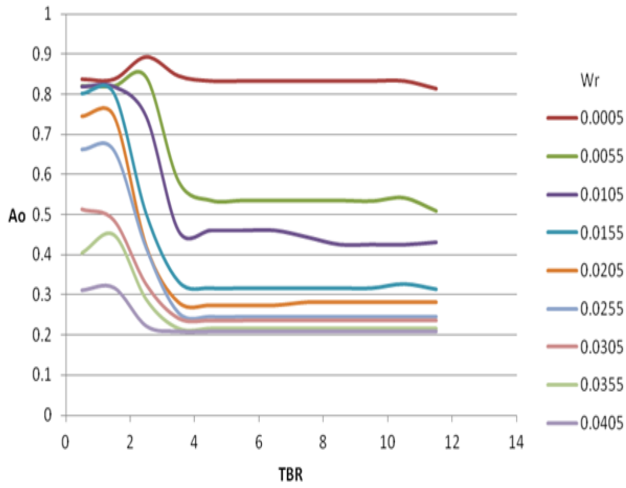

Figure 4: Sensitivity of Ao to TBR and Wr, for Mt = 2

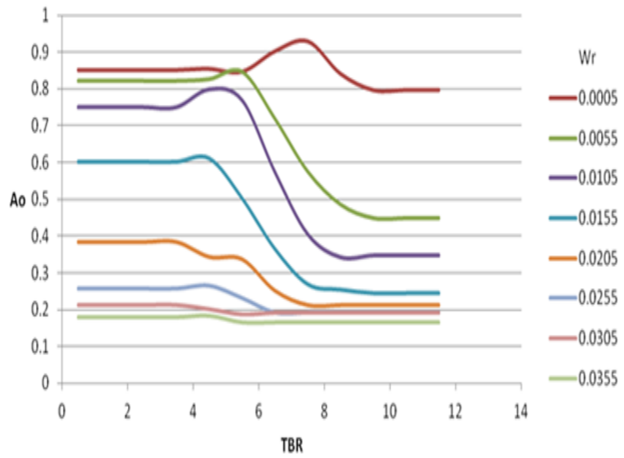

Figure 5: Sensitivity of Ao to TBR (days) and Wr, for Mt = 3

Cost Simulation Analysis

The following Figures (Figure 6 and Figure 7), illustrate the relationships that OA and cost (as defined above) have with Tcbm and TBR. In other words, the graphs show how the OA and cost are affected by earlier CBM, or faster time between replacements. The relative efficiency of CBM vs. SPM is clearly visible. SPM can attain higher levels of operational availability than CBM, but at a much greater cost. These findings mostly agree with intuition regarding these two maintenance regimes. The bumps in the OA are actually a result of the Mt and the way that SPM is implemented, as explained in the above section.

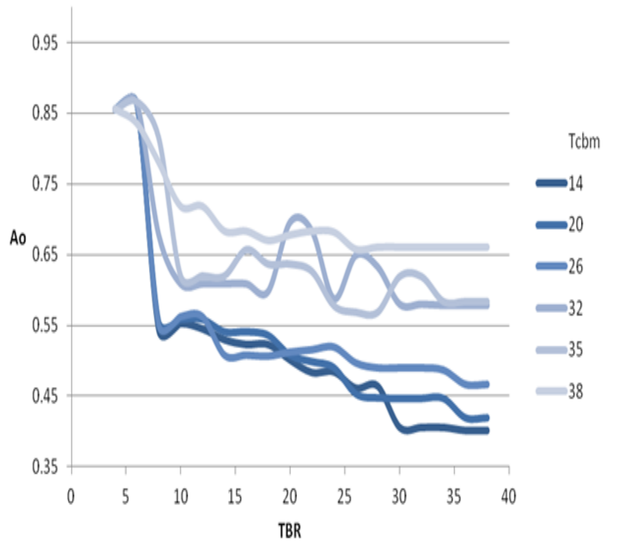

Figure 6: Ao as a function of TBR and Tcbm, Ms = 16

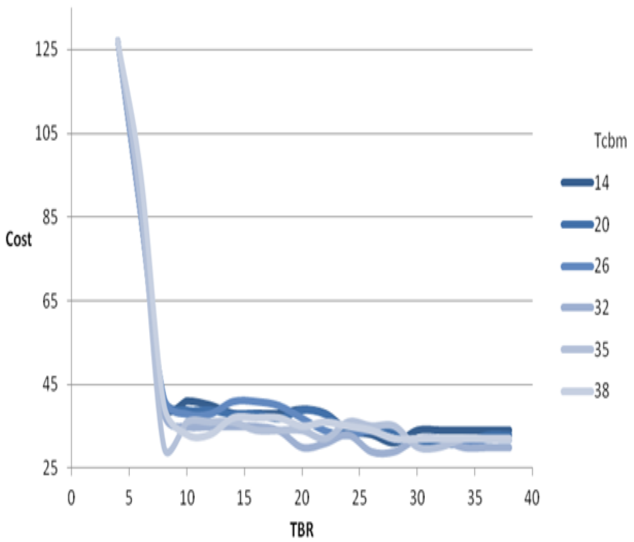

Figure 7: Cost as a function of TBR (days) and Tcbm, Ms = 16

The Wr is on the lower side because it slows down the system wear, to allow SPM and CBM to interact more. Similarly, the Mt was set to 4 because it shows the relationship more clearly.

Tcbm has little effect on OA when TBR is small, because the scheduled maintenance "catches" every failure before CBM has a chance to trigger. As TBR becomes larger, the SPM triggers less often, so CBM catches more failures. There is a clear "sweet spot" where both of them are effective, and that is related to the Mt, and the tire wear rate. The results are very chaotic because the way the three (CM, CBM, and SPM) maintenance regimes interact can be complex, particularly because parts can fail during a task.

When Fspm is no longer triggering (at around 34 days), increasing the Tcbm from 14 to 38 results in a ~16% increase in OA for negligible increase in total cost.

When Tcbm is not triggering (SPM catches failures first), decreasing the TBR from 14 to 6 results in approximately 25-37% increase in OA , for a staggering 45-62 unit increase in total cost.

The most "efficient" system state, for these variables, is at Tcbm = 35, TBR = 8, which results in an average of 2.7% OA per unit cost. The model significantly decreases in efficiency when TBR is low and Tcbm is high, because there are a lot of premature replacements. The highest achievable OA, for these variables and this system, is 87%, at Tcbm = 35 and TBR = 6, resulting in an average of 0.98% OA per unit cost. For contrast, increasing the TBR by one day with the same Tcbm gives an OA of 82%, for an average of 2.7% OA per unit cost.

The reason that CBM is so effective and efficient is that most of the repairs in a simulation (with the exception of ones where SPM occurs before every task), are CM repairs that happen when a part fails during a task. CBM allows parts for both CM and CBM to be ordered ahead of time, this means that when a part fails during a task, it bypasses the supply time.

A much lower Ms allows CBM to surpass the maximum OA of SPM (as shown below in Figure 8 and Figure 9), for almost no extra spare parts. However, CBM reaches a ceiling, bounded by the repair time, and any higher values of Tcbm result in lower OA's for significantly more spare parts. This ceiling happens at around Tcbm = 35 for the settings in Figure 8 and Figure 9.

Although it seems like CBM is better across the board, situations with a high relative Ms and/or cheap parts can create very advantageous scenarios for SPM. The installation and monitoring of a CBM system can also cost also more than it is worth in the end. Detailed models are capable of illustrating the most effective system and parameters for most scenarios.

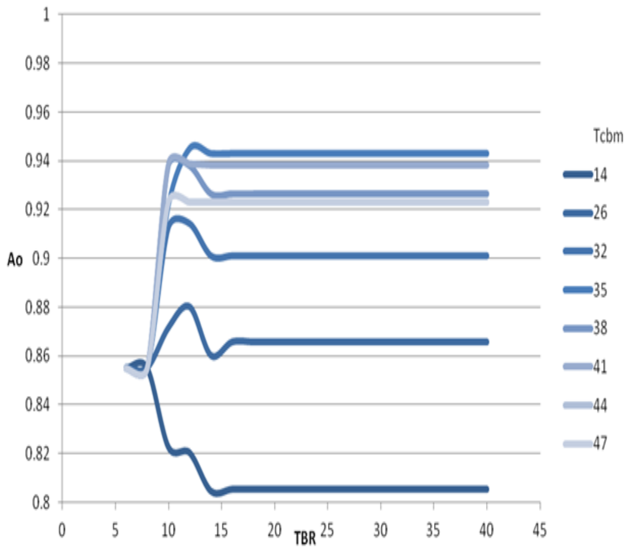

Figure 8: Ao values as a function of TBR and Tcbm, Ms = 4

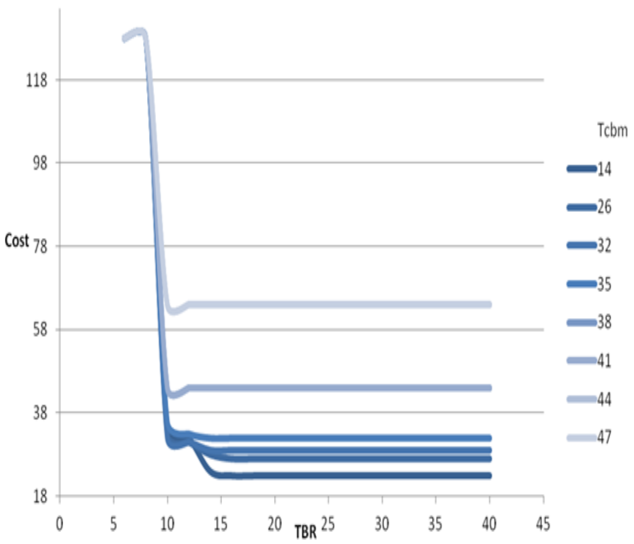

Figure 9: Cost as a function of TBR and Tcbm, Ms = 4

POSSIBLE IMPROVEMENTS

Several improvements to the model are possible at the design and implementation levels. From implementation perspective, tasks could be implemented in a future study according to a probability distribution, and the standby time should be measured as the time the vehicle was in the waiting queue. Also, current implementation uses a variable to keep track of spares; this is adequate when there is only one type of spare modelled (since there is only one type of part that can fail), but with multiple types of parts, multiple vehicles, keeping track of the shipment of spares to maintenance site will be much easier to handle by representing them as entities in the ARENA model.

Different design improvements could considered in a future studies. Among these design improvements we cite: multiple types of breakable parts, damage due to failure causes more parts to require replacement, enable vehicles to be taken offline for CBM maintenance as soon as an ordered spare arrives at the maintenance site, and include demand forecasting to decrease the wait time when CM is required, or to decrease the number of cycles a vehicle experiences after an SPM or CBM has been triggered.

CONCLUSIONS

The objective of this paper was to study the military Land equipment availability under different maintenance regimes. A generic framework was used to support the study of several maintenance regimes on OA namely Corrective Maintenance (CM), Scheduled Preventive Maintenance (SPM), and Condition-Based Maintenance (CBM). A discrete event simulation model was implemented using the ARENA modelling environment, covering CM, CBM and SPM. Simulations based on the implementation were run with various probability distributions for the various process durations such as task duration, time between failure, repair time, supply delay and non-operating time. The results indicate that the framework and implementation properly capture the important trends of OA for a system such as Military Land Systems for the CM, CBM and SPM regimes.

The simulations results showed that as TBR becomes larger, the SPM triggers less often, so CBM catches more failures. There is a clear "sweet spot" where both maintenance regimes are effective, and that is related to the Mt, and the tire wear rate. The results showed also that way the three maintenance regimes (CM, CBM, and SPM) interact can be complex, particularly because parts can fail during a task. The simulations results showed that CBM is an effective and efficient maintenance regime. The reason that CBM is so effective and efficient is that most of the repairs in a simulation (with the exception of ones where SPM occurs before every task), are corrective maintenance repairs that happen when a part fails during a task. CBM allows parts for both CM and CBM to be ordered ahead of time, this means that when a part fails during a task, it bypasses the supply time.

The cost simulations results gave us a very clear picture of the "cost" of maintaining a certain OA with given repair regimes. The analysis of these results shows how the OA and cost are affected by earlier CBM, or faster time between replacements. The relative efficiency of CBM vs. SPM is clearly visible. SPM can attain higher levels of operational availability than CBM, but at a much greater cost.

Many possible improvements were identified, at the design, implementation, and results levels.

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