SIMULATION AS A DECISION SUPPORT TOOL IN MAINTENANCE FLOAT SYSTEMS – SYSTEM AVAILABILITY VERSUS TOTAL MAINTENANCE COST

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ABSTRACT

This paper is concerned with the use of simulation as a decision support tool in maintenance systems, specifically in MFS (*Maintenance Float Systems*). For this purpose and due to its high complexity, in this paper the authors explore and present a possible way to construct a MFS model using Arena® simulation language, where some of the most common performance measures are identified, calculated and analysed. Nevertheless this paper would concentrate on the two most important performance measures in maintenance systems: system availability and maintenance total cost. As far as these two indicators are concerned, it was then quite clear that they assumed different behavior patterns, specially when using extreme values for periodic overhauls rates. In this respect, system availability proved to be a more sensitive parameter.

Keywords: Simulation, Discrete Event Simulation, Maintenance, Preventive Maintenance, Waiting Queue Theory, Float Systems.

1. INTRODUCTION

In production areas and service systems such as transport companies, health service systems and factories, the main goal is to achieve high levels of competitiveness and operational availability. In this environment the need for equipment to work continuously is very likely in order to maintain high levels of productivity. This is why MFS has an important role on equipment breakdown and production stoppage has a high and direct impact on production process efficiency.and, as a consequence, on their operational results. Therefore, maintenance control and equipment use optmization become not only an important aspect for the mentioned reasons, but also for personnel security matters and to prevent negative environmental impact.

In general, preventive maintenance implementation increases equipment control and avoids unexpected stoppages. However, to overestimate these actions makes the maintenance costs too high for the required availability.

In production systems involving identical equipments such as the float systems it is an advantage to integrate maintenance management with materials and human resources. An example of this to have spare equipment to replace those that fail or need review. Then, the direct and indirect costs due eqiupment stoppage are minimized and the level of production or service requirements fullfield. Although the existance of spare equipment is important to maintain the production process working it is recommended to keep the number of spare equipment in an optimal level for economic reasons.

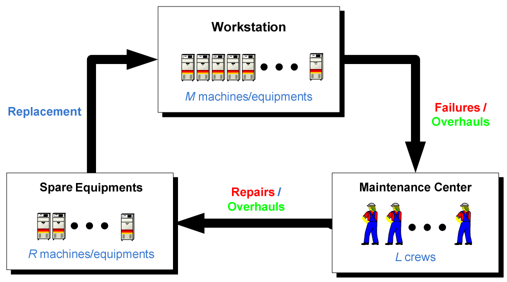

Fig. 1 –Typical *Maintenance Float System*

A typical Maintenance Float System is composed of a workstation, a maintenance center with a set of maintenance crews to perform overhauls and repair actions and a set of spare machines (Fig.1). The workstation consists of a set of identical machines and the repair center of a limited number of maintenance crews and a limited number of spare machines. The maintenance crew is responsible for the repair and overhaul actions and also responsible for:

a) the transportation of the spare macines from the maintenance centre wharehouse to the workstation;
b) the removal and transportation of the machines needing repair or overhaul action to the maintenance centre;
c) the installation of the spare machines in the workstation, replacing machines removed for repair or overhaul action.

After having described the maintenance float system under consideration, the next section of this paper focus on the literature review on analytical models for this type of maintenance system, thus allowing some type of validation for the simulation results achieved.

The following section describes the simulation model developed, based on the purpose of analysing system availability and total maintenance cost.

Next, this paper includes a section for output analysis, in order to evaluate sensitivity, precision and robustness of both performance measures under consideration.

Conclusions and Further Developments are the closing sections for this paper.

2. RESEARCH BACKGROUND

As far as float systems maintenance models is concerned, (Lopes 2007) refers some studies where simulation has been used to produce results based on specified parameters. Due to the fact that these simulation models were only concerned with the input/output process, without dealing with what is happening during the simulation data process, some metamodels have emerged (Madu and Kuei 1992a; Madu and Kuei 1992b; Madu and Lyeu. 1994; Kuei and Madu 1994; Madu 1999; Alam et al. 2003). The metamodels express the input/output relationship through a regression equation. These metamodels can also be based on taguchi methods (Madu and Kuei 1992a; Kuei and Madu 1994) or on neuro networks (Chen and Tseng 2003). These maintenance system models were also recently treated on an analytical basis by (Gupta and Rao 1996; Gupta 1997; Zeng and Zhang 1997; Shankar and Sahani 2003; Lopes 2007). However, the model proposed by (Lopes 2007) is the only one that deals, simultaneously, with three variables: number of maintenance teams, number of spare equipments, and time between overhauls, aiming the optimization of the system performance. Although this proposed model already involves a certain amount of complexity it may become even more complex by adding new variables and factors such as: a) time spent on spare equipment transportation, b) time spent on spare equipment installation; c) the introduction of more or different ways of estimating efficient measures; d) allowing the system to work discontinuously; e) speed or efficiency of the repair and revision actions; f) taking into account restrictions on workers timetable to perform the repair and revision actions; g) taking into account the workers scheduling to perform the repair and revision actions; h) taking into account the possibility of spare equipment failure; etc. Anyway these mentioned approaches would aim at ending up with MFS models very close to real system configurations. In fact, the literature review showed that most of the works published, involving either analytical or simulation models, concentrate on a single maintenance crew, or on a single machine on the workstation or even considering an unlimited maintenance capacity – thus overcoming the real system complexity and therefore not quite responding to the real problem as it exists.

As far as the model presented by (Lopes et al. 2005; Lopes et al. 2006; Lopes 2007) is concerned it is assumed that systems works continuously, its availability is not calculated and the system optimazation is only based on the total maintenance cost per time unit. Moreover, it considers that the total system maintenance cost is the same without taking into account the number of machines unavailable, which in many real situations it is not the best option. Finally the referred analytical model only allows that its failures occur under an homogeneous Poisson process (HPP).

Another important aspect on the companies management strategic definition is to have their tasks correctly planned. To help this planning procedure it is important to know different indicators such as: machine availability, equipment performance and maintenance costs, among others. Therefore one should consider new factors that affect these float systems indicators: possibility of some machine failure, efficiency, repair time.

Moreover, when preventive maintenance policy is used, the time for individual replacement is smaller than time for group replacement. It means that the latter situation requires more machine on the process to be stopped, and also implies an increase for a certain time, on the maintenance crews.

In general companies policy lies on using economic models to define their best strategies. Profits maximization or costs minimization are the most frequent goals used. However, strictly from the maintenance point of view availability is frequently used as an efficient measure of the system performance, and sometimes more important than the cost based process. In this work availability is calculated dividing the time the system is up (Tup) by the time the system is up plus the time the system is down (Tdown) for maintenance reasons. Some authors, however, calculate availability through the ratio between *MTBF* and *[MTBF+MTTR]*. Being, *MTBF* the-Mean Time Between Failures and *MTTR* the Mean Time To Repair.

3. THE SIMULATION MODEL

The Arena® simulation language environment was chosen for the development of the simulation model for this MFS (Kelton 2004; Pidd 1989; Dias et. al 2006 and Pidd 1993).

This simulation model (see details on Peito et. Al 2011) follows the general assumptions of the analytical model proposed by (Lopes et al. 2005; Lopes et al. 2006; Lopes 2007) when considering a Maintenance Float System with 10 active and identical machines (M), 5 spare machines (R) and 5 maintenance crews (L). The active machines considered operate continuously. Machines that fail are taken from the workstation and sent to the maintenance park waiting queue, where they will be assisted according to arrival time. Machines that reach their optimal overhaul time are kept in service until the end of a period T without failures. However they will be also kept on a virtual queue to overhaul. If the number of failed machines plus the number of machines requiring overhaul is lower than the number of maintenance crews available, machines are replaced and repaired according to FIFO (*First In First Out*) rule. Otherwise if it exceeds the number of maintenance crews, the machines will either be replaced (while there are spare machines available) or will be sent to the maintenance queue. The machines that complete a duration period T or time between overhauls in operation without failures are maintained active in the workstation, where they wait to be assisted, and they are replaced when they are retired of the workstation to be submitted to a preventive intervention. Its replacement is assured by the machine that leaves the maintenance center in the immediately previous instant. If an active machine happens to fail it awaits for the accomplishment of an overhaul, then it will be immediately replaced, if a spare machine is available or as soon it is available.

Furthermore the time to replace a machine that needs overhaul or has failed is also included in our model and this is a parameter that could be adjusted during a simulation run.

In the MFS here analized, it is assumed that the M active machines of the workstation have a constant failure rate (Francisco et al. 2011). Moreover time between failures are assumed as independent and identically distributed following an Exponential Distribution for all machines (failures occur under a *Homogeneous Poisson Process*). However, during a simulation run, this value could be adjusted based on time between overhauls. Obviously a smaller time between overhauls implies greater time between failures.

In this first version of the simulation model the time between overhauls could be adjusted during a simulation run.

As far as time to overhaul and time to repair are concerned, we have assumed the *Erlang*-2 distribution, eventhough considering overhaul time significantly lower than the repair time.

For this MFS, the following three parameters and ten relevant variables are identified:

Parameters

1. Number of active machines (M);
2. Number of maintenance crews (L);
3. Number of spare machines (R);

Variables

4. Machine- Overhauls rate (λ_{rev})*;
5. Machine-Initial Failures rate (λ_f)*;
6. Crews-Repair rate (μ_{rep})*;
7. Crews-Overhaul rate (μ_{rev})*;
8. Failure cost (C_f);
9. Repair cost (C_{rep});
10. Overhaul cost (C_{rev});
11. Replacement cost (C_s);
12. Cost due to loss production (C_{lp});
13. Holding cost per time unit (h);
14. Labour cost per time unit (k);
15. Time to convey and install spare machine ($T_{ConvInst}$).

(*) This variable can be adjusted during the simulation run.

The different types of input mentioned above occur in specific developed input menus – Visual Basic for Applications within Arena model.

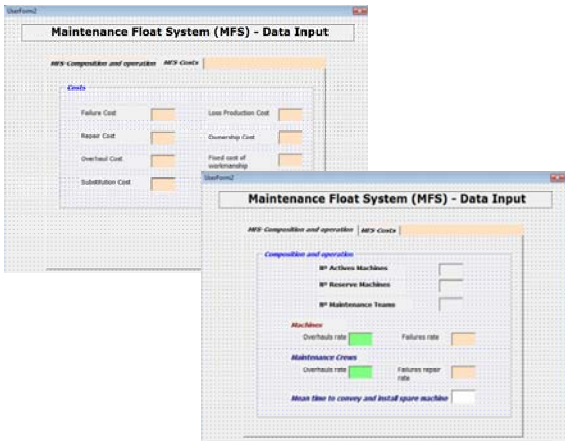

Fig. 2 - Data input area sample screenshot

Figures 2 and 3 highlight both input variables window and output updates – numerically and graphically. Fig. 4 shows an application screenshot including simulation animation.

The developed simulation application for a *Maintenance Float System* allows the estimation of the following global efficiency measures:

a) Average system availability *(AvgSAv);*
b) Total maintenance cost per time unit [*(AvgTCu)* and *AvgTCu(*)*].

Total Maintenance Cost per Time Unit would be estimated in two different ways:

- Fixed cost, independent of the number of available machines in the system;
- Variable cost, proportionaly dependent on the number of available machines in the system.

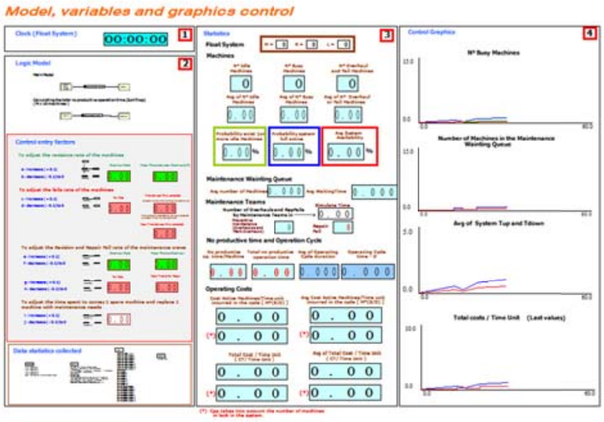

Fig. 3 - Variables and graphics control

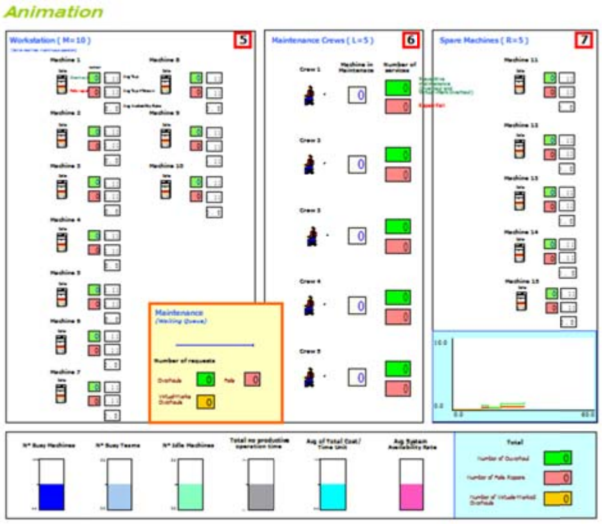

Fig. 4 – Animation area sample screenshot

However, some other performance measures can be estimated, such as:

c) Average number of missing machines at the workstation *(AvgM$_{eq}$)*,
d) Average number of machines in the maintenance waiting queue *(AvgLq)*;
e) Average waiting time in the maintenance waiting queue (*AvgWt)*;
f) Average operating cycle time (*AvgD*);
g) Probability of existing 1 or more idle Machines *(Prob$_{im}$)*;
h) Probability of the system being fully active *(Prob$_s$)*;

And, finally, the simulation model also computes some individual efficiency measures per machine or maintenance crew, i.e.:

i) Utilization rate per machine;
j) Utilization rate per maintenance crew;
k) Number of overhauls and repair actions performed per maintenance crew;
l) Average availability per machine.

This paper will focus on the two general performance measures mentioned above – system availability and total maintenance cost per time unit.

Simulation length was set to 9.000 hours (approximately one year) – warm-up period was set to 3.500 hours.

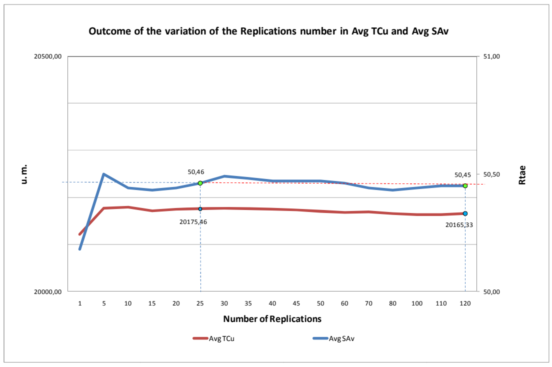

Fig. 5 – Outcome of the variation of the Replications number in *AvgTCu* and *AvgSAv* variables

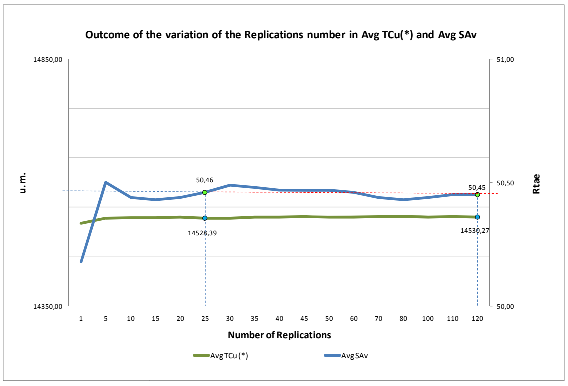

Fig. 6 – Outcome of the variation of the Replications number in *AvgTCu(*)* and *AvgSAv* variables

For each set of input parameters and pattern for variables, the simulation output variables *AvgSAv, AvgTCu* and *AvgTCu*(*) were estimated based on 25 replications – for an adequate system stabilization and results robustness for both performance measures (Figures 5 and 6) and also due to computational time required to run the model.

4. SIMULATION RESULTS AND DISCUSSION

Bearing in mind the twelve variables of MFS previously referred, simulation models were used to test and estimate the behaviour of the two global efficiency measures mentioned on the previous section. Simulation models were carried out for (1-60) hypothetical scenarios with different review rates (*λrev*). These different review rates are associated with different times between review (*T*) which are defined accordingly to the preventive maintenance policy aiming the best option.

Table 1- Global efficiency measures outcomes in the MFS model after 25 replication

(Values estimated by simulation after 25 replication)

Scenario	λ_{rev} (/hour)	*T (hour)*	*AvgSAv (%)*	*AvgTCu (m.u./hour)*	*AvgTCu(*) (m.u./hour)*
1	0,10	10,000	29,25	21064,60	17304,37
2	0,20	5,000	34,75	21127,96	16646,80
3	0,30	3,333	40,79	21065,24	15870,35
4	0,40	2,500	45,26	20915,39	15287,79
5	0,50	2,000	48,12	20751,46	14908,68
⋮	⋮	⋮	⋮	⋮	⋮
52	9,00	0,111	48,71	20195,00	14776,87
53	15,00	0,067	48,52	20212,24	14807,21
54	20,00	0,050	48,54	20228,63	14815,57
55	25,00	0,040	48,56	20223,63	14814,18
56	30,00	0,033	48,54	20230,24	14816,98
57	35,00	0,029	48,62	20226,82	14811,16
58	40,00	0,025	48,54	20229,16	14820,31
59	45,00	0,022	48,50	20228,80	14822,78
60	50,00	0,020	48,52	20226,42	14815,55

(*) *Considers that the cost of lost production changes in function of the number of active machines lacking in the system.*

Table 2 – Observe percentual change in the global efficiency measures after 25 replication

MPO -Observe percentual change			
Scenario	*AvgSAv*	*AvgTCu*	*AvgTCu(*)*
1-2	15,83%	0,30%	-3,95%
2-3	14,80%	-0,30%	-4,89%
3-4	9,87%	-0,72%	-3,81%
4-5	5,95%	-0,79%	-2,54%
⋮	⋮	⋮	⋮
52-53	-0,14%	0,06%	0,10%
⋮	⋮	⋮	⋮
58-59	-0,07%	0,00%	0,02%
59-60	0,04%	-0,01%	-0,05%

Max.	15,83%	-0,79%	-4,89%
Mean	0,80%	-0,07%	-0,27%

A first global analysis of the values prsented in tables 1 and 2 indicate that the precision obtained on the three efficient measures analysied is different. An individual analysis of each meaure indicates that *AvgTCtu* shows the smaller variation (MPO lower). In Table 1 it can also be observed that when *T* takes very small values ($T \leq 0.111$ or $\lambda_{rev} \geq 9$) the three efficient measures *[AvgTCtu, AvgTCTu(*) and AvgSAv]* are kept practically unchangeable. This fact can be confirmed in Fig. 7 or in Table 2 where the MPO for these values of *T* is extremely low, almost zero. On the other hand, when *T* assumes very high values ($T \geq 2,5$ or $\lambda_{rev} \leq 0,4$) the efficiency measures *AvgTCTu(*) and AvgSAv* present high MPO values in opposition to *AvgTCtu* that shows very small values. In Table 2 it can also be observed that *AvgTCtu* presents the lowest MPO average value of the three efficiency measures and that *AvgSAv* has the highest value.

In order to simplify the interpretation and analysis of these global efficiency measures, figures 7, 8 and 9 pinpoint the maximum and minimum values (table 2 and 3) as well as other points considered relevant for the analysis.

Table 3 - Maximum values of the main efficiency measures

	Statistics (Maximum)	λ_{rev} *(/hour)*	*T (hour)*
AvgSAv *(%)*	50,70%	0,90	1,111
AvgTCu *(m.u./hour)*	21127,96	0,20	5,000
AvgTCu (*) *(m.u./hour)*	17304,37	0,10	10,000

Note: *Red points in the graphics*

Table 4 - Minimum values of the main efficiency measures

	Statistics (Minimum)	λ_{rev} *(/hour)*	*T (hour)*
AvgSAv *(%)*	29,25%	0,10	10,000
AvgTCu *(m.u./hour)*	20096,90	1,80	0,556
AvgTCu (*) *(m.u./hour)*	14518,77	1,20	0,833

Note: *Yellow points in the graphics*

Tables 3 and 4 show that the *T* value corresponding to the minimum value of *AvgSAv* corresponds the maximum value, as expected, of *AvgTCu(*).* When compared with the minimum of *AvgTCu,* there is a significant *T* gap (≈ 5 hours), although, its remains practically the same when the value of *T* changes from 5 to 10 hours (Fig. 9).

When comparing the *T* value corresponding to the maximum value of *AvgSAv* with the *T* value corresponding to the minimum value of *AvgTCu(*),* there is only a small gap, which is clearly higher in the case of the *T* value orresponding to the minimum of the *AvgTCu* (Fig. 9)

Table 5- Correlation coefficients

	T	*AvgSav*	*AvgTcu*	*AvgTcu(*)*
T	1	-0,9021	0,8279	0,9017
AvgSav	-0,9021	1	-0,7980	-0,9986
AvgTcu	0,8279	-0,7980	1	0,8237
AvgTcu (*)	0,9017	-0,9986	0,8237	1

A carefull analysis of the correlation coefficients of three efficiency measures, table 5, shows that *T* variations are better explained by *AvgSav* and *AvgTCu(*)* (≈90%). It is also verified that there is a high inverse correlation between *AvgSav* and

AvgTCu(*) (≈99,8%). However when *AvgTCu* is compared with *AvgTCu(*)* or with *AvgSav,* the correlation coefficient decreases to 82,37% and to 79,80%, respectively. This partially explains why in tables 3 and 4 the *T* value corresponding to the maximum of *AvgSav* does nor correspond exactly to the *T* value corresponding to the minimum of the *AvgTCu* and *AvgTCu(*)* and that difference being higher in the case of *AvgTCu(*)* (Fig. 9).

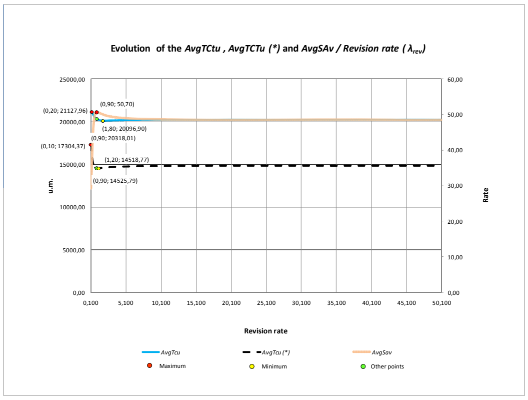

Fig. 7 - Evolution of the *AvgTCtu, AvgTCTu(*)* and *AvgSAv / Revision rate* (λ_{rev})

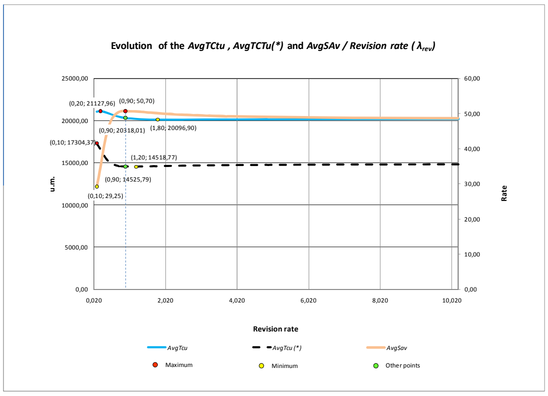

Fig. 8. Evolution of the *AvgTCtu, AvgTCTu(*)* and *AvgSAv / Revision rate* (λ_{rev}) [Zoom Fig.7]

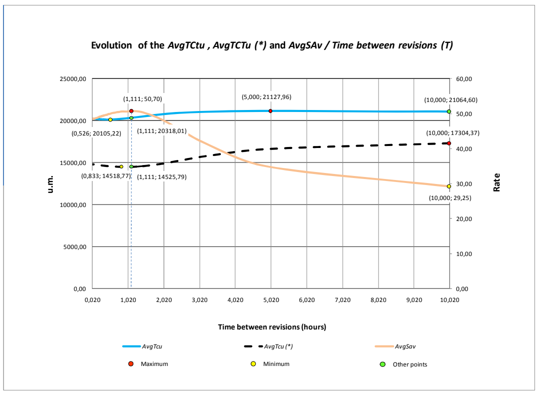

Fig. 9- Evolution of the *AvgTCtu, AvgTCTu(*)* and *AvgSAv / Time between revisions* (*T*)

As it can be observed in Fig.7 and more clearly in figures 8 and 9, for the MFS analysed, the three global measures of efficiency being studied only present small variations for values of λ_{rev} between 0,10 and 9,00 (or *T* between 10,000 and 0,111 hours). For values of λ_{rev} higher than 9.00 the three global measures of efficiency remain practically unchanged.

Table 6 - Comparison among the *AvgTCu* values estimates by the simulation model and analytic model (Lopes, 2007)

T	Model	*AvgTCu* (m.u./hour)	*AvgTCu(*)* (m.u./hour)	Δ_1 (%)	Δ_2 (%)	Δ_3 (%)
1,66	Simulation	20381,74	14554,5	-40%	-12%	-25%
	Analytic	18130,56	----	----		
3,33	Simulation	20126,65	14555,62	-38%	-19%	-17%
	Analytic	16968,39	----	----		
1,66	Simulation	20111,24	14628,02	-37%	-16%	-18%
	Analytic	17303,65	----	----		
3,33	Simulation	21065,24	15870,35	-33%	-16%	-14%
	Analytic	18167,34	----	----		
			mean	-37%	-16%	-18%

Note: *M=10; R=5; L=5.*
(*) Considers that the cost of lost production changes in function of the number of active machines lacking in the system.
Δ_1 *– Difference among Simulation AvgTCu and Simulation AvgTCu(*)*
Δ_2 *– Difference among Simulation AvgTCu and Analytic AvgTCu*
Δ_3 *– Difference among Analytic AvgTCu and Simulation AvgTCu(*)*

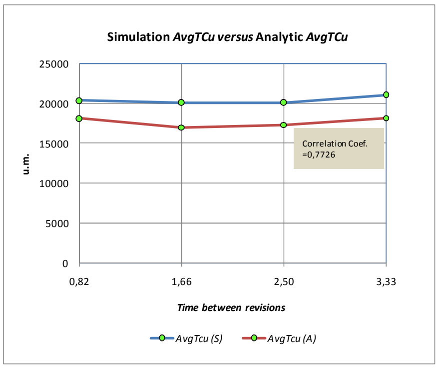

Fig. 10 - Comparison among the *AvgTCu* values estimates by the simulation model and by the analytic model (Lopes, 2007)

In Table 6 there is a comparison between the values obtained from the simulation model developed by the authors in a former (Peito et al 2011) and the analytical model developed by (Lopes 2007). The sample size of the results presented and compared in this case was limited by the number of results presented by the author in her work (Lopes, 2007) . In this table it can be verified that when the two global efficiency measures are both estimated from the simulation model the difference (Δ_1) is on average -37%, presenting *AvgTCu* always higher values. However when *AvgTCu* is estimated through the analytical model that difference (Δ_3) is on average -18%. When the same efficiency global measure based on the analytical model is compared with the one calculated based on the simulation model, *AvgTCu*, this if calculated from the analytical model presents lower values, on average, of 16%. It is also observed that the analytical model always presents for its efficiency measure values that lie between the two efficiency measures estimated from the simulation model.

Finally, through Fig. 10 it can be verified tha the behaviour of *AvgTCu* is identical in both models. However this results analysis lacks confirmation due to small sample size dimension.

5. CONCLUSIONS

This paper shows similar estimated values for the performance measures analysed – system availability and total maintenance cost per time unit, for both simulation model and analytical model, as far as a *Maintenance Float System* with *M*=10, *R*=5 and *L*=5 is concerned. Nevertheless a difference of nearly 15% is noticed. Also, it is quite clear that variance is different for both global efficiency measures analysed, specially when using extreme values for periodic overhauls rates. In this respect, *AvgSav* is the most sensitive parameter. As expected, the least sensitive parameter is *AvgTCu* , as it does not take into consideration the number of available machines, i.e., the cost for production loss is constant, irrespective of the number of available machines in the system.

6. FUTURE DEVELOPMENTS

The simulation model here presented, incorporating analysis of usual performance measures, also drives its concern towards new efficiency measures, enabling new trends for the analysis and discussion of the best decisions as far as a specific *Maintenance Float System* is concerned. Nevertheless the authors are now aiming to the development of an advanced simulation model, incorporating flexibility. This target would be reached by developing and incorporating new modules in our simulation tool, following past experiences found on literature (Luís S Dias, 2005, 2006 and Vilk, P., 2009, 2010) where the automatic generation of simulation programs enables desired model flexibility, i.e., making the model generating specific simulation programs for specific *Maintenance Float Systems*. These mentioned future developments also intend to potentiate the known capability of simulation to efficiently communicate with managers and decision makers, even if they are not simulation experts.

REFERENCES

Alam, Fasihul M.; McNaught, Ken R. and Ringrose, Trevor J. (2003), “Developing Simulation Metamodels for a Maintenance Float System”, AMORG, Engineering Systems Department, Cranfield University, RMCS Shrivenham, Swindon SN6 8LA, UK

Chen, M. C. and Tseng, H. Y. (2003), "An approach to design of maintenance float systems," Integrated Manufacturing Systems, vol. 14, pp. 458-467.

Dias, Luis M. S; Rodrigues, A. J. M. Guimarães; Pereira, Guilherme A. B. (2005), An Activity Oriented Visual Modelling Language with Automatic Translation to Different Paradigms, Proceedings of the 19th European Conference On Modelling And Simulation (ECMS 2005), Riga, Letónia. Ed. Yury Mercuryev et al. Junho de 2005. pp. 452-461

Dias, Luis S; Pereira, Guilherme A. B. and Rodrigues, A. J. M. Guimarães (2006), “A Shortlist of the Most ‘Popular’ Discrete Simulation Tools”, ASIM 2006 - 19th Symposium on Simulation Technique. SCS Publishing House. Ed. M. Becker and H. Szczerbicka. Hanover, Alemanha. pp. 159-163.

Dias, Luis S.; Pereira, Guilherme A. B. and Rodrigues, A. J. M. Guimarães (2006), “Activity based modeling with automatic prototype generation of process based arena models”, EMSS 2006 - 2nd European Modeling and Simulation Symposium. Barcelona, Espanha. pp. 287-296

Gupta, V. and Rao, T. (1996), "On the M/G/1 machine interference model with spares," European Journal of Operational Research, vol. 89, pp. 164-171.

Gupta, S. M. (1997), "Machine interference problem with warm spares, server vacations and exhaustive service," Performance Evaluation, vol. 29, pp. 195-211.

Ingalls, Ricki G. (2001), "Introduction to Simulation", in Proceedings of 2001 Winter Simulation Conference, B.A. Peters, J.S. Smith, D.J. Medeiros, and M. W. Rohrer, eds.

Kelton, W. David; Sadowski, Randall P. and Strurrok, David T. (2004), "Simulation With Arena", (3rd edition), McGraw-Hill, (1998-2004).

Kuei, C. H. and Madu, C. N. (1994), "Polynomial metamodelling and Taguchi designs in simulation with application to the maintenance float system," European Journal of Operational, Reseach, vol. 72, pp. 364-375.

Lopes, Isabel S. (2007), "Técnicas Quantitativas no Apoio à Decisão em Sistemas de Manutenção", Tese de Doutoramento, Universidade do Minho.

Lopes, Isabel S.; Leitão, Armando L. F. and Pereira, Guilherme A. B. (2005), "Modelo de Custos de Manutenção para um Sistema com M Unidades Idênticas", in C. G.Soares, A. P. Teixeira e P. Antão (eds), Análise e Gestão de Riscos, Segurança e Fiabilidade 2: p 603-620, Lisboa: Edições Salamandra (ISBN 972-689-230-9).

Lopes, Isabel S.; Leitão, Armando L. F. and Pereira, Guilherme A. B. (2006), "A Maintenance Float System with Periodic Overhauls", in Guedes Soares & Zio (eds), Safety and Reliability for Managing Risk 1: p 613-618, London: Taylor & Francis Group (ISBN 0-415-41620-5).

Madu, C. N. and Kuei, C. H. (1992a), "Group screening and Taguchi design in the optimization

of multi-echelon maintenance float simulation metamodels," Computers and Operations Research vol. 19, pp. 95-105.
Madu, C. N. and Kuei, C. H. (1992b), "Simulation metamodels of system availability and optimum spare and repair units," IIE Transactions, vol. 24, pp. 99-104.
Madu, C. N. and Lyeu, P. (1994), "On the use of simulation metamodeling in solving system availability problems," Microelectronics Reliability, vol. 34, pp. 1147-1160.
Madu, I. E. (1999), "Robust regression metamodel for a maintenance float policy," International Journal of Quality & Reliability Management, vol. 16, pp. 433-456.
Mamede, Nuno (1984), "Simulação Digital de Processos", Tese de Mestrado em Engenharia Electrotécnica e de Computadores (Telecomunicações e Computadores), Instituto Superior Técnico.
Pegden, C.D.; Shannon, R. E.and Sadowski, R. P. (1990) "Introduction to Simulation Using SIMAN, McGraw-Hill", New York, USA. v. 2. 1990.
Pidd, Michael (1989), "Computer Modelling for Discrete Simulation", (Editor), Wiley.
Pidd, Michael (1993), "Computer Simulation in Management Science", Third Edition, Wiley.
Peito, Francisco; Pereira, Guilherme; Leitão, Armando; Dias, Luís (2011), "Simulation as a Decision Support Tool in Maintenance Float Systems" ,17th European Concurrent Engineering Conference (ECEC´2011). London, England. pp.68-74.
Rodrigues, Guimarães and Carvalho, Valério (1984), "CAPS - ECSL, Experiência de modelagem e simulação aplicada a um sistema de elevadores", Relatório Técnico, Universidade do Minho.
Rubinstein, Reuven Y. and Melamed, Benjamin (1998), "Modern Simulation and Modeling", Wiley Series in Probability and Statistics, Applied Probability and Statistics Section, A Wiley-Interscience Publication, John Wiley & Sons, INC., ISBN 0- 471-17077-1.
Shannon, Robert E. (1998), "Introduction to the Art and Science of Simulation", in Proceedings of 1998 Winter Simulation Conference, D.J.Medeiros, E.F. Watson, J.S. Carson and M.S. Manivannan, eds.
Shankar, G. and Sahani, V. (2003), "Reliability analysis of a maintenance network with repair and preventive maintenance," International Journal of Quality & Reliability Management, vol. 20, pp. 268-280.
Vik, P.; Pereira, G. and Dias, L. (2009), "Software Tools Integration for the Design of Manufacturing Systems", Proceedings of the Industrial Simulation Conference, Loughborough, eds. Diganta Bhusan Das, Vahid Nassehi and Lipika Deka, pp 127-131
Vik, P.; Dias, L. and Pereira, G. (2010), "Automatic Generation of Computer Models Through the Integration of Production Systems Design Software Tools". ASMDO2010 - Third International Conference on Multidisciplinary Design Optimization and Applications. Paris (France)
Vik, P.; Dias, L.; Pereira, G. and Oliveira, J. (2010), "Improving Production and Internal Logistics Systems – An Integrated Approach Using CAD and Simulation". ILS2010 - 3rd International Conference on Information Systems, Logistics and Supply Chain - Creating value through green supply chains. Casablanca (Morocco), April 14-16.
Zeng, A. Z. and Zhang, T. (1997), "A queuing model for designing an optimal three-dimensional maintenance float system", Computers & Operations Research, vol. 24, pp. 85-95.

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