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Scheduled Maintenance and Downtime Cost in Aircraft Maintenance Management

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***Abstract*—**During aircraft maintenance scheduling, operator calculates the budget of the maintenance. Usually, this calculation includes only the costs that are directly related to the maintenance process such as cost of labor, material, and equipment. In some cases, overhead cost is also included. However, in some of those, downtime cost is neglected claiming that grounding is a natural fact of maintenance; therefore, it is not considered as part of the analytical decision-making process. Based on the normalized data, we introduce downtime cost with its monetary value and add its seasonal character. We envision that the rest of the model, which works together with the downtime cost, could be checked with the real life cases, through the review of MRO cost and airline spending in the particular and scheduled maintenance events.

***Keywords*—**Aircraft maintenance, downtime, downtime cost, maintenance cost.

I. Introduction

AVIATION industry has grown rapidly since the first scheduled commercial aviation started one hundred years ago. Every operator aims to undertake the minimum operating cost and the maximum gain profit. One of the significant elements of aircraft's operating cost is the maintenance cost. Dupuy et al. [1] stated that at the time the maintenance is performed, operator is also subject to indirect maintenance cost. One element of the indirect maintenance cost is covered in [2] and [3] as overhead cost. Overhead cost does not contribute directly to the maintenance program but it does contribute to the overall cost that the operator undertakes during maintenance. In addition to overhead cost, there is another element of indirect maintenance cost that appears due to aircraft downtime. Hurst [4] asserted that it is important to control the rate of aircraft downing event since it makes an aircraft unavailable to fly. The cost element related to downtime is described as downtime cost. It appears due to the fact that aircraft stays on the ground and ceases to operate throughout maintenance.

Kumar et al. [5] stated that scheduled and preventive maintenance are usually performed when the system is not required to be operational. Therefore, they noted that this idle period does not have any impact on the revenue generating capacity of the aircraft. On the other hand, Saranga [6] stated that whenever a system stops to operate, whether it is scheduled or unscheduled, the cost of lost revenue is an unavoidable cost. He asserted that downtime cost is a very complex component, which relies on the season type, business environment, unscheduled or scheduled type of downtime and some other factors. For those reasons, he concluded those both scheduled and unscheduled downtimes are expensive.

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II. Scheduled Maintenance Cost Elements

When aircraft operator outsources its base maintenance requirements to a third party Maintenance, Repair and Overhaul (MRO) organization, the cost breaks down mainly into labor and material elements. They are labor rate (LBR), MPD tasks labor (MTL), engineering order labor (EOL), non-routine labor (NRL), cosmetic items labor (CIL), MPD tasks material (MTM), engineering order material (EOM), non-routine material (NRM) and cosmetic items material (CIM). Each element has a source from the maintenance program. But since a substantial portion of the elements are uncertain, the type and age of the aircraft and the point of time in the maintenance history affect the magnitude of both labor and material costs at each base maintenance event (check).

Labor rate (LBR) is the dollar value per each man-hour that a maintenance organization charges for its services on the aircraft. This rate changes in accordance with the cost base (e.g. according to the geographical location of the maintenance facility). However, location is not the only factor of this rate change. Market conditions, special service requirements and seasonal factors also affect the labor rate. Base maintenance service contracts incorporate this rate for a fixed price and also for non-routine and additional services. It is common that labor rate may differ within an organization, through fixed price services and different skill sets.

MPD tasks labor (MTL) represents the labor requirement of maintenance program tasks. Since MTL defines routine works, the planners could determine this parameter in advance. This element will be the same for each aircraft going under the exact same scope of work in a base maintenance event. However, changes will appear amongst different maintenance service providers, which are explained by the term MRO efficiency factor (MEF).

MRO efficiency factor (MEF) is a factor, which represents the ratio of the average man-hour required by a MRO to complete a maintenance task and the man-hour for that task given in manufacturer's Maintenance Planning Document (MPD). For a MRO with high ranking in terms of delivery performance, the MEF value is expected to be low. Therefore, it is acceptable to see MRO organizations with lower MEF value, have higher LBR. In the other words, MRO organizations with lower LBR are supposed to have higher MEF, which increases all labor related cost elements. MEF is a value above 1, where 1 can only be reached in ideal conditions. Personnel training and experience, tool and material availability and hangar conditions are some factors that affect MEF. MEF value decreases as MRO has higher investment (in maintenance environment) and experiences on a specific task or aircraft type.

MPD tasks material (MTM) is another deterministic element. The routine works and the associated material requirements are pre-defined for each task, which is grouped into a scheduled maintenance check per interval limitations. Therefore, MTL and MTM cost elements are not probabilistic. Two other deterministic elements are EOL (engineering order labor) and EOM (engineering order material). These are the labor amount and the material cost arising from Engineering Order requirements. MTL, MTM, EOL and EOM can be observed to increase on an aging aircraft. However, these parameters can still be determined during the check-planning phase. Nevertheless, not all the cost elements have deterministic character. The non-routine related labor and the material cost elements tend to change with type, age and operation condition of aircraft. General assumptions could be made; however, the most accurate cost of these elements could only be calculated after the performance of the check. Therefore, the cost of a scheduled airframe maintenance check can be calculated by the following equation:

$$MTC = LBR * \left(MEF * ((MTL + EOL) + NFL\ * (NRL + CIL)\right) + MTM + EOM + NFM * (NRM + CIM) \qquad (1)$$

where all the material-related variables such as MTM, EOM, NRM (Non-Routine Material) and CIM (Cosmetic Items Material) are already given in dollars. Furthermore, to identify the probabilistic character of non-routine related labor and material costs, the terms NFL, which corresponds to non-routine labor factor and NFM, which corresponds to non-routine material factor, are used. These factors are expected to increase on old aircrafts and should also differ for each aircraft and check type.

Turn-around time (TAT), which does not appear in (1), is the most crucial element. TAT does not contribute to direct maintenance cost but it contributes to the downtime cost of the aircraft. Assuming that the sum of the elapsed time of critical maintenance tasks is lower than TAT, then TAT can be calculated by:

$$TAT = MEF * \frac{MTL+EOL+NFL*(NRL+CIL)}{MLC} \qquad (2)$$

where MRO labor capacity (MLC) is the maintenance facility's daily labor production capacity, which depends on the number of the assigned technicians to the aircraft and the daily working hours (shift pattern).

In some cases, when there are substantial non-routine works, TAT becomes the sum of the total critical tasks (routine and non-routine) of the scheduled maintenance check. In addition, logistic factors such as long durations of material procurement of non-routine tasks could also increase TAT. In this study, TAT of a scheduled maintenance check will be incorporated in the maintenance cost with the term downtime (DT).

$$TAT = DT \qquad (3)$$

III. Downtime Cost

A. Operator Revenue vs MRO Revenue

A set of operation and revenue data of a scheduled operator (operator ABC) and a MRO organization (MRO XYZ), both based in Istanbul, Turkey, are analyzed. Given the nature of business, neither MROs nor airlines allow disclosure of such financially sensitive data in their relevant competitive markets. For this confidentiality reason, normalization is utilized. In the operation of the scheduled operator ABC, two types of seasons are taken into account. They are winter season, which lasts from November to March, and summer season, which lasts from April to October. The average monthly revenue generated by each aircraft (B737-800), is plotted in Fig. 1. As expected, the resulting plot shows similar seasonal characteristics with the aircraft seasonal demand plot given by Muchiri and Smit [7]. There, aircraft demand is at peak between April-October; therefore, this interval is classified as high season. On the other hand, between November-March, the demand is low; consequently, the interval is classified as low season. This aircraft seasonal demand plot explains why the revenue of operator ABC is high throughout summer and low throughout winter.

The direct maintenance cost that appears to the operator during maintenance is a cost, which is offered by the MRO organization as maintenance service provider. As the revenue of scheduled operator varies seasonally, the revenue of MRO organization is also expected to fluctuate according to the season or the time of the year. In order to observe this effect, the average monthly revenue from base maintenance of MRO XYZ is analyzed and the result is plotted as shown in Fig. 2.

It can be seen that the plot of operator's revenue in Fig. 1 is more or less the mirror image of the plot of MRO organization's revenue in Fig. 2. Throughout high season, the revenue of operator is high, while the revenue of MRO organization is low. Muchiri and Smit [7] explained this trend in which during that period, the demand of aircraft is high and therefore instead of having maintenance performed on their aircrafts, operators prefer to fly them to meet the demand. For that reason, the demand for maintenance service is low. On the other hand, throughout low season, the demand of aircraft is low, thus as a consequence; the revenue of operator is also low. On that account, operators prefer to perform the required maintenance during this period so that their aircraft will be at the required reliability level before high season arrives. As a result, the demand for maintenance is high and that reflects on the increase in the revenue of MRO organization.

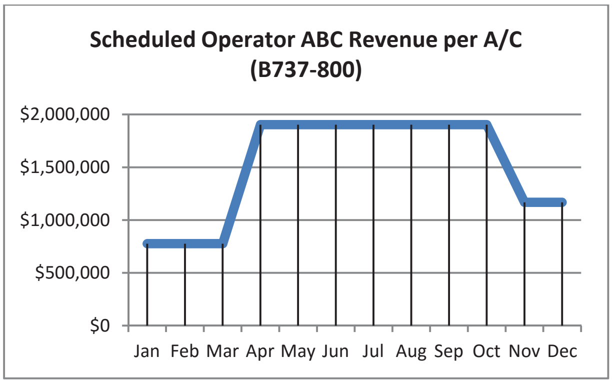

Fig. 1 Scheduled operator ABC revenue per A/C

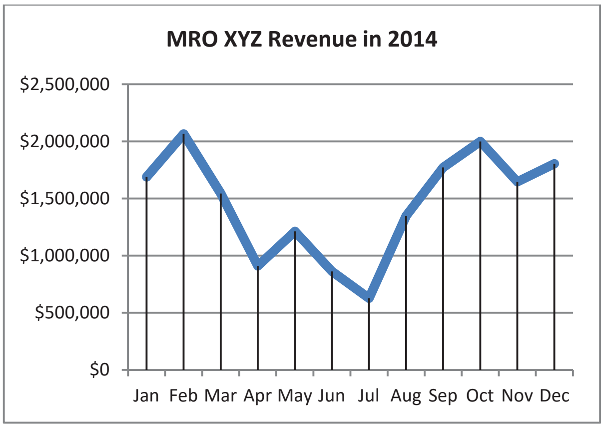

Fig. 2 MRO XYZ revenue from base maintenance in 2014

From Figs. 1 and 2, operators can see that during high season, there is a possibility of having better commercial terms of agreement, including maintenance price and rates from MRO organization. However, operators need to calculate the downtime cost and analyze its variation for different time periods. There may exist a period where downtime cost is lower than direct maintenance cost. For each period, operator may sum downtime cost with the offered maintenance cost to have the total maintenance cost.

B. Downtime Cost Elements

The first element of downtime cost is aircraft ownership cost. Whether aircraft flies or not, its monthly lease cost is inevitable. Aircraft lease cost varies depending on aircraft's type, age and configuration [8]. It will also vary depending on the market condition, the lessee fleet size and aircraft's financial status. For the same aircraft type, the lease rate is cheaper for older aircraft. The aircraft's total ownership cost during downtime (AOC) can be calculated by:

$$AOC = \frac{MLR}{NDM} * DT. \tag{4}$$

Recall that MLR, NDM and DT correspond to monthly lease rate, number of days in one month and downtime number of days respectively.

In case of aircraft availability does not meet the regular demand, both scheduled and ACMI operators may sub charter aircraft from another operator to fulfill the demand. One of the reasons why aircraft is not available to meet the demand is due to maintenance. There exists two possible ways of sustaining the operations, while the aircraft is on the ground. First, operators may modify the schedule of the remaining aircraft and put the schedule of the aircraft under maintenance to another aircraft. Operators may not need to modify the existing schedule if they do have a spare aircraft on ground. However, most operators keep spare aircraft only in very rare and specific operation contracts and such application is not commonly seen in the industry. Secondly, if a spare aircraft is not available and schedule modification is also not possible, in order to keep fulfilling the demand, operators may sub charter aircraft from another operator. Within this context, when an airline has to sub charter a portion of its operations to another airline, the cost occurred due to this service could be defined as another element of downtime cost. It shall be noted that scheduled operators should provide service according to their predefined schedules. It is generally not an option to cancel any given flight except during bad weather conditions. Therefore, it becomes a must to use either sub charter services or a spare aircraft to cover the unscheduled unavailability, which is a direct cost of downtime. Sub charter cost during downtime (SAC) can be calculated by:

$$SAC = \frac{BH*SCR}{NDM} * DT, \tag{5}$$

Recall that BH and SCR correspond to monthly block hour and sub charter rate respectively.

Another element of downtime cost is the cost of revenue loss as mentioned in [5] and [6]. This could also be defined as the cost of opportunity loss as airplane being grounded instead of flying [1]. Such element is applicable for both scheduled and ACMI operators. The basic salaries of the crew are constant and independent from the flight schedule. Direct costs such as fuel and navigation charges and the flight compensations and hotel costs will arise only when the flight takes place. Therefore, it is reasonable to choose operator's average profit, which is the profit that operator would be able to generate if the aircraft does not cease to operate, as one element of downtime cost. The opportunity cost per flight (OPF) can be calculated by:

$$OPF = ACP * LF * NPP \tag{6}$$

Recall that ACP, LF and NPP correspond to aircraft capacity, load factor and net profit per passenger respectively. The total opportunity cost (OPC) can be calculated by summing the OPF of every flight that usually exists during the period where maintenance is planned.

C. Downtime Cost Model

As the profit level of an airline increases, either by the operation type or by seasonal effect, the overall impact of downtime increases. In this study, two types of downtime cost are proposed. The first one is downtime cost with sub charter option (DTCs), and the second one is downtime cost with no sub charter option (DTCn). It is important to note that the opportunity cost will appear only if operator decides not to take sub charter option to substitute the aircraft that is down for maintenance. In the case where operator chooses to sub charter an aircraft to keep the operation, instead of opportunity cost, sub charter cost will appear. On that account, downtime cost of an operator with sub chartering an aircraft as an option is given by:

$$DTCs = AOC + SAC. \tag{7}$$

Subsequently, downtime cost of an operator with no sub charter option, is given by:

$$DTCn = AOC + OPC. \tag{8}$$

Taking into account the seasonal characteristics of each element, aircraft ownership cost (AOC) is assumed to be constant. However, sub charter (SAC) and opportunity cost (OPC) can be higher in the course of high season than in the course of low season. This is crucial because in addition to the duration of downtime, the accuracy of the downtime period becomes significantly important. In the region where Turkey is located, the high season for aircraft passenger traffic takes place throughout summer. On the contrary, there is relatively less demand for flights during winter. There are exceptions to the high and low seasons, as there are temporary peaks of demands during religious holiday periods of Ramadan, Christmas and Haj. Since the dates of some of these religious holidays vary every year, downtime cost forecasting of charter/ACMI operator becomes very challenging. On the other hand, scheduled operators can perform better predictions on their downtime cost since their flight schedules are already established in advance.

Finally, the total maintenance cost with sub charter option is given by:

$$TMCs = MTC + DTCs \tag{9}$$

Following that, the total maintenance cost with no sub charter option can be calculated by:

$$TMCn = MTC + DTCn, \tag{10}$$

recall that DTCn corresponds to downtime cost of an operator with no sub charter option.

IV. Case Study

This case study examines the total maintenance cost, which includes maintenance cost (MTC) and downtime cost (DTC), of an A320 aircraft during one light C check. The case study uses real data coming from a MRO, an airline and IATA. A scheduled operator operates the aircraft, which seats 180 passengers. In this case, the average of 10-block hour daily utilization is chosen, which approximately corresponds to five scheduled flights each day. The elements of MTC and downtime (DT), such as CIL, EOL and MTL are obtained from MRO XYZ based in Istanbul, Turkey. The other parameters such as MTM, CIM and EOM, are obtained by multiplying 10% of MTL, 20% of CIL, and 40% of EOL by 50 dollars respectively. The 10%, 20%, and 40% values are based on the normalized historical maintenance data of MRO XYZ. The NFL and NFM percentages are 100%, taking into account the worst case where all non-routine tasks must be performed. The labor rate (LBR) values of $50 in winter and $40 in summer and the MRO labor capacity (MLC) of 160 MH/day in winter and 200MH/day in summer are also procured from MRO XYZ. The seasonal load factor (LF) and monthly block hour (BH) values are obtained by taking the average values throughout a year of scheduled operator ABC. Besides that, scheduled operator ABC also provided information regarding the seasonal sub charter rate per block hour (SCR). The monthly lease rate (MLR) is taken from Aircraft Value News [8]. The net profit per passenger (NPP) is the airline profit value per passenger in 2015 proposed by IATA [9].

The data are tabulated in Table I. In order to see how maintenance cost and downtime cost vary from one MRO to another, calculations are performed for four MROs with different MEF and LBR values. MEF varies from 1.8 to 2.1 and LBR varies from $60 to $40 respectively. As we have mentioned before, MEF value is lower for MRO with higher ranking in terms of delivery performance. As a consequence, the LBR value of the corresponding MRO will be high. The results of the calculation are tabulated in Table II. DT is calculated using (2). MTC is calculated using (1). AOC is calculated using (4). SAC is calculated using (5). OPF is calculated using (6) and OPC is obtained by multiplying OPF with five. Afterwards, DTC for leased aircraft with sub charter option and no sub charter option are calculated with (7) and (8), respectively. Finally, the total maintenance cost (TMC) for sub charter and no sub charter option are calculated by using (9) and (10), respectively.

Taking into account the results given in Table II, three important points are observed. The first one is that load factor (LF) and net profit per passenger (NPP) play important roles in determining the opportunity cost of the operator. In this case study, for opportunity cost calculation, NPP given by [9] is a constant value at $7.08 both throughout winter and summer. While in fact, as load factor varies according to the season, net profit value per passenger shall vary as well. Hence, OPC is sensitive to the variation of NPP and LF.

Secondly, as MEF decreases, MTC increases. This is because low MEF value corresponds directly to high LBR. For that reason, MRO_4, which has the highest MEF and the lowest LBR value, gives the lowest MTC both in winter and summer. Unfortunately, this does not mean that MRO_4 yields the lowest downtime cost (DTC) at the same time. From Table II, we can see that in reverse, as MEF increases, this time DTC increases. Hence, MRO_1 with the lowest MEF and highest LBR value gives the lowest downtime cost for winter and summer. This is due to the fact that higher MEF means higher performance delivery, which corresponds directly to lower turn around time or downtime (DT). Nonetheless, the analysis could not stop only in MTC and DTC calculations. The total maintenance cost (TMC) shall be calculated.

TABLE I
PARAMETER VALUES

Acronym	Seasonal	Winter	Summer
ACP	No	180	180
BH	Yes	250	300
CIL	No	500	500
CIM	No	\$5,000	\$5,000
EOL	No	250	250
EOM	No	\$5,000	\$5,000
LF	Yes	60%	80%
MLC	Yes	160	200
MLR	No	\$250,000	\$250,000
MTL	No	1000	1000
MTM	No	\$5,000	\$5,000
NDM	No	30	30
NFL	No	100%	100%
NFM	No	100%	100%
NPP	No	\$7.08	\$7.08
NRL	No	500	500
NRM	No	\$5,000	\$5,000
SCR	Yes	\$2,200	\$2,800

TABLE II
CASE STUDY OF DIFFERENT MRO

Season	Variable	MRO_1	MRO_2	MRO_3	MRO_4
Winter	LBR	\$60	\$55	\$50	\$40
	MEF	1.8	1.9	2	2.1
	DT	25	26	28	29
	AOC	\$208,333	\$216,667	\$233,333	\$241,667
	SAC	\$458,333	\$476,667	\$513,333	\$531,667
	OPC	\$95,580	\$99,403	\$107,050	\$110,873
	DTCs	\$666,667	\$693,333	\$746,667	\$773,333
	DTCn	\$303,913	\$316,070	\$340,383	\$352,539
	MTC	\$268,000	\$260,125	\$250,000	\$214,000
	TMCs	\$934,667	\$953,458	\$996,667	\$987,333
	TMCn	\$571,913	\$576,195	\$590,383	\$566,539
Summer	LBR	\$55	\$50	\$45	\$35
	MEF	1.8	1.9	2	2.1
	DT	20	21	22	23
	AOC	\$166,667	\$175,000	\$183,333	\$191,667
	SAC	\$560,000	\$588,000	\$616,000	\$644,000
	OPC	\$101,952	\$107,050	\$112,147	\$117,245
	DTCs	\$726,667	\$763,000	\$799,333	\$835,667
	DTCn	\$268,619	\$282,050	\$295,481	\$308,911
	MTC	\$247,750	\$238,750	\$227,500	\$190,375
	TMCs	\$974,417	\$1,001,750	\$1,026,833	\$1,026,042
	TMCn	\$516,369	\$520,800	\$522,981	\$499,286

Thirdly, from Table II, we can conclude that DTC and TMC for sub charter option are much higher compared to no sub charter option. Assuming that these values are acceptable, this case study shows that sub chartering during maintenance is not feasible. However, for a scheduled operator, which already has their flights scheduled and published in advance, sometimes cancelling a flight would not be possible and therefore, sub chartering is unavoidable. On top of that, from Table II, it can be deduced that sub chartering during summer is more expensive than in winter.

As a conclusion, by comparing the total maintenance cost of four different MRO in winter and summer for sub charter and no sub charter option, no sub charter option yields the lowest total maintenance cost both throughout winter and summer. Thus, this case study provides the evidence that in many cases the cheapest maintenance pricing is not the most economical solution and the traditional maintenance scheduling practices do not yield the best overall cost performance. In this respect, this study validates the new method to investigate further the new aspects of maintenance scheduling.

V. CONCLUSION

This study is the beginning of the detailed analysis of downtime cost calculation during the maintenance scheduling. Two models, one for sub charter option and the other one for no sub charter option are introduced. However, these models need to be improved further to be able to catch the uncertain characteristics, not only due to non-routine originated maintenance costs but also due to variation in aircraft's demand according to the season and geographical region. These uncertainties will not only affect sub charter cost and opportunity cost, but also the maintenance cost offered by MRO. Such improvement can be done by using stochastic modeling of the overall maintenance cost including downtime and non-routine elements of the maintenance cost.

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Gokhan Inalhan received his B.Sc. degree in Aeronautics from Istanbul Technical University (ITU) in 1997 and M.Sc. and Ph.D. degrees in Aeronautics and Astronautics from Stanford University in 1998 and 2004 respectively. In 2003, he received his Ph.D. Minor from Stanford University on Engineering Economics and Operations Research (currently Management Science and Engineering). Between 2004 and 2006 he worked as a Postdoctoral associate at Massachusetts Institute of Technology. During this period he led the Communication and Navigation group in the MIT-Draper Laboratory NASA CER project. Currently, he is a Full Professor at ITU, Faculty of Aeronautics and Astronautics and serves as the Vice Chair of the Aeronautical Engineering Department. He has published more than 100 publications on flight controls and avionics systems, spacecraft design and controls, formation flight, design of manned aircraft and unmanned vehicles, air transportation management, large-scale optimization, advanced guidance, navigation and controls. He is the founder and the Director of the Controls and Avionics Laboratory of ITU. He is a senior member of AIAA and elected member of IEEE Technical Committee on Aerospace Controls and IFAC Transportation Systems Technical Committee. He is also a Eurocontrol Agency Team (ART) member. He is a founder of the Air Transportation Management Program in ITU