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UAV BASED ADVANCED MONITORING SYSTEM: FLEET AND LOGISTIC SYSTEM SIZING BY OBJECT-BASED MODEL AND MONTE-CARLO SIMULATION

Sergio Chiesa*, Marco Fioriti*, Roberta Fusaro*
***Politecnico di Torino**

Keywords: *UAV, logistic, Monte Carlo Simulation, fleet sizing*

Abstract

The article deals with the sizing of UAV fleet, its operations and related logistic support system, in order to guarantee the possibility of performing scheduled and emergency operations. Considering the high-level of complexity and the presence of a high number of stochastic elements, a simulation model is here proposed. The model has been developed exploiting the capability of an object-oriented software and the Monte-Carlo method has been selected as simulation technique. After the description of the methodology used to build the model, some sizing cases are reported and the results analyzed.

1 General Introduction

The aim of this paper is to show an UAV fleet sizing methodology, highlighting the most important results. This sizing activity has been performed within the SMAT (Sistema di Monitoraggio Avanzato del Territorio – Advanced Territory Monitoring System) research program, a project funded by Regione Piemonte e Fondo Europeo di Sviluppo Regionale, now at its second phase. SMAT F2 proposes to study and demonstrate an advanced monitoring system to accomplish with planned tasks and to prevent and monitor different types of emergency (e.g. floods, fires, landslips, terrorism, etc.).

In particular, the research focuses on a fleet of several UAVs belonging to different categories (MALE, MAME, Light, Mini and Micro) and operating from a certain number of possible bases. The aim is to minimize both costs and service losses, maximizing the system effectiveness. Although, the word effectiveness is a widely used term, a proper and in-context definition will be given in a following section. In order to simply introduce the concept, the effectiveness of a system is the parameter that measures the quality of the considered system. As far as a fleet optimization problem is concerned, the effectiveness could be defined as the ratio between the number of successfully completed missions and the number of total requests [1] [2].

Accordingly with the desire of performing sizing estimations of the main elements of this operative and logistic support system, lots of elements should be taken into account in order to describe it properly. In particular, as it has been already highlighted in other works [1][2][3], the fleet, or even better the system, should be characterized in terms of number of aircraft, aircraft performances, aircraft RAM (Reliability, Availability and Maintainability) characteristics, number and location of operative bases, number of maintainers teams, maintainers teams features, infrastructures characteristics, operative environment, operative and logistic costs. The system is also deeply influenced by the number and the type of mission requests and by the scenario and environment in which the fleet is supposed to operate. Considering a real Operative and Logistic System, all the above-mentioned elements are strictly related and characterized by high-levels of uncertainties. For example, it is not possible to define the exact number of emergency calls for floods in a certain period of time, or the number of failures that will affect each UAV. These are only two of the main sources of uncertainties that prevent researches from describing this type of system using classical deterministic models. In order to overcome this problem, stochastic models have been considered and among the most common probabilistic forecasting methods, Monte Carlo Simulation was selected. Moreover, in order to create a tool able to represent all the features of the system and their mutual relationships, an object-oriented software, namely Simio®, has been selected as a platform in order to build the model.

Once the software and the stochastic method have been selected, each important element of the system was studied in-depth, reserving a relevant attention to those characteristics that would have a direct impact on the system effectiveness (Section 2). Then the model has been implemented in Simio®. A detailed scenario has been selected among the mission proposed by SMAT F2 research activities and the simulation results are reported (Section 3). Then, the results were analysed and the main advantages and disadvantages of tool were revealed. In the very last part of this work, general considerations and further improvements to the software are suggested in order to enhance the forecasting capability of the model (Section 4).

2 The system description

The aim of this section is to describe the general features of all the above-mentioned elements that characterize the system. Moreover, the operative environment in which the fleet will operate should be taken into account because it can influence the number of mission required, especially for the emergency calls.

2.1 Mission requests

The basic idea of a project like SMAT F2 is to design and size a fleet of UAV able to guarantee the proper answer to the highest possible number of users. As far as UAVs are concerned, recent market outlooks and every day experience show the increasing interest in the application of this type of aircraft in even more different fields. In particular, this research focuses on the use of UAV to monitor the territory, both in case of scheduled activities and emergency conditions. To identify a realistic scenario, some possible interested users have been interviewed. From the analysis of the possible stakeholder, a list of interesting missions has been drawn up. Among them, some have a precise characterization in terms of number of required aircraft, number of event in a certain period of time (usually one year), required persistency on the target, target location. On the other hand, the interviews revealed the enhancing need of having the capability of being able to operate in case of emergency. In these cases, the exact numbers of events as well as many other parameters are unknown and we are forced to use stochastic distributions in order to describe the system.

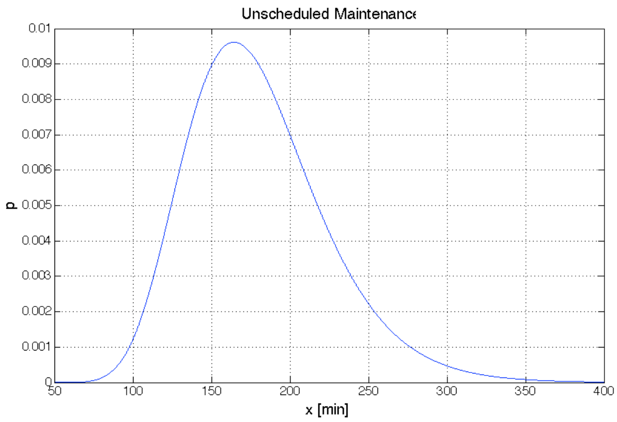

Fig. 1. An example of stochastic Lognormal distribution.

Looking at these information carefully, the customer should understand which type of UAV would better suit the Users needs and evaluating the proper number of aircraft in order to maximize the User satisfaction at the minimum cost. This activities has been completed by other SMAT F2 partners and as a result of the analyses of the present market, some missions have been selected in order to describe a possible real scenario. In particular, it has been imagined that on a national territory (that we supposed to be Italy, indeed), the users could be very interested in:

- the control of the road safety and traffic problem detection and Informability.
- communication network, images and data acquisition in emergency conditions (Avalanche, Flood, Landslide, Fire, Terrorism, etc.).

- Border Surveillance & Critical Infrastructure Surveillance.

For each of these types of missions, some detailed operative scenarios have been identified. The reader should be noticed that also in the case of the second and the third type of missions, both scheduled and emergency activities could be required. Furthermore, it also important to understand that with the term emergency missions, we don't mean the real urgency only but all those activities on which it is not possible to perform precise forecasting.

As far as non-scheduled activities are concerned, the main sources of uncertainties are strictly related to:

- The moment in which the emergency happens.
- The frequency of the events
- The location of the emergency
- The severity of the event

These data are essential to simulate the system and in order to overcome the absolute lack of deterministic data, statistical distributions should be selected and implemented. One of the main advantages of using Simio® as platform to built our model, it is the possibility of using both continuous (normal, lognormal, etc.) and discrete variables, depending on the available data.

2.2 The missions

After the request (for either scheduled or unscheduled activities) has been generated, the system should be able to simulate the mission, mainly in terms of time spent to complete it. To this purpose, after the request has been released, if two or more bases are supposed to be operative, the closest to the target should be selected. Furthermore, the software evaluates the presence of the desired UAV in the selected place; if it isn't available, the following one will be examined. As it is outlined in Figure 2, this process rests both in case the base that hosts the interested aircraft is found and if there is not an available aircraft able to perform the mission. This last event could happen if the software estimates a total duration of the mission (accounting for the all flight phases) is higher than the maximum endurance. In all the cases it is not possible to detect an available aircraft able to accomplish the mission, a penalty is assigned to the system. The value depends on the type of the mission requested in order to take into account the higher level of priority of the emergency missions.

Once the aircraft has been selected, before the mission can start, the maintainers should check if the mounted configuration is the one required for that specific mission. Otherwise, the UAV should be subjected to a preliminary maintenance operation in order to install the required sensors. Then, if the aircraft is in the right configuration, the mission can start.

Remembering that the main focus of this research was the operative and logistic system that would allow the UAV fleet to be operative, there isn't a particular interest in simulating the mission in detail. For this reason, it is only characterized by the time spent from the departure to the landing and for the time estimation, the mission is simply divided into several parts and for each of them the required time is evaluated, according with the characteristics of the aircraft (Specific Fuel Consumption SFC, Rate of Climb, Rate of Descent, Maximum Power, Cruise Speed, etc.).

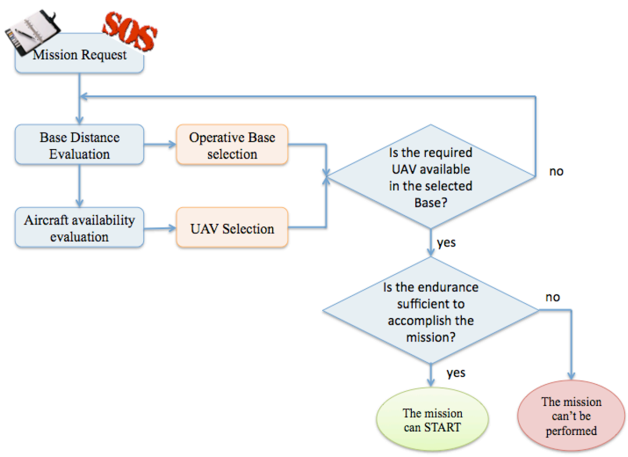

Fig. 2. Base and UAV selection flow-chart

2.3 The fleet

SMAT F2 project want to study a complex fleet system in which there are several UAV belonging to different categorizes. In particular, it focuses on UAVs belonging to one of the following categories: MALE (Medium Altitude Long Endurance), MAME (Medium Altitude Medium Endurance), Light, Mini or Micro. For the purpose of our work, all the studied applications refer to a fleet of only MALE and MAME. Indeed, these two families of UAV present similar characteristics, like the need of a prepared surface (operative base) to perform take-off and landing activities and the required maintenance activity.

Parameter	***Value***
Max take-off weight [kg]	3600
Wing Span [m]	25
Wing Area [m^2]	25
Length [m]	10,2
Engine Type	2 x Piston diesel engine
Engine Power [hp]	2 x 225
Payload Weight [kg]	450
Simultaneous payload [#]	3
Max Speed [km/h]	330
Operational Speed [km/h]	260
Max Endurance [h]	30
Service ceiling [m]	14000
Take-off/landing requirements	Conventional Take-off and landing
Take-off/landing length [m]	1300/800
Communication Type	LOS/BLOS
Environmental Conditions	STANAG 4370

Tab. 1. MALE main characteristics (hypotheses).

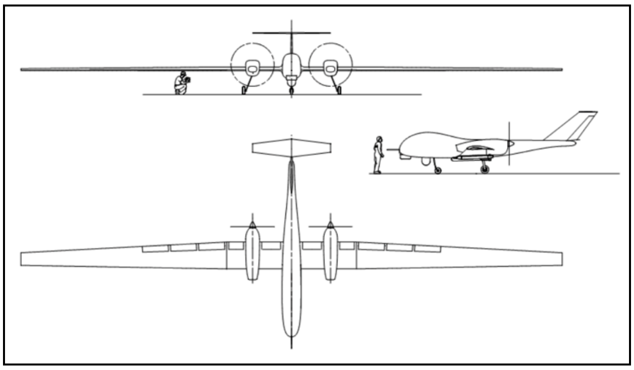

Fig. 3. MALE 3-views sketch.

In Figures 3 and 4, three-views pictures of MALE and MAME are proposed and Tables 1 and 2 reports some of the most interesting and indicative data of these two types of considered UAV.

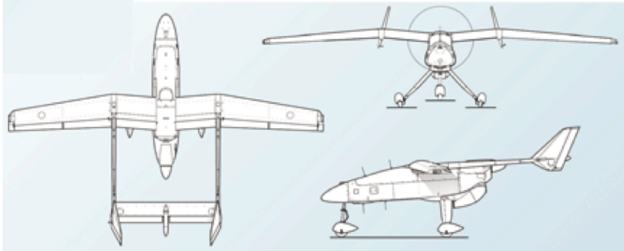

Fig. 4. MAME three-views sketch.

Parameter	***Value***
Max take-off weight [kg]	420
Wing Span [m]	7,20
Height [m]	1,80
Length [m]	5,25
Engine Type	3-blade propeller
Engine Power [hp]	75
Payload Weight [kg]	70
Simultaneous payload [#]	2
Max Speed [km/h]	216
Operational Speed [km/h]	130
Max Endurance [h]	14
Service ceiling [m]	5000
Take-off/landing requirements	Automatic Conventional Take-off and landing or Catapult launch
Link Range [km]	200
Environmental Conditions	STANAG 4370

Tab. 2. MALE main characteristics (hypotheses).

2.4 The maintenance activities

To properly size the real system, maintenance activities cannot be neglected because they introduce a high level of uncertainties. In particular, the duration of each maintenance step and the RAMS (Reliability Availability Maintainability and Safety) characteristics should be properly taken into account [4], [5], [6]. Among these features, MTBF (Mean Time Between Failures) and MTTR (Mean Time To Repair) are considered as input parameter.

Considering a standard operative base, two levels of maintenance are performed:

- field level maintenance that consists of a Pre-Flight Check, a Sensors Configuration Change (if requested) and a Post Flight Check.
- superior level maintenance that includes scheduled and unscheduled operations.

Figure 5 shows the logical sequence of the maintenance activities. Once the mission has been requested and a certain aircraft belonging to a precise base has been selected, the Pre-Flight Check activities are performed. During this maintenance activity, three possible situations may occur. Indeed, maintainers may find some damages or failures and may order additional corrective maintenance activities before the takeoff, the aircraft may to be subjected to change configuration to proper accomplish the mission or the aircraft can be defined ready for the departure.

Similarly, once the mission has been completed and the aircraft has come back to its original base, a Post-Flight Check is immediately, or as soon as possible considering maintainers availability, performed. Then, some failures may be discovered requiring unscheduled maintenance operations. Complementary, if there are no relevant failures, the aircraft can reach the parking, unless scheduled activities will be required [4], [5].

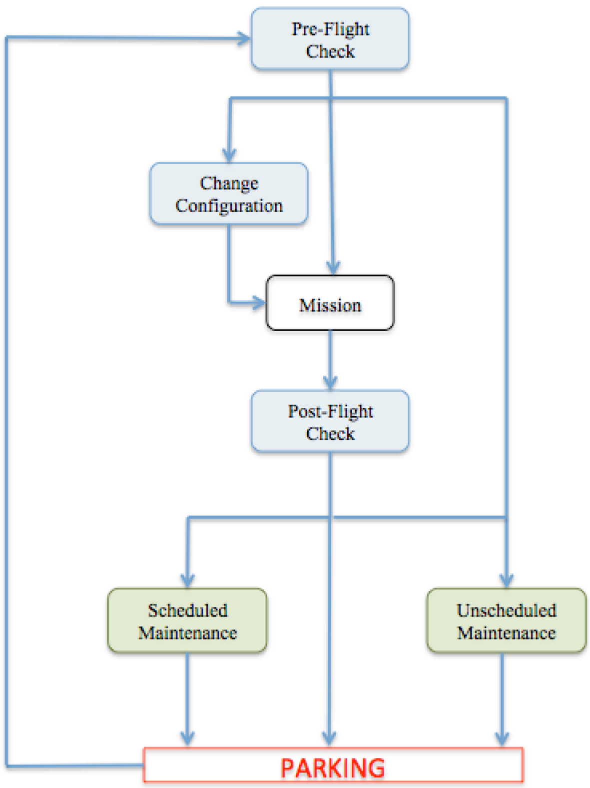

Fig. 5. Maintenance activities overview.

3 Operative and logistic system sizing

In the previous sections, all the most important features of an operative and logistic system have been explained. Moreover, a brief description of the guidelines that led us during the tool building process has been explained. In the present section, the ad-hoc built tool is used to perform the sizing of a specific system.

This application has two main goals: the first is to propose the sizing for a real operative system to make UAVs operative. Moreover, this section of the paper aims to show the main characteristics of this tool, highlighting related advantages and disadvantages.

3.1 Scenario description

The case study has been selected among the scenarios proposed by SMAT F2 project. In detail, this section deals with the simulation of a sizing process involving a single operative base, able to support up to three MAMEs with a consistent number of mission requests: both scheduled and unscheduled. The system will be located in the North Italy and shall guarantee some routines services such as:

- Traffic surveillance on the metropolitan area of Turin, Milan and on the whole North Italy highways network. Accordingly to the local institutions interviewed, this mission requires from 7 up to 12 hours of minimum required period of target observation (depending on the area extension) and has a daily frequency.
- Hydrographic control of the North and Centre Italy in order to prevent floods. This mission is required to be performed twice a month with a period of observation of up to 12 hours.
- Alpine arch avalanche surveillance. It is scheduled only in particular month of the years (when the risk is higher) and it should be performed every three days for at least 7 hours.
- North and Centre Italy landslide prevention. This mission is required to

be performed twice a month with a period of observation of up to 12 hours.

Accordingly with these characteristics and the additional requirements imposed by the stakeholders, the customer should elaborate these input data editing a sequence table. In addition, the system should be able to guarantee some services also in case of emergency. In this case, among all the possible types of non-scheduled requests, the following missions have been considered:

- Traffic control emergency of Turin and Milan metropolitan Area
- Fire emergency on North and Centre Italy
- Floods emergency on North and Centre Italy
- Landslide emergency on North and Centre Italy

3.2 Scenario simulation: Results and Analysis

The system has been simulated for an operative period of 4 months. This period of time has been selected in order to produce meaningful outputs (highlighting seasonal effects too) avoiding excessive computational efforts. The base has been set in Piacenza (LAT. 45,05°; LON: 9,7°) but further consideration on the selection of the base location will be reported later.

Fig. 6. North Italy Map

The first aim in order to size the UAV fleet is to verify the minimum number of aircraft able to perform at least the 85% of the missions that are requested in the reference period. This threshold level has been selected in order to guarantee the maximum level of satisfaction for the stakeholder.

To this purpose, the system has been simulated with the presence of one, two or three aircraft accounting for the same maintenance system configuration (that will be describe later in this section). The following table summarizes the different level of effectiveness as a function of the number of available aircraft. The second column reports an estimation of the effectiveness parameter accordingly to the following equation [1], [2]:

$$E = \frac{\#\, missions\ performed}{\#\, missions\ required} \qquad (1)$$

Number of aircraft	*Effectiveness*	*Status*
1	24.86 %	Non acceptable
2	51.71 %	Non acceptable
3	88.82 %	**Acceptable**

Tab. 3. Effectiveness Levels

The table reveals that the higher is the number of available aircraft, the higher is the effectiveness of the system. Furthermore, the simulations performed suggest that the minimum number of aircraft to accomplish the above-stated requirement is three. In order to create a user-friendly tool, all these general results are visible in a specific window as it can be seen in Figure 7. It summarizes all the important mission data, highlighting the details about the type of requests and of performed or loss missions.

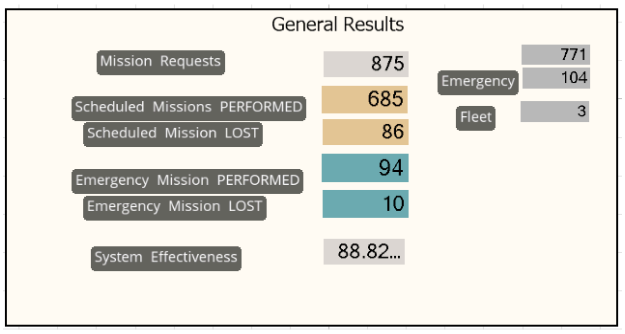

Fig. 7. General Results window.

Figure 7 shows also that the percentage of emergency mission lost is lower if compared to the percentage of scheduled mission lost. This is mainly due to the capability of the tool of recognizing the different priority levels of the requests. Obviously, the emergency requests have a higher level of priority and to this purpose a proper logic has been implemented. Moreover, this is a clear example that shows also the parametric capability of the tool.

A part from the number of available aircraft, the system effectiveness is deeply influenced by other elements of the system. For example, the location of the operative base can be considered strategic for the evaluation of the distances that the aircraft should cover before and after the target observation period. For this simulation, Piacenza has been selected for its central location, allowing the aircraft to reach the different targets requested. Different solutions (among them, Levaldigi, in the north-western part of Italy and Istrana in the north-eastern part) have been tested. As a result, it has been seen that, for this specific scenario that includes events that could happen both in the North and Centre of Italy, Piacenza revealed the highest level of effectiveness. This is another clear example of the usefulness of a parametric tool.

Figure 8 highlights another important aspect that can influence the level of effectiveness of the system. It represents the number of missions performed by each aircraft during a simulated period of a week. This has been done for to enhance the comprehension only. While the x-axis has no physical value but only represents the sequential number assigned to each requests, the y-axis represent the duration of each mission. The value, which is reproduced through the simulation, depends not only on the required period of observation of the target. It is deeply affected by the performance of the aircraft and from the relative distance between target and operative base, which represents both the starting and the ending point. Furthermore, the mission can end before it has been complete, because of a failure occurred when in flight as it is shown in Figure 8. Once the number of aircraft is set (we selected 3), the model can be used to verify other peculiar aspect of the system and to size the operative and logistic base mainly in terms of maintainers.

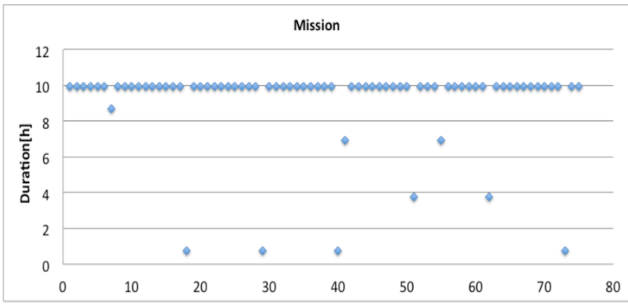

Fig. 8. Failures effect on missions.

In particular, each team of workers can stay in three different operative modes: Busy, Idle, Off Shift. In accordance with the input data that have been inserted in the model (see Figure 9), there are 3 shifts of 8 hours each.

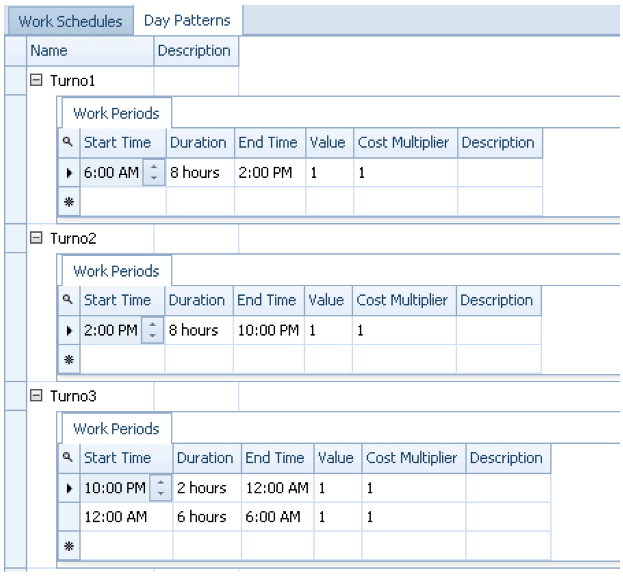

Fig. 9. Work schedules definition on Simio®.

Using the output data available after the simulation, the user can easily verify the level of occupation of the single maintenance team. Considering the 1st level maintenance team, each shift can be composed of three workers: a maintainer devoted to the refueling, one for the aircraft movements operation and another one for performing general inspections. Conversely, if the 2nd level maintenance activities have to be performed, the team should account for at least 4 people, a propulsion specialist, a structure/mechanical specialist, an electro/avionic specialist and one person dedicated to the payload.

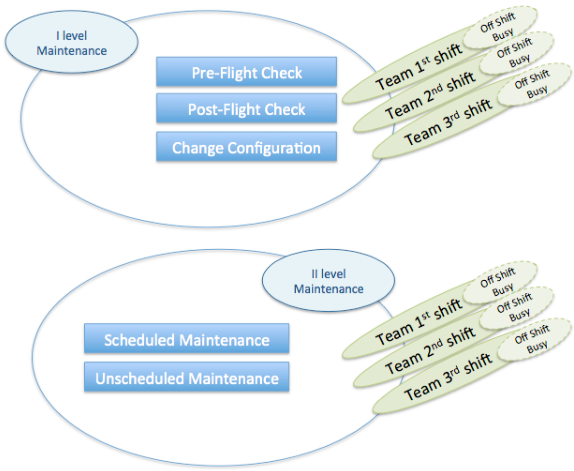

Fig. 10. General organization of maintenance activities.

In general, both for I or II level activities, the characteristic duration of each maintenance step has been defined accounting for a global characteristics MMH/FH=3 (Maintenance Man Hour / Flight Hours). This value that has been inserted as input has been verified with simple calculations at the end of the simulations, with a reversal engineering approach and referring to literature studies [6] . In particular, failure rates and other important RAMS characteristics have already been evaluated in a previous activity performed within the first phase of SMAT project [7] [8].

In order to summarize the results of the simulation performed for the maintainers, pie charts have been used. Figures 11, 12 and 13 graphically describes the occupation of the I level maintenance team during their scheduled period of work. The here presented output data refer to the entire period of simulation. It can be noticed that there is a difference among the distributions of work and it is mainly due to the effect of Saturdays and Sundays, where there is a different work schedule. Indeed, on Saturdays, we assume the absence of the third shift and on Sundays, the presence of the first shift only. For this reason, Figure 11 presents the highest level of occupation, while Figure 13 reveals the lowest one. The same effect can be noticed also in II level maintenance activities.

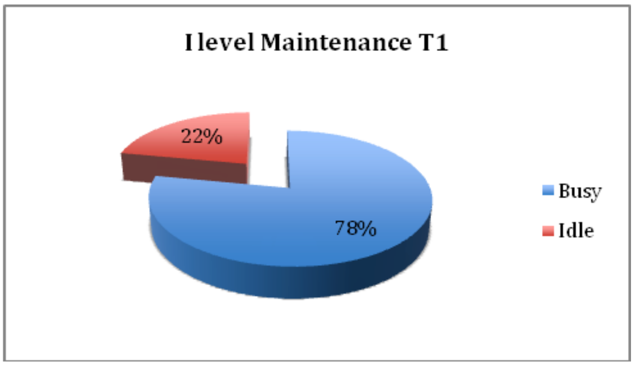

Fig. 11. Occupational levels for I level maintenance worker during T1.

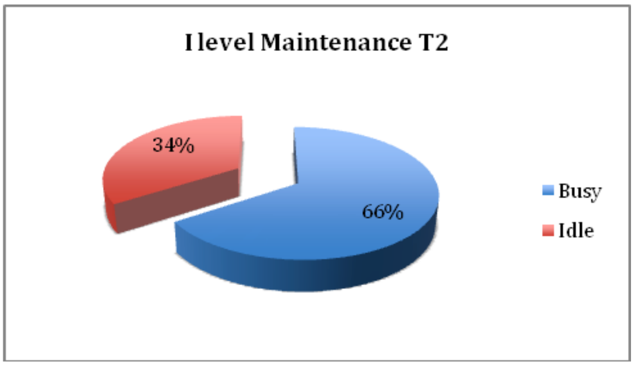

Fig. 12. Occupational levels for I level maintenance worker during T2.

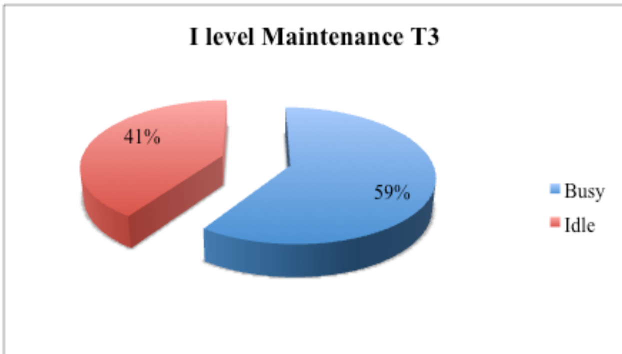

Fig. 13. Occupational levels for I level maintenance worker during T3.

These pie charts refer to a simulation that accounts for three MAMEs. If a smaller number of aircraft is available, the idle periods would be more relevant and this has negative effects on the effectiveness of the system and on its level of efficiency. Thus, the presence of 3 vehicles in the base can be considered an optimal choice, for both system effectiveness and efficiency. This is highlighted in Figure 14, where the level of occupation for the same maintenance team has been simulated in case of a single aircraft available in the system and compared with the case in which the whole fleet of 3 MAME is available.

The same considerations can be done for the second level maintenance in which scheduled and unscheduled activities are concerned. Also in this case, three aircraft appear to be the optimal number to obtain the right occupational level.

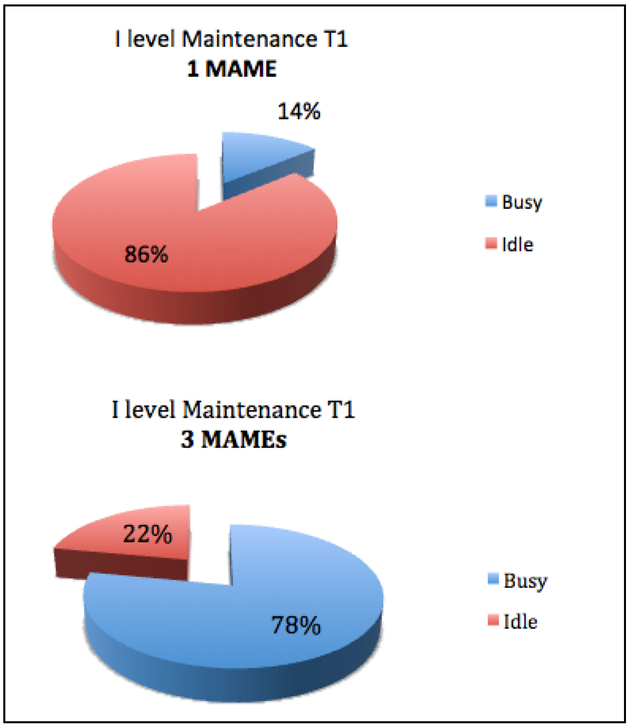

Fig. 14. Number of aircraft effects on the occupational level.

Moreover, on Saturdays and Sundays, if the following shift is not present, the workers can perform off shift work, if required. This is a characteristic of the model that has been reproduced with a strong effort by the Authors in terms of programming because it was necessary to create logical decisional process.

In order to conclude the analysis of the system performances, output data referring to the different maintenance steps have been reported. As it has been described in the previous section, the processing time of each of these activities can't be defined through a deterministic value, but the use of stochastic distributions is necessary. Although statistical studies reveled that these types of processes could be easily described through Lognormal laws, in case the variance is a very small value, the phenomena can be also described through a Uniform distribution. Figure 15, for example, is focused on pre-flight check activities. Accordingly to the input data of this simulation, this maintenance activities processing time should be described by a stochastic uniform distribution with a minimum value of 0.4 hours and a maximum value of 0.7 hours. These input hypotheses are well reflected in the output results. The Figure 15 that refers to the activities performed on the first of the available MAMEs shows that the majority of the activities are contained within the above-mentioned boundaries. The actions that require a higher time are the one performed in particular conditions, especially for the unavailability of the maintainers, simultaneously involved in other I level activities or not present in the operative base (if on Saturdays or Sundays).

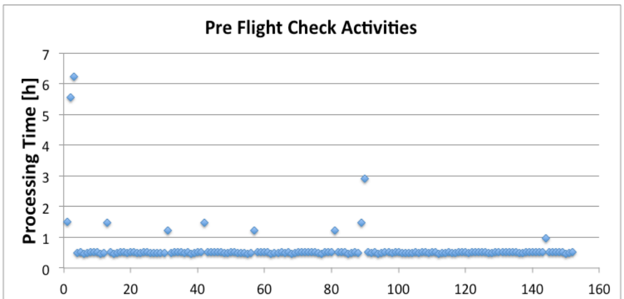

Fig. 15. Pre-Flight Check maintenance activities.

Similarly Figure 16 reveals the processing time required to perform Post Flight Activities. Considering the types of inspections that are generally performed at this level, the same considerations done for the pre flight check activities are still valid. Although the same hypotheses have been done in the input definition phase, Figure 16 reveals a higher number of activities with a processing time higher than the upper boundary of the uniform distribution if compared to Figure 15. This is due to the different level of priority of these two activities. In fact, in case both a pre flight check and a post flight check are required, the pre flight check activity is performed immediately and then all the other maintenance actions. This is a design choice that has been done in order to ensure the model to be closer to the real system, where pre flight check has to be performed first, to avoid delays.

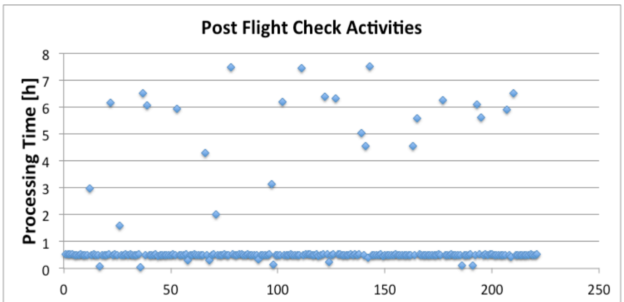

Fig. 16. Post-Flight Check maintenance activities.

Data output for II level activities reveals the same peculiar aspects already described in the previous lines (Figure 17).

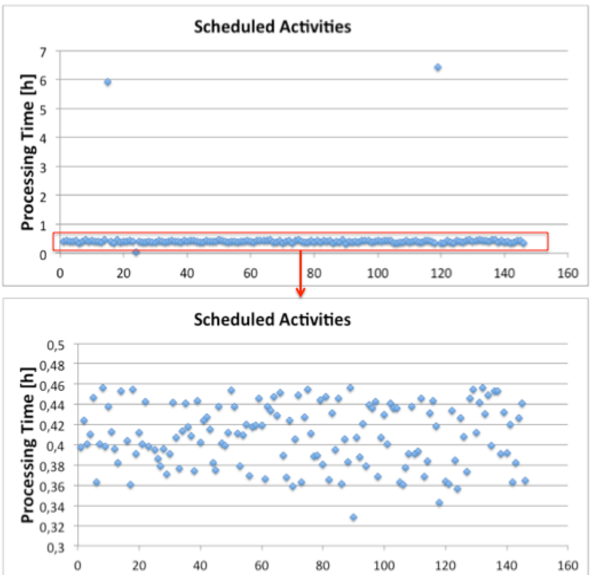

Fig. 17. Scheduled maintenance activities.

4 Conclusions

The case study proposed in Section 3 reveals that high level of confidence of the tool that has been built for sizing purposes. Moreover, the importance of some peculiar aspect of the software, such as its parametric capability, the versatility and the stocasticity has been stressed.

The case study here presented is only one of the possible applications of this powerful tool. In future works, different sizing case will be proposed and other peculiar aspects analyzed. For example, the tool is able to simulate in detail the maintenance activities performed in each maintenance step. Moreover, CAD models for each element can be imported on the simulation window ensuring a higher understanding of the phenomena described.

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