

# **A life-cycle system dynamics model of aircraft-engine maintenance**

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## **Abstract**

*The purpose of this paper is to describe the development and use of a framework for studying the dynamics of the maintenance system of a fleet of military-aircraft engines in a holistic way, as far as both time and place are concerned. The framework is based on a modular system dynamics simulation model of all the inter-related systems, which are involved throughout the life-cycle of the engines (preventive maintenance, repair maintenance, factory-level maintenance, maintenance human resources management, spares management and engine disposal). The proposed model can be used for understanding the complex relationships among the systems and their elements, for evaluating vendor proposed maintenance systems, as well as for developing effective maintenance strategies.*

**Keywords:** *Maintenance system, maintenance policy evaluation, system dynamics application*

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## 1. Introduction

The maintenance of technical systems has been an old problem, which has received considerable attention equally by many researchers and practitioners. For the vast majority of these studies, the focus of interest has been purely operational, i.e. how to schedule and mix preventive maintenance (PM) with corrective maintenance so that the costs of idle equipment (or, generally, the overall system's performance deterioration) on the one hand, and repairs on the other, are minimized. Factors such as age and utilization of equipment, personnel productivity, and range of skills and maintenance-department productivity have been taken into account as stochastic variables with constant or variable parameters (Sherif and Smith, 1981; Valdez-Flores and Feldman 1989; Gopalakrishnan et al, 1997; Cho and Parlar, 1991). Mathematical programming techniques of varying complexity (single - or multi-criteria decision making) have been used for the optimization of a variety of stochastic Markov models (Hosseini et al 1999; Gopaldaswamy et al, 1993). As far as the practice of maintenance is concerned, a number of tools have been developed to help maintenance engineers and managers with their every-day planning and control tasks (Pintelon and Van Wassenhove 1990; Majstorovic 1991; Marteel et al 1993). Certainly, a well-scheduled preventive maintenance program can reduce costly breakdowns and hence deciding what sort of PM to do and when, constitutes an important operational decision. However, maintenance decisions have to be made at the strategic level too, i.e. at the time a system is designed, installed or, more generally, when its operations strategy is determined. When a new system is designed or selected for installation, the consideration of maintenance plays an important role on the final choices made. An apparently cheap system may require intense and expensive maintenance resources, which burden heavily its cost of operation throughout its life-cycle. On the opposite, what it looks like an expensive system may be associated to a lean maintenance system, reducing its overall cost of operation. As far as strategic maintenance decisions are concerned, in general, the emphasis is given on the cost-effective selection, deployment and management of assets and capabilities (e.g. the recruitment and training policies for maintenance personnel over the life-cycle of the system) which are necessary for effective maintenance with respect to the systems long-term operating requirements, and which, in some cases, may provide the source for competitive advantage. Tsang (2002) identified four strategic dimensions to maintenance management: service-delivery options, organization and work structuring, maintenance methodology and support systems and the importance of human resources and information flows in achieving the strategic objectives of maintenance was emphasized. In the same line, Horner et al (1997) and Sterman (2000) demonstrated the strategic importance of the choice of overall maintenance policy (preventive vs. corrective maintenance vs. condition-based) for different industries, while Coyle and Gardiner (1991) and Gopaldaswamy et al, (1993) showed the importance of embedding maintenance in the general operations strategy of the organization.

At the strategic level, decision-makers should understand the dynamics of the evolution of the maintenance system over time, as well as the medium- to long-term effects of the feedback loops, which are formed by the different sub-systems and their elements, which may operate in different departmental and organizational contexts and with a variety of objectives (Jambekar 2000; Sherwin 2000). In addition, the focus of attention

at this level is on the rates of flow and accumulation of the system elements (equipment, spare parts, personnel) over time, rather than on the occurrence and timing of individual events (e.g. the exact time of arrival of an engine at the maintenance department, the probability of individual failures, etc.)

The procurement of military aircraft is a very complex and enormously expensive decision in which, in addition to the technical specifications, the life-cycle operating cost and availability of the airplanes should be taken into account. The maintenance requirements and their associated policies for both the airplanes and their engines are of crucial importance and constitute decisive selection criteria. Therefore, understanding the dynamics of the life-cycle maintenance system as a whole is of vital economic and defense strategy importance.

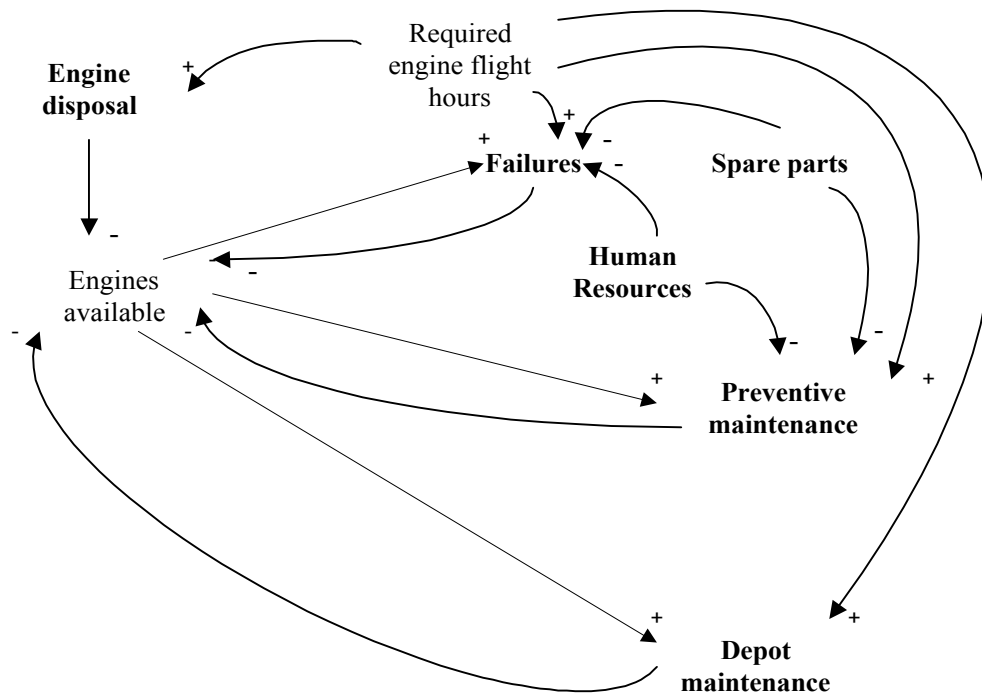
The contribution of this paper is towards this end. Unlike other contributions (Kumar 1999; Cini and Griffith 1999; Sandberg and Stromberg 1999) which view the problem from the manufacturer's/vendor's perspective, i.e. how to produce an aircraft with a specific maintenance system, or see only parts of the problem (e.g. Alfares 1999), our approach is from the user's perspective, i.e. what are the implications of different maintenance systems on the user's organization. Using a systems approach, we first describe the maintenance operations that take place throughout the engines lives within the framework of the operations of a fleet of military aircraft. Then, we present a system dynamics model of the generic maintenance system calibrated using hypothetical data, which we then use for the analysis of different policies regarding operations conditions, maintenance policy and personnel mobility. The model can be used by policy makers and planners who are responsible for the purchase and operation of a fleet of military aircraft, to understand the maintenance-related parameters, which influence the operational dynamics of the fleet throughout its life cycle. In addition, the model can be used for the evaluation of different maintenance systems proposed by different engine vendors.

## **2. Description of the problem**

A typical life-cycle system of a fleet of aircraft engines can be thought to consist of six sub-systems, which are inter-related as shown in the cause-effect diagram of figure 1. The engines available, the required flight hours and the rate of failures are the parameters according to which the specifics of the six sub-systems should be adjusted for the effective operation of the whole system. Following, we briefly describe the operation of the six sub-system components.

### ***2.1 The planned (preventive) maintenance system***

An engine, once bought from a manufacturer, enters a period of fleet service. During this period the engine is supported by its parent base, while carrying out operational duties. Every time an engine reaches a pre-defined level of usage (flying hours), it is taken off the aircraft and undergoes preventive maintenance within the premises of the organization. After the maintenance activities are completed, the engine enters a new fleet service period.



**Fig. 1. The aircraft-engine management system**

### **2.2 The reactive (repair) maintenance system**

When a failure is detected before the predefined usage level has been reached, the engine is grounded, taken off the aircraft and the necessary repairs are accomplished again, in the premises of the organization by its maintenance personnel.

### **2.3 The factory-level (depot) maintenance system**

When the engine reaches a predefined long-term level of usage, the engine is taken off the aircraft and sent to a certified contractor for factory-level maintenance. There, a detailed inspection of the engine is carried out and repairs and replacements of worn out components take place.

### **2.4 The engine disposal system**

There is a (rare) possibility that an engine exhibits a malfunction, which cannot, or is not feasible economically, to be repaired. The engine is withdrawn, decommissioned and possibly disposed.

### **2.5 The spares management system**

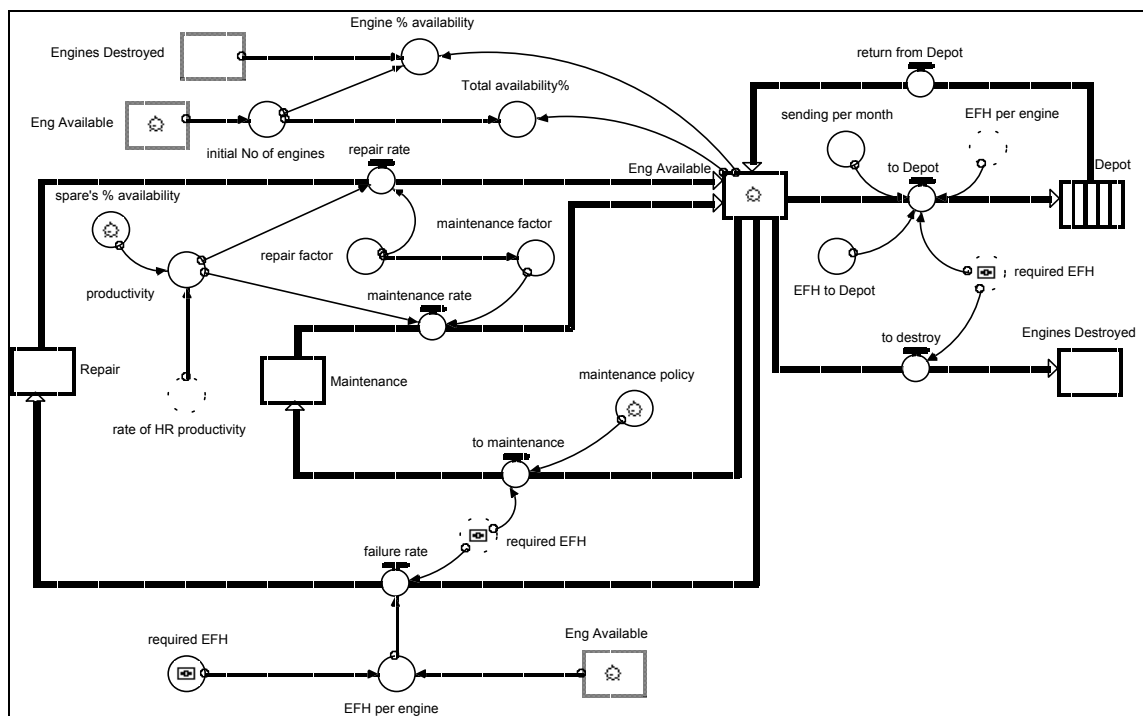
The maintenance (both scheduled and unscheduled) of aircraft engines is supported by spare parts, which are stocked within the facilities of the maintenance department. When the replacement of a part is required, a spare from the stock is used. The damaged part is usually sent to the appropriate repair facility, from where, after the repair (when the repair is feasible), is sent back to replace the stock. Usually, the stocked spare parts cover 90% of the possible problems.

## 2.6 The human resources management system

The maintenance department employs a number of permanent specialized engineers and technicians. Still, the effective number of every day personnel is reduced by absences due to illness, training or vacations. In addition, some maintenance personnel leave the organization permanently for various reasons (retirement, different job, etc). Hence, the organization has to plan for the hiring and training of new personnel. In our consideration, it is assumed that all the engineers and technicians can undertake any maintenance task. Their continuous involvement in the maintenance of the same type of engines, results in the accumulation of experience and knowledge, which, in turn, results in the increase in the department's productivity, which shortens the maintenance lead times.

Having in mind the above, the organization is interested in evaluating holistic maintenance policies to support the operational requirements of the fleet of airplanes in a cost effective way, by employing the necessary number of trained personnel and by keeping the required stock of spare parts. In addition, the organization is interested in understanding the dynamics and the operational limits of its maintenance system in order to plan different organizational structures when the flight demand changes.

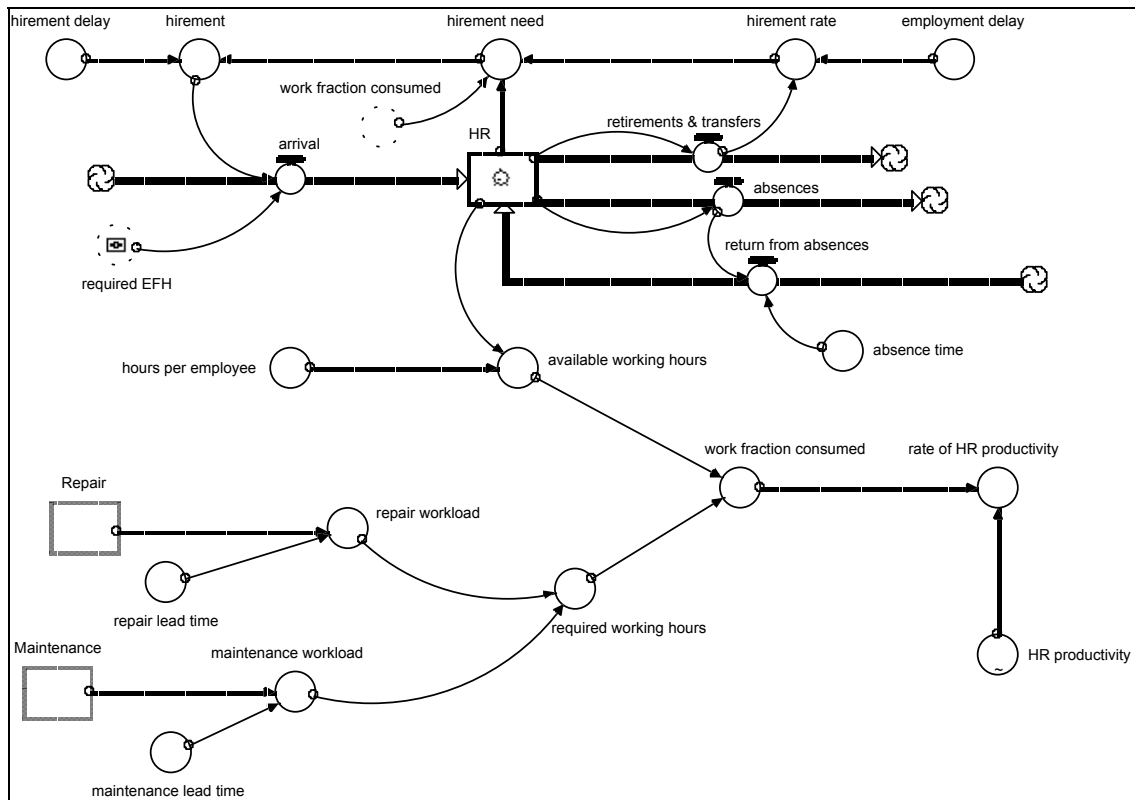
## 3. The system dynamics model of the aircraft engine maintenance system



**Fig. 2. The system dynamics model for the life-cycle maintenance of a fleet of military aircraft engines**

Figure 2 above shows the system dynamics simulation model developed for the life-cycle maintenance of a fleet of military aircraft engines. The model and the sub-models were developed using the i-think<sup>®</sup> system dynamics software simulation package (Analyst version 6.0.1). The model was initially calibrated according to the following vendor and operational requirements.

Every month the whole fleet consumes on average 700 flight hours (EFH) in total. According to the manufacturer, a fleet service period ends when the engine has completed 200 EFH. Every month, on average, four (4) engines enter the scheduled maintenance department. The number for engines requiring unscheduled maintenance depends on the engine usage and distress since the more an engine flies the more its probability of failure increases. However, both the engine repair and engine maintenance rates depend on the personnel (HR) productivity, along with the level of spare parts availability. Maintenance activities are carried out by a total of 25 engineers and technicians employed by the organization. The contractor, performing the factory level maintenance, has a capacity of inspecting up to 8 engines simultaneously. There, the maintenance activities last 6 months on average, after which the engine returns to its parent base. As mentioned above, engine disposal is a rare phenomenon and depends on the engine usage. As far as human resources are concerned (Figure 3), a monthly absenteeism rate of 10% and a 10% rate of withdrawal on a yearly basis are assumed. Every employee, after having completed the necessary training (which lasts about 6 months) can start working in the maintenance department, accumulating experience and knowledge, and contributing to the decrease of the maintenance and repair lead times which consume in average 500 and 800 man-hours, respectively. The overall productivity of the maintenance department depends on the rate of productivity of human resources and the availability of spare parts and is cast to the maintenance and repair activities. The specific equations, which govern the dynamic behaviour of the model, are given in the Appendix.



**Fig. 3. The system dynamics model for the productivity of the personnel involved in the maintenance of a fleet of military aircraft engines**

The overall system dynamics model consists of three balancing loops which result in the reduction of the available engines whenever an engine undergoes maintenance of in any form. The factors, which contribute to the increase of the number of available engines, are the availability of spares and human resources. On the contrary, the number of available engines is reduced with the increase of the required engine flight hours per month (EFH/mo).

**TABLE I. Model Variables**

<b>Performance metrics</b>	Engines Available
	Total Cost
	Performance Factor
<b>Decision Variables</b>	Initial No of Engines
	Human resource (HR)
	Spare Availability
	Maintenance Policy
<b>Constraints</b>	Engine Flight Hours (EFH)

The model variables can be classified into *design parameters* (which are the decision variables), *performance metrics* or *countable parameters* (flows produced by the system), and *constraints* (the required engine flight hours) (Table I).

The design parameters (Table II) are:

- The number of engines bought initially from the manufacturer
- Human Resources (the number of employees)
- Maintenance policy (time intervals between scheduled maintenance)
- Spare Availability (the percentage level of spares available for installation when requested)

**TABLE II. System Design Parameters**

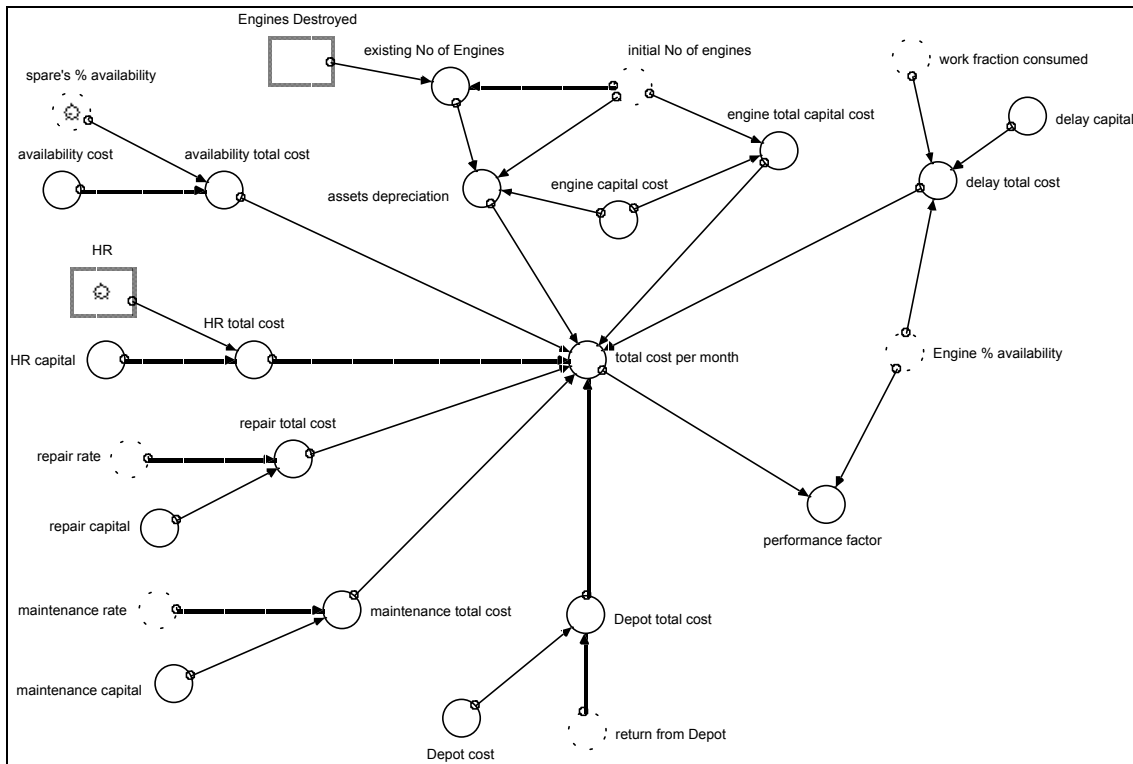
<b>Design Parameters</b>	<b>Values</b>
Engines Available (Eng)	40-45-50
HR (employee)	20-25-30
Maintenance Policy (EFH)	100-200-300
Spare Availability (%)	70-80-90-100

The combination of the above values results in different policies whose analysis is used for evaluating the system's behavior and for implementing various systemic interventions by setting the values of converters and flows.

- The parameters measured during and after completing each simulation are:
- The percentage of engine availability (Eng % Avail) in the end of every time interval (for the specific system is a month)
  - Total cost per month (i.e. the sum of the individual costs)
  - The overall system's performance factor, which is a metric introduced to reflect the ratio of percentage availability to the total cost required in achieving the particular availability.

Although for the operational performance measurement of the maintenance function quite sophisticated measurement systems, such as ABC and Balanced Scorecard, seem necessary (Mirghani 2001; Tsang 1998), the above simple measurements constitute a sufficient measurement system for the purposes of the adopted level of strategic analysis.

Figure 4 below shows the network of cost variables, which contribute to the evaluation of the total operational cost.



**Fig. 4. The calculation of the total cost per month as the result of the performance of the different maintenance activities on the fleet of military aircraft engines**

The actual meanings of the values of the three performance metrics are shown in Table III.



**TABLE III. System variable classification**

Factor	Range	Meaning
Engine Availability	0 - 70%	Low availability
	70% - 85%	Medium availability
	85% - 100%	High availability
Total cost	0 – 9 millions	Low cost
	9 - 10 millions	Medium cost
	Over 10 millions	High cost
Performance Factor	0 – 0.075	Low performance
	0.070 – 0.085	Medium performance
	Over 0.085	High performance

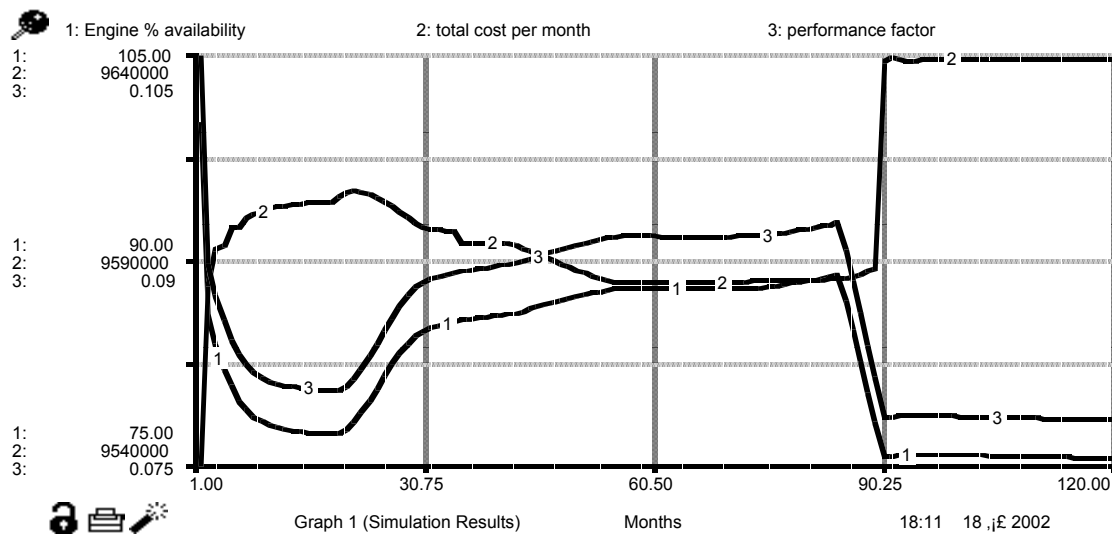
All the simulations of the model have been run for a period of 10 years (120 months). This period may not be the entire life-cycle for the majority of the engines, but during this period, most of the engines of the fleet will have gone through the depot maintenance and will have returned to the organization. So, the life-cycle of the engines should be easily considered as a set of consecutive such periods.

It should be noted that our model was validated using real data whose source and exact values are not specified in this paper for obvious reasons.

#### 4. The use of the model

##### 4.1 Keeping the same organizational parameters

Figure 5 shows a typical pattern of simulation output of the model with the initial set of parameters (Engines available: 45, Human Resources: 25 employees, maintenance policy: 200 EFH, and spares availability: 90%).

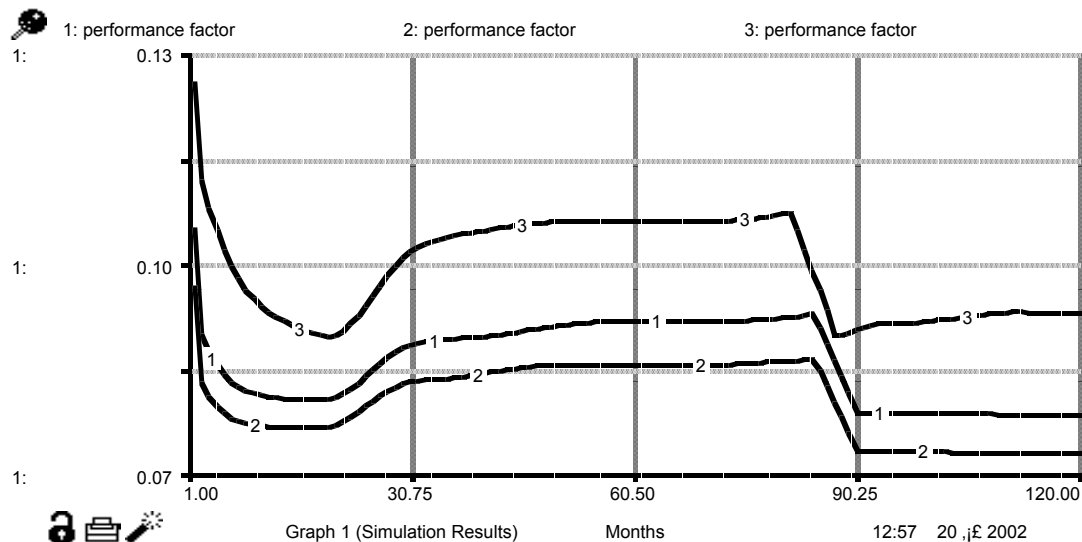


**Fig 5. Typical output of a simulation run with the initial set of parameters**

The three traces in the diagram show the progressive variation in engine availability, total cost and overall performance factor. The values of the first two parameters determine the overall performance factor, which was multiplied by  $10^3$  in order to harmonize its scale with the other two diagram scales.

The diagram shows an initial progressive increase in the engine availability with a simultaneous decrease in total cost, which result in an increase of the overall performance factor. Later, however, (just before the 90<sup>th</sup> month) an inversion of the above values is observed, which results in a decrease of the performance factor. This is because at this stage the engines begin to complete the Depot limit (1500 EFH) and they are removed and sent for major maintenance activities.

Keeping the same organizational parameters, the sensitivity analysis performed indicated that not all other parameters contribute equally to the system's behavior and robustness. Figure 6 shows the variation of overall system performance when different policies are implemented. Trace 1 presents the performance of the system with the initial parameter settings. As it can be easily seen, a better engine availability is achieved if the spare parts availability is increased. However, this is not a cost effective policy since it results in a higher total cost per month (required for maintaining the increased spare parts availability), and consequently in a lower overall performance factor (trace 2). A more cost effective decision (trace 3) is to increase the time intervals between scheduled maintenance from 200 to 300 EFH, and simultaneously to decrease the spare parts availability. This means that a supplier, whose engines require preventive maintenance at longer time intervals and who can provide fast response to spares parts shortages (the organization need not stock large amounts of spare parts), is in an advantageous position.



**Fig. 6.** The behavior of the performance factor under different maintenance policies

Table IV summarizes the effects of different policies of schedule maintenance and spares availability of the performance metrics of the system.

**TABLE IV. Effects of different maintenance policies**

<b>Engines</b>	<b>HR</b>	<b>Scheduled Maintenance time intervals (EFH)</b>	<b>Spares Availability %</b>	<b>Engines Availability %</b>	<b>Total cost per month (\$*100)</b>	<b>Performance factor</b>
45	25	300	70	70.11	8,034	0.087
45	25	200	70	68.31	8,046	0.085
45	25	300	80	74.52	8,825	0.085
45	25	300	90	79.53	9,610	0.083
45	25	200	80	72.39	8,838	0.082
45	25	200	90	77.31	9,624	0.080
45	25	300	100	81.45	10,407	0.078
45	25	100	70	62.25	8,084	0.077
45	25	200	100	79.27	10,420	0.076
45	25	100	80	65.53	8,879	0.074
45	25	100	90	68.90	9,671	0.071
45	25	100	100	70.55	10,468	0.067

#### ***4.2 Implementation of different organizational structures***

For the case when the organization is interested in implementing different internal structures (as far as total number of engines and human resources are concerned), each parameter has to be weighted, since, as it is clearly understood, an optimum decision does not exist, but instead, a spectrum of possible alternative structures can be implementing, each improving the system in a different way.

As mentioned above, not all the decision variables (engines, HR, maintenance policy intervals, spares availability) affect the system's sensitivity and robustness in the same way. Table V summarizes the effect of alternative decisions as far as the number of available engines, the number of total personnel available, the periods between preventive maintenance and the spares availability are concerned.

As detected, the only parameter with a normal variation is spares availability, since a proportional increase in spares availability results in a corresponding increase both in the engine availability and in the total cost per month. Varying the total number of engines has a positive effect only when the value is increased form 40 to 45. The same effect is not observed when the organization decides to buy 5 more engines. The same is observed for the time interval between scheduled maintenance.

An interesting fact is the effect of the variation of the number of employees in the organization. Although one should expect an improvement in engine availability with the hiring of a small number of technicians, a remarkable decrease is detected. This is due to the fact that the daily absenteeism rate depends on the overall number employed, so the bigger the number employed, the more the daily absences and the less the engines maintained concurrently.

**Table V. Effects of changes in the system design parameters**

	(Number)	Engine Availability	Total cost per month (\$*100)	Performance Factor
Number of engines (HR: 25, PM: 200, Sp. Avail: 90%)	<b>40</b>	62.96	9,010	0,698
	<b>45</b>	72.78	9,240	0,787
	<b>50</b>	79.90	9,473	0,843

	(Employees)	Engine Availability	Total cost per month (\$*100)	Performance Factor
HR (Eng: 45, PM: 200, Sp. Avail: 90%)	<b>20</b>	76.82	9,220	0,833
	<b>25</b>	71.48	9,244	0,773
	<b>30</b>	67.33	9,260	0,727

	(EFH)	Engine Availability	Total cost per month (\$*100)	Performance Factor
Preventive Maintenance (Eng: 45, HR: 25, Sp. Avail: 90%)	<b>100</b>	66.29	9,273	0,714
	<b>200</b>	73.63	9,232	0,797
	<b>300</b>	75.72	9,219	0,821

	(%)	Engine Availability	Total cost per month (\$*100)	Performance Factor
Spares Availability (Eng: 45, HR: 25, PM: 200)	<b>70</b>	66.92	8,051	0,831
	<b>80</b>	70.82	8,844	0,800
	<b>90</b>	73.77	9,637	0,765
	<b>100</b>	76.01	10,433	0,728

## 5 Conclusions

In this paper we have presented the development of a system dynamics simulation model for the maintenance system of a fleet of military aircraft engines. The model has successfully represented the behavior of integer aircraft engines over a 10-year term operational cycle. In addition, we have shown how the model can be used for the evaluation of different maintenance systems and different maintenance policies at-large. System dynamics theory dictates that any simulation model does not consist an end upon designed, but should be regarded as a means to support the decision making process within the organizational design and change management framework. Moreover, every decision-maker, through the model developed, can analyze a system to a desired level. By considering the cost of the various maintenance activities as an exogenous variable, using the proposed model one can determine the occasional dominant cost variable and define the best system performance. In addition, the quantitative and qualitative point where the maintenance of an engine is no longer cost-effective for the organization can be determined. Furthermore, the time and optimum number of spare engines to be bought to ease the operational needs in case of increased flight demands can also be deduced. The human resources productivity and the consequent improvement in maintenance and repair lead times achieved through the experience and knowledge accumulated, is a very interesting point, which can be

investigated using our model. Finally, and most importantly, it should be noted that the simulations presented were executed using static decisions as far as the system design parameters were concerned. However, it is our view, that the importance of the proposed framework lies in its use as a Management Flight Simulator allowing the users to adjust their decisions according to the observed system behavior.

### **Appendix: The Equation Formulation Aspects**

Every month, 4 engines on average undergo preventive maintenance within the premises of the organization:

$$\textit{To maintenance} = 1.25 * \textit{required EFH/maintenance policy}$$

where 1.25 is a factor introduced to calibrate the above flow.

Upon failure detection before the predefined usage limit is achieved, the engine is taken off and sent for immediate failure compensation. The failure rate is a portion of the operational workload:

$$\textit{Failure rate} = 18 * 10^{-5} * \textit{EFH per engine} * \textit{Required EFH}$$

where  $18 * 10^{-5}$  is a calibration factor too.

The rate of dispatch of the engines for Depot maintenance is:

$$\textit{(EFH to Depot} = 1500)$$

*To DEPOT* = IF (*EFH per engine* \* *time* > *EFH to Depot*) THEN *sending per month* ELSE 0 and

$$\textit{sending per month} = 1$$

The engine disposal is proportional to the engine distress:

$$\textit{To destroy} = 23 * 10^{-6} * \textit{required EFH}$$

As far as Human Resources (HR) are concerned:

$$\textit{HR} = 25$$

$$\textit{Absences} = \textit{ROUND} (\textit{HR} * 0.1) \textit{ και } \textit{Absence time} = 1$$

$$\textit{Return from absences} = \textit{DELAY} (\textit{absences}, \textit{absence time})$$

$$\textit{Retirements \& transfers} = \textit{HR} * 10^{-2}$$

*Hiring need* = IF (*HR* < *INIT (HR) \* 0.9*) OR (*work fraction consumed* > 1) THEN *hiring rate* ELSE 0 and

$$\textit{Hiring rate} = \textit{DELAY} (\textit{retirements \& transfers}, \textit{employment delay}) \textit{ and}$$

$$\textit{Employment delay} = 2$$

$$\textit{Hiring delay} = 6$$

The man-hours consumed for maintenance activities are:

$$\textit{Hours per employee} = 160$$

$$\textit{Available working hours} = \textit{HR} * \textit{hours per employee}$$

$$\textit{Required working hours} = (\textit{Repair workload}) + (\textit{Maintenance workload}) \textit{ where}$$

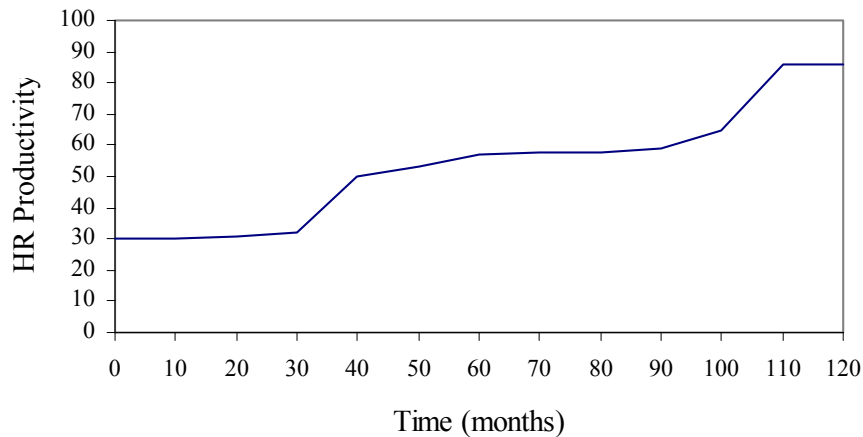
$$\textit{Repair workload} = \textit{Repair} * \textit{Repair lead time} \textit{ and}$$

$$\textit{Maintenance workload} = \textit{Maintenance} * \textit{maintenance lead time} \textit{ where}$$

$$\textit{Maintenance lead time} = 500 \textit{ and } \textit{Repair lead time} = 800$$

$$\textit{Work fraction consumed} = \textit{required working hours} / \textit{available working hours}$$

HR productivity is represented as a function of time:



*HR productivity=Graph of TIME and*

*Rate of HR productivity=work fraction consumed\*HR productivity*

The overall productivity is a function of spare availability and HR productivity:

*Productivity=Rate of HR productivity\*spare's % availability*

The percentage of engine availability is:

*Eng % Avail=(Eng Available/(initial No of engines-Engines Destroyed))\*100*

As far as total cost is concerned, it is the sum of the cost of the individual activities of the organization:

*Total cost per month= assets depreciation + availability total cost + delay total cost + engine total capital cost + HR total cost + maintenance total cost + repair total cost + Depot total cost where*

*HR total cost= HR\*HR cost*

*Availability total cost=spare % availability\*availability cost*

*Repair total cost=repair rate\*repair cost*

*Maintenance total cost=maintenance rate\*maintenance cost*

*Depot total cost=Depot cost\*return from Depot*

*Delay total cost=IF (work fraction consumed>1) THEN delay capital\*work fraction consumed\*(1-(Engine % availability/100)) ELSE (1-(Engine % availability/100))*

*Engine total capital cost=engine capital cost\*initial No of engines*

*Assets depreciation=(engine capital cost/120)\*(initial No of engines- (0.2\*existing No of Engines))*

Finally, the performance factor is the ratio of percentage availability to the total cost, spent to achieve the particular availability:

*Performance factor = Engine % availability/(total cost per month/10000)*

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