Aircraft Engineering and Aerospace Technology

Kulkarni, A. and Yadav, D. and Nikraz, H. 2017. Aircraft maintenance checks using critical chain project path. Aircraft Engineering and Aerospace Technology. 89 (6): pp. 879-892. DOI: 10.1108/AEAT-10-2013-0186

Emerald Aircraft Engineering and Aerospace Technology: An International Journal

Aircraft maintenance checks using critical chain project path

Journal:	*Aircraft Engineering and Aerospace Technology*
Manuscript ID	AEAT-10-2013-0186.R1
Manuscript Type:	Research Paper
Keywords:	airline, aviation, flight, maintenance, management, project

Aircraft maintenance checks using critical chain project path

Abstract

Purpose – Aircraft operators incur significant costs when an aircraft is taken out of service for maintenance. This paper presents a method for reducing time duration of aircraft maintenance checks using critical chain project management (CCPM) principle.

Design/methodology/approach - A case study of a typical heavy maintenance check performed on an Airbus 320 aircraft is undertaken for the analysis. The critical chain method is applied to develop a plan with a reduced duration and a survey and field observations to validate the findings have also been carried out as a part of this study.

Findings - The paper compares the traditional project management method with CCPM in view of reducing the aircraft down time duration for maintenance. This study repositions buffers and other techniques to shorten the chain path and a reduction in the total duration of the project by 5 days is achieved.

Research limitations/implications - It is argued that application of CCPM principle can reduce the duration of an aircraft maintenance check, but this study is done in a single project situation focusing on project planning and execution. Therefore, additional study may be required to examine other issues.

Originality/value - Cost of the maintenance is second highest expenditure factor for an airline operator. Therefore, it is necessary to drive the maintenance cost down. The paper demonstrates that the duration of a maintenance check can be reduced by 8.9% using the method suggested in this study.

Keywords - Airline, aviation, flight, maintenance, management, project, safety.

Article type - Research paper.

Introduction

Scheduled maintenance checks and inspections of a civil aircraft are mandatory and they are required to be carried out in accordance with the aircraft flying hours and calendar periods. Primary objective of aircraft maintenance is to provide an airworthy aircraft when it is required by the operator at a minimum cost (Knotts, 1999). An efficient maintenance management is not only about cutting costs, but it also reduces negative influences on a maintenance worker and contributes to flight safety. Prescribed maintenance checks are necessary to ensure airworthiness of the aircraft. Every aircraft manufacturer provides documents indicating required maintenance tasks and procedures to be carried out in view of keeping the aircraft to mandatory airworthiness standard set by respective national civil aviation authority and the International Civil Aviation Organisation (Karadzic et.al, 2012).

Kulkarni, A. and Yadav, D. and Nikraz, H. 2017. Aircraft maintenance checks using critical chain project path. Aircraft Engineering and Aerospace Technology. 89 (6): pp. 879-892. DOI: 10.1108/AEAT-10-2013-0186

Traditionally, these maintenance tasks are divided into line maintenance, check A, B, C, and D enabling an aircraft operator to plan the maintenance work, effectively. Regular checks, such as A and B are known as light maintenance work (Pandit, 2007). This can be performed generally in less than two working days. Besides, Airbus (2012) states that the checks C and D are classified as heavy maintenance tasks and they are required to be carried out after an elapse period of every 15-21 months and 5-6 years, respectively. Average time needed to complete a typical C check is generally 2-3 weeks, but a D check is the most comprehensive and demanding work that takes approximately two months to finish. The heavy maintenance work is required to be performed in an appropriate aircraft hangar using specialised equipment and personnel (Fig.1). Though maintenance errors contribute to 12% of major airline aircraft accidents and 50% of engine related flight delays, airlines consider aircraft maintenance as a none-core business (Herrera et al. 2009). Consequently, these checks are frequently outsourced to maintenance repair and overhaul (MRO) companies by airlines operators (Hamad et al. 2007).

Figure 1 An aircraft undergoing heavy maintenance

Airlines incur revenue loss when an aircraft is taken out of service for maintenance. With rising competition and operating costs, the airlines aim to remain profitable by reducing maintenance expenses and aircraft down time. The maintenance activities range from 10% to 20% of an operator's direct operating costs depending on the fleet size, age, and usage (Papakostas et al. 2009). However, Marya et al. (2013) argue that only few major cost-reduction efforts have fully reached their goals. Consequently, the future of some commercial aviation players is at risk. It seems that some companies consider cost as a supply-chain problem, an operations problem or an engineering problem. Essentially, working across traditional functional boundaries is required to achieve success. Therefore, the aircraft maintenance management needs to explore teardown execution approaches, lean maintenance operations, and contemporary project management techniques to further reduce the cost encounters in performing heavy maintenance of an aircraft.

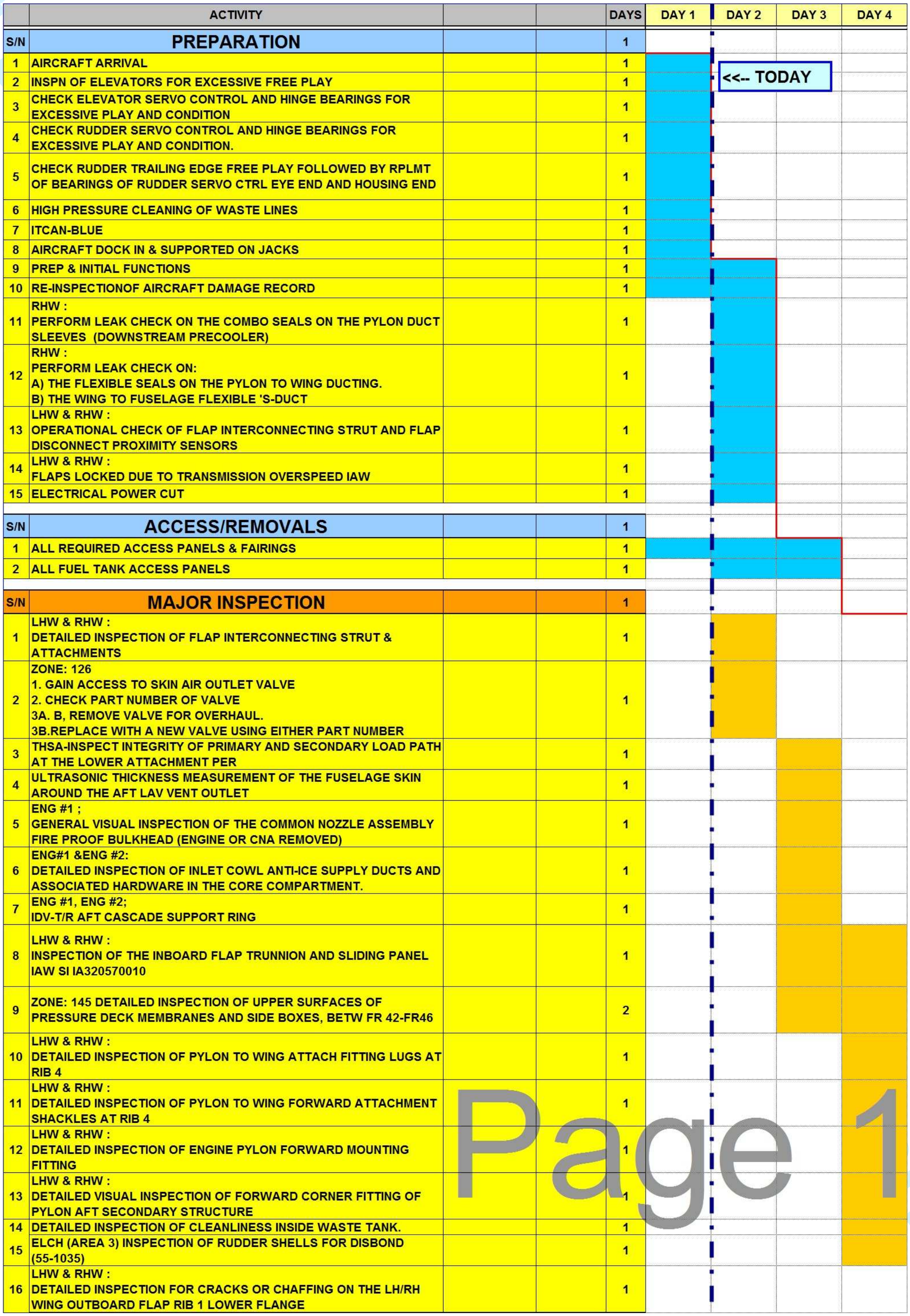
A typical heavy maintenance check of an aircraft involves completion of several technical tasks within a specified amount of time, reasonable cost, and meeting the approved airworthiness standard. According to Kerzner (2006), a project is defined as a series of activities and tasks having constraint of time, cost, and resources while meeting the desired specification or performance standard. Therefore, the maintenance check is a project in a perspective. Consequently, reducing the amount of time in view of cutting the cost can be examined as a project management issue using critical chain project management (CCPM) method. Primary objective of this paper is to explore possibilities of CCPM method to reduce the amount of time taken in completing a heavy maintenance check of an aircraft. The duration of a heavy maintenance check can be affected by long term strategic and tactical issues, such as available manpower and aircraft spares, negotiated project value, and time. However, the paper focuses on operational planning and execution in a single project environment. To this end, a case study covering a heavy maintenance check plan is carried out to investigate factors affecting the duration. After analysing current and CCPM techniques, the paper suggests a method to reduce the duration using the CCPM techniques. Additionally, possible limitations of the method are also discussed in this study.

Methodology

Critical chain project management is a method for planning, executing and managing single and multiple projects. CCPM methodology was developed to address poor performance of projects and it is used to provide solution to problems in projects that take longer than expected durations, frequently miss deadlines, exceed costs, and deliver lower outcomes than those originally promised (Goldratt, 1997).

A typical heavy maintenance check C carried out on an Airbus 320 by a major maintenance repair and overhaul (MRO) company was selected for this study. Relevant maintenance planning documents for the check, questionnaires, and observation data were collected and analysed. Results of the analysis are used to assess issues affecting the duration. The case study method was chosen due to lack of available data related to a maintenance check in the public domain. Subsequently, the data were collected by direct observation of a typical maintenance check at the MRO facilities. Various issues identified by the case study can be generalised for the other categories of heavy maintenance checks mentioned above, because a check C is considered as the most frequently carried out heavy maintenance work on an aircraft. This is the primary reason behind selecting check C for this study.

Table 1 Maintenance schedule (Adopted from Airbus, 2012)



	ACTIVITY			DAYS	DAY 1	DAY 2	DAY 3	DAY 4
S/N	**PREPARATION**			1				
1	AIRCRAFT ARRIVAL			1	🟦			
2	INSPN OF ELEVATORS FOR EXCESSIVE FREE PLAY			1	🟦	<<-- TODAY		
3	CHECK ELEVATOR SERVO CONTROL AND HINGE BEARINGS FOR EXCESSIVE PLAY AND CONDITION			1	🟦			
4	CHECK RUDDER SERVO CONTROL AND HINGE BEARINGS FOR EXCESSIVE PLAY AND CONDITION.			1	🟦			
5	CHECK RUDDER TRAILING EDGE FREE PLAY FOLLOWED BY RPLMT OF BEARINGS OF RUDDER SERVO CTRL EYE END AND HOUSING END			1	🟦			
6	HIGH PRESSURE CLEANING OF WASTE LINES			1	🟦			
7	ITCAN-BLUE			1	🟦			
8	AIRCRAFT DOCK IN & SUPPORTED ON JACKS			1	🟦			
9	PREP & INITIAL FUNCTIONS			1	🟦	🟦		
10	RE-INSPECTIONOF AIRCRAFT DAMAGE RECORD			1	🟦	🟦		
11	RHW : PERFORM LEAK CHECK ON THE COMBO SEALS ON THE PYLON DUCT SLEEVES (DOWNSTREAM PRECOOLER)			1		🟦		
12	RHW : PERFORM LEAK CHECK ON: A) THE FLEXIBLE SEALS ON THE PYLON TO WING DUCTING. B) THE WING TO FUSELAGE FLEXIBLE 'S-DUCT			1		🟦		
13	LHW & RHW : OPERATIONAL CHECK OF FLAP INTERCONNECTING STRUT AND FLAP DISCONNECT PROXIMITY SENSORS			1		🟦		
14	LHW & RHW : FLAPS LOCKED DUE TO TRANSMISSION OVERSPEED IAW			1		🟦		
15	ELECTRICAL POWER CUT			1		🟦		
S/N	**ACCESS/REMOVALS**			1				
1	ALL REQUIRED ACCESS PANELS & FAIRINGS			1	🟦	🟦	🟦	
2	ALL FUEL TANK ACCESS PANELS			1		🟦	🟦	
S/N	**MAJOR INSPECTION**			1				
1	LHW & RHW : DETAILED INSPECTION OF FLAP INTERCONNECTING STRUT & ATTACHMENTS			1		🟧		
2	ZONE: 126 1. GAIN ACCESS TO SKIN AIR OUTLET VALVE 2. CHECK PART NUMBER OF VALVE 3A. B, REMOVE VALVE FOR OVERHAUL. 3B.REPLACE WITH A NEW VALVE USING EITHER PART NUMBER			1		🟧		
3	THSA-INSPECT INTEGRITY OF PRIMARY AND SECONDARY LOAD PATH AT THE LOWER ATTACHMENT PER			1			🟧	
4	ULTRASONIC THICKNESS MEASUREMENT OF THE FUSELAGE SKIN AROUND THE AFT LAV VENT OUTLET			1			🟧	
5	ENG #1 ; GENERAL VISUAL INSPECTION OF THE COMMON NOZZLE ASSEMBLY FIRE PROOF BULKHEAD (ENGINE OR CNA REMOVED)			1			🟧	
6	ENG#1 &ENG #2: DETAILED INSPECTION OF INLET COWL ANTI-ICE SUPPLY DUCTS AND ASSOCIATED HARDWARE IN THE CORE COMPARTMENT.			1			🟧	
7	ENG #1, ENG #2; IDV-T/R AFT CASCADE SUPPORT RING			1			🟧	
8	LHW & RHW : INSPECTION OF THE INBOARD FLAP TRUNNION AND SLIDING PANEL IAW SI IA320570010			1			🟧	🟧
9	ZONE: 145 DETAILED INSPECTION OF UPPER SURFACES OF PRESSURE DECK MEMBRANES AND SIDE BOXES, BETW FR 42-FR46			2			🟧	🟧
10	LHW & RHW : DETAILED INSPECTION OF PYLON TO WING ATTACH FITTING LUGS AT RIB 4			1				🟧
11	LHW & RHW : DETAILED INSPECTION OF PYLON TO WING FORWARD ATTACHMENT SHACKLES AT RIB 4			1				🟧
12	LHW & RHW : DETAILED INSPECTION OF ENGINE PYLON FORWARD MOUNTING FITTING			1				🟧
13	LHW & RHW : DETAILED VISUAL INSPECTION OF FORWARD CORNER FITTING OF PYLON AFT SECONDARY STRUCTURE			1				🟧
14	DETAILED INSPECTION OF CLEANLINESS INSIDE WASTE TANK.			1				🟧
15	ELCH (AREA 3) INSPECTION OF RUDDER SHELLS FOR DISBOND (55-1035)			1				🟧
16	LHW & RHW : DETAILED INSPECTION FOR CRACKS OR CHAFFING ON THE LH/RH WING OUTBOARD FLAP RIB 1 LOWER FLANGE			1				

Table 2 Questionnaire and response

Planner questionnaire			
S/N	Question	Number of Respondents	
		Yes	No
1	Is the planned task duration more than Elapsed Time indicated in MPD/AD/SB	9	1
2	Is the planned task duration based on historical values (from previous checks)	10	0
3	Is resource allocation done during planning phase	1	9
4	Is the project progress tracked regularly	1	10
5	Are the work breakdown structure and Gantt charts created during planning	0	10
Engineer questionnaire			
S/N	Question	Number of Respondents	
		Yes	No
1	Do you perform additional work in more than 40% of the tasks executed	8	2
2	Do you face unexpected problems in more than 40% of tasks performed	7	3
3	Do you work on more than one task most of the time	9	1
4	Are you scheduled to start a task without adequate resources?	8	2
5	Do you report an early finish of a task?	0	10

Since planning and execution of various heavy maintenance checks are similar, the problems encountered during these checks are also identical. Furthermore, the aircraft maintenance industry is highly regulated under national civil aviation safety regulations in order to ensure airworthiness of aircraft and flight safety. Therefore, the maintenance practices and procedures followed to carry-out the checks are either identical or similar. Consequently, a typical maintenance check chosen for the study in a single project situation is considered as a suitable sample.

Duration of the observation was 11 working days and more than 100 different maintenance tasks were executed in order to complete this check during the observation. A project plan was created by maintenance planners and it was handed over to a maintenance team for execution. The team was divided into four groups identified as airframe, engine, avionics, and non-destructive testing (NDT). They were allocated the relevant maintenance task in different sections of the aircraft, such as wing, nose-tail, engine, cabin, and avionics. To ensure an effective monitoring of time taken to carry out the allocated tasks, job cards related to the tasks were required to be signed-off by approved certifying personnel before handing over to the planners on daily basis. A survey was carried out during the observation on a focused group of licensed aircraft engineers and planners involved in the check to validate the observation. The questionnaire was focused around project tasks, activities, planning documentation, and duration as denoted in Table 2. Additionally, associated maintenance documents, such as approved schedule of maintenance check C as indicated in Table 1 and maintenance planning document (MPD) published by the aircraft manufacturer were also examined. The schedule of maintenance shown by Table 1 reveals a sample of the specific tasks required to be carried out during the check C.

Factors affecting the duration of a heavy maintenance checks

According to Masmoudi (2010), total period of completion of a heavy maintenance check of an aircraft is influenced by strategic, tactical, and operational decisions made by the project manager. The duration may also be affected by long term strategic decisions, such as utilisation of maintenance facility area, staffing, a number of critical resources, and an acceptable level of under-utilisation of the available resources. The researchers also found that the horizon of strategic plan may vary from one to several years. For example, a long term decision to reduce spare inventory level in aircraft maintenance stores of the maintenance company may affect the turnaround time caused by unavailability of spare parts required for the maintenance. Similarly, tactical decisions involve capacity planning, due-date milestones, and project value influencing overtime work and resource allocations. Under operational planning, work packages are broken down into smaller activities specifying expected duration to complete and resource usages based on technical details of the task. This is done using Gantt charts and critical path method (CPM).

However, the operational planning suffers uncertainty and variation in the project that may affect the period of completion (Adam, 2012; Srinivasan et al. 2007; Samaranayake, 2006; Srinivasan and Best, 2006; The TOC Centre of Australia Pty Ltd, 2006). The researchers argue that it happens due to resource and task interdependency, multi-project environment, multitasking, and wastage of safety buffers during execution. For example, a task of installing and checking a landing gear on an aircraft may take few hours to many days depending on unpredictable complexities arise while carrying out the task (Samaranayake, 2006). Similarly, structural corrosion may be anticipated on certain types of aircraft, but it is hard to predict. Consequently, the unanticipated work caused by the corrosion or complexity of a task may increase the total period to complete the maintenance check that was originally planned. Furthermore, certain unanticipated tasks may require approval from the aviation regulator or customer. Generally, a typical heavy maintenance check requiring approximately 45,000 man-hours of work may end up using an additional 10,000 hours of unanticipated work (Srinivasan et al. 2007).

The literature also suggests that only about 50% of the total work and parts replacement required during a heavy maintenance check can be planned (Samaranayake, 2006). The researcher further suggests that the other half remains unplanned and it can be identified by gradual inspections during the maintenance. In an uncertain environment with constantly changing priorities, the project manager requires to synchronise various elements of the project. For example, in case of unavailability of an aircraft component and long lead times, the engineers may need to transfer the required item from other aircraft to service the aircraft which is undergoing heavy maintenance or vice versa to maintain the schedules. This requires an additional work resulting in an increase in the planned duration for completion of a heavy maintenance check. A similar situation may apply in case of task interdependency and multitasking. For example, hundreds of different activities continue during final assembly stage of an aircraft undergoing a heavy maintenance check. Srinivasan et al. (2007) argue that these activities are required to be completed in a defined sequence. Hence, each of these activities may cause a potential delay, which will increase the duration of the maintenance check, as a result. Additionally, a multi project environment at the maintenance organisation significantly influences the schedule of a heavy maintenance check. Several in-house aircraft maintenance projects competes with each other for resources, such as specialised technical personnel, aircraft spare parts, and special tools.

An important risk management tool, for instance a safety buffer included in the schedule of a maintenance check to address contingency or slack time is also considered as a factor for the potential delay. The maintenance checks durations are evaluated by simply adding up the buffer time along the longest sequence of dependent activities and there is no inbuilt incentive for finishing a task before the allocated time. Knowing that the task durations are inflated, the workers tend to go slow or put off working on a task until its due date comes closer and they aim to complete the work by the milestone date or later depending on an accepted delay, but hardly earlier. As a result, the safety buffers are wasted during execution. Consequently, the project duration increases and it also reduces productivity. Conversely, the probability of delay in a project schedule increases without a safety buffer.

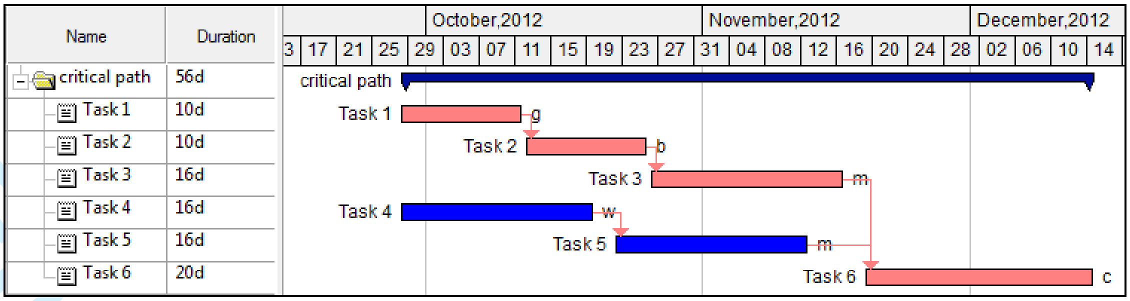
Applying CCPM practices in a heavy maintenance program

Primarily, the CCPM method is used for a project, which has high probability of slipping schedules, cost excursions, and delivering lesser than expected. Under traditional project management system, success of a project depends on completing individual tasks according to a planned schedule (Goldratt, 1997). Therefore, estimations of the individual tasks duration must be accurate enough with a high probability of completing the task according to the schedule. Subsequently, a safety buffer is added to the task duration while planning to ensure that the task completion probability remains at 95-100% level (Goldratt, 1997).

While the tasks are managed by deadlines or milestones using traditional project management tools, task owners are held responsible for delays. Thus, the task owners resist reporting any early completions assuming that they may be blamed for inaccurate estimation of the expected duration of the completion. Furthermore, the management may reduce the duration of another project of similar content. The reduction in duration may not offer a safety margin of time should the project require an unexpected variation. Hence, the task owners intend to have a hidden buffer period for every task. This affects the total duration of the project and advantage of an early completion of a task does not pass on to the project. Therefore, it can be concluded that the traditional tools, such as critical path method (CPM), program evaluation and review technique (PERT), and bar chart do not entirely tackle excursion of a task duration in a heavy aviation maintenance project.

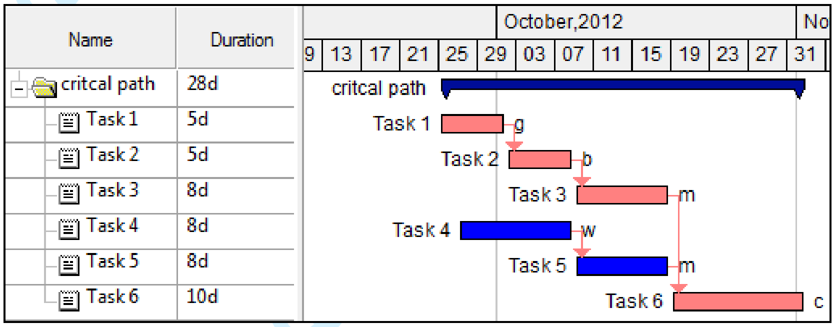
Conversely under CCPM, a critical chain is the longest chain of dependent events that consider both task and resource dependencies. It differs from the CPM, which considers only logical task dependencies, but ignores resource dependencies when calculating estimated project duration. The critical chain also solves the problem of multitasking, because a resource is allocated to perform one task at a time under this system. According to Goldratt (1997), the Student and Parkinson syndromes are reduced by aggressive estimation of the task duration at a 50% confidence level by using critical chain method. This brings down the total duration by one half (Leach, 2000; Goldratt, 1997).

The critical chain in figures 2 through 5 indicates reduction of task duration, arrangement of tasks according to latest start date, and resource conflict resolution. Tasks 1 through 6 in the critical path are performed by resources *b*, *w*, *m*, and *c* in 56 days (Fig.2). The critical path with reduced duration is shown in Fig.3. This presents a 50% reduction in the duration and tasks are arranged in accordance with latest start dates possible. As a result, all the tasks are completed in 28 days. Fig.4 presents conflict resolution for resource *m*. In view of resource constraint, the critical chain representing tasks 4, 5, 3, and 6 is the longest among all.



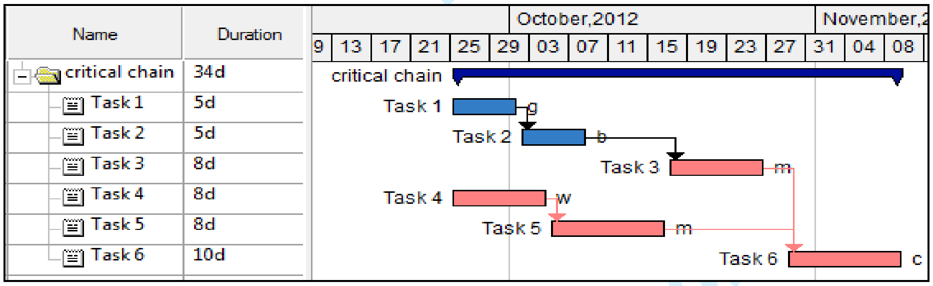
Name	Duration
critical path	56d
Task 1	10d
Task 2	10d
Task 3	16d
Task 4	16d
Task 5	16d
Task 6	20d

Figure 2 Identifying tasks and respective resources



Name	Duration
critcal path	28d
Task 1	5d
Task 2	5d
Task 3	8d
Task 4	8d
Task 5	8d
Task 6	10d

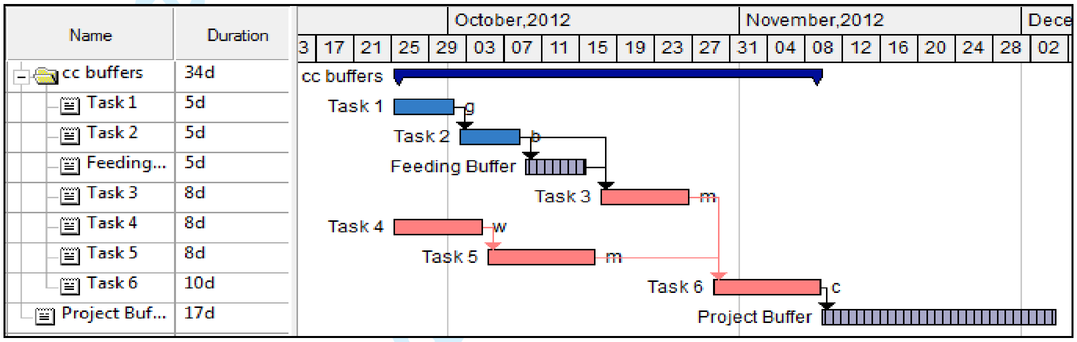
Figure 3 Reduction of duration



Name	Duration
critical chain	34d
Task 1	5d
Task 2	5d
Task 3	8d
Task 4	8d
Task 5	8d
Task 6	10d

Figure 4 Conflict resolution and the longest chain

Three types of buffers known as project buffer, feeding buffer, and resource buffer are used in CCPM method to manage impacts of variation and uncertainties in a project. Therefore, the buffers are placed at strategic points in the project flow. A project buffer is inserted at the end of the critical chain as shown in Fig.5 assuming that delays in the critical chain may consume some of the buffer period without affecting due date of a task. The project buffer is computed by isolating buffers from each task on the critical chain and adding them as feeding buffer and project buffer (Fig.5). A feeding buffer is inserted between the last task on a feeding path and the critical chain to absorb delay. Typically, it is 50% of the size of safety-time taken out of the feeding path. Similarly, a resource buffer is inserted in the critical chain, but it is not shown on the chart. A typical resource buffer is calculated depending on availability of resources excluding multi-tasking. Fig.5 also indicates that the critical chain is protected by buffers. Duration of the project buffer is set to 50% of the critical chain duration. According to Fig.5, the duration of the critical chain is 34 days and the feeding buffer in connecting chain of tasks 1 and 2 is 5 days. The feeding buffer is set at 50% of the feed chain and length of the feed chain is 10 days. As a result, the critical chain length is 34 days and total duration of the project including project buffer is 51 days against 56 days, which was originally estimated by the critical path method. This demonstrates that duration of a project can be reduced using CCPM method in a heavy aircraft maintenance program.



Name	Duration
cc buffers	34d
Task 1	5d
Task 2	5d
Feeding...	5d
Task 3	8d
Task 4	8d
Task 5	8d
Task 6	10d
Project Buf...	17d

Figure 5 Strategic locations of buffers

Execution of the project under CCPM method ensures that resources are dedicated to a task until it is completed to prevent multi-tasking. Consequently, tasks are prioritised according to rate of the buffer consumption. Therefore, priority is given to complete a task that affects a critical chain of the project instead of a task on a feeding path. Similarly, a task owner is not held responsible for delay in completing the task, because the management monitors rate of the buffer consumption and it intervenes to reduce the rate. Planned buffers and remaining duration of tasks are monitored during execution, because the amount of project buffer and feeding buffer consumed with respect to project progress indicate potential delay in project delivery. Project buffer variation plotted on a buffer consumption chart in Fig.6 compares percentage of completion buffer remaining (CBR) with percentage of critical chain remaining (CCR). No corrective action is required according to Fig.6, if the variation lies in green region, but preparation of a recovery plan becomes necessary for variation in amber region. Implementation of the recovery plan is essential, if the variation fall into red area shown in the figure. Tasks are monitored according to remaining duration instead of percentage of completion in order to design an effective recovery plan, because an estimate based on percentage of completion of a task assumes that an equal amount of time is required to complete all parts of a task. This may lead to an unreliable estimation. For example, 80% of a task is completed using 20% of the allocated time, but the last 20% of the task may consume 80% of the allocated time.

Conversely, if monitoring is done considering the remaining time, the issues causing slow progress can be identified and resolved.

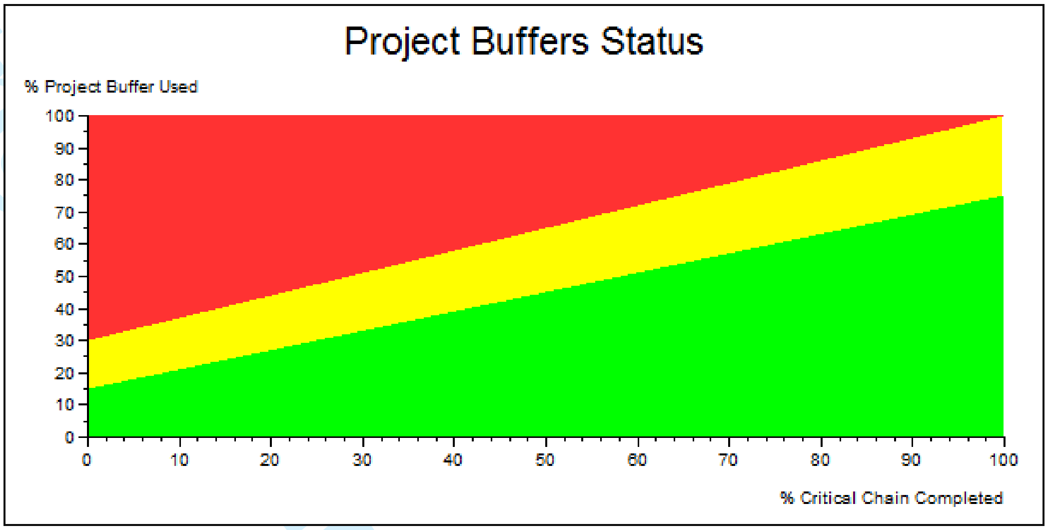


Figure 6 Buffer consumption chart

(Critical chain 100%= 6 days; Project buffer 100% = 3 days; Project status GREEN – Watch; Project status AMBER - Prepare a recovery plan; Project statusRED - Implement recovery plan; Project status = % completion buffer remaining / % critical chain remaining)

Discussion and analysis

An investigation of aircraft maintenance checklist and scope of work mentioned in Table 1 indicates that the tasks are interdependent. For example, inspection and modification tasks of an aircraft can begin after providing facilitation, such as opening of a panel or technical access doors on the aircraft structure. Furthermore, the observation in the field suggests that tasks are performed by multiple specialist teams of personnel exhibiting resource interdependency. For example, to carry out an avionics modification task by an avionics team, the relevant access panel opening and closing is done by an airframe team; modification hardware kit is supplied by inventory department, and the work procedure documents are issued by technical service personnel. Similarly, response to questions 1 and 2 of engineer questionnaire of the survey mentioned in Table 2 shows that 8 out of 10 respondents perform additional work in an assigned task. This signifies task variations. Likewise, 7 out of the 10 respondents to question 2 experience unexpected problems demonstrating uncertainty. Observation of an aircraft refuelling task validates that duration of the task had to be extended due to late arrival of allocated fuel tanker. This substantiates the interdependency of tasks in a heavy aircraft maintenance project.

Estimation of task duration in comparison with maintenance planning document (MPD) supplied by the aircraft manufacturer is indicated by Table 3 below. The comparison between planned task duration in proposed maintenance plan and the duration recommended by MPD in Table 3 suggests over estimation. Additionally, response to question 1 and 2 of planner questionnaire of the survey stated in Table 2 reveals that 9 out of the 10 planners increase task duration and all of them use historical values for estimating the duration. Response to question 3 and 4 of the engineer questionnaire in Table 2 denotes that 9 of the 10 engineers involve in multitasking and 8 out of the 10 are scheduled for tasks without considering availability of other necessary resources. The field observation also suggests the same. As a result, certain teams had to wait and more resources were allocated when become available to compensate for the lost time. This leads to multitasking that further increases the duration as a consequence. Further evaluation of question 5 of the engineer questionnaire suggests reporting issues. According to the survey, every engineer does not report early completion. Direct observation in the field had demonstrated that the tasks were either completed on time or they were delayed. This leads to believe that the buffer included in a task time during planning stage is wasted as postulated by the Student and Parkinson law effect.

Table 3 Estimation of task duration

S/N	ACTIVITY	Planned duration (Hours)	Maintenance Planning Document (MPD) duration (Hours)	Area
	PREPARATION:			
1	AIRCRAFT ARRIVAL	13.00	0.00	
2	INSPECTION OF ELEVATORS FOR EXCESSIVE FREE PLAY	13.00	2.00	Nose Tail
3	CHECK ELEVATOR SERVO CONTROL AND HINGE BEARINGS FOR EXCESSIVE PLAY AND CONDITION	13.00	1.15	Nose Tail
4	CHECK RUDDER SERVO CONTROL AND HINGE BEARINGS FOR EXCESSIVE PLAY AND CONDITION.	13.00	0.60	Nose Tail

5	CHECK RUDDER TRAILING EDGE FREE PLAY FOLLOWED BY REPLACEMENT OF BEARINGS OF RUDDER SERVO CONTROL EYE END AND HOUSING END	13.00	2.00	Nose Tail
6	HIGH PRESSURE CLEANING OF WASTE LINES	13.00	5.00	Cabin
7	ITCAN-BLUE	13.00	0.00	
8	AIRCRAFT DOCK IN AND SUPPORTED ON JACKS	13.00	4.00	All
9	PREPARATION AND INITIAL FUNCTIONS	26.00	3.00	All
10	RE-INSPECTION OF AIRCRAFT DAMAGE RECORD	26.00	0.00	
11	RIGHT HAND WING (RHW): PERFORM LEAK CHECK ON THE COMBO SEALS ON THE PYLON DUCT SLEEVES (DOWNSTREAM PRECOOLER)	13.00	0.10	Wing
12	RHW: PERFORM LEAK CHECK ON: A) THE FLEXIBLE SEALS ON THE PYLON TO WING DUCTING. B) THE WING TO FUSELAGE FLEXIBLE 'S'-DUCT	13.00	1.00	Wing
13	LEFT HAND WING (LHW) AND RHW: OPERATIONAL CHECK OF FLAP INTERCONNECTING STRUT AND FLAP DISCONNECT PROXIMITY SENSORS	13.00	0.10	Wing
14	LHW AND RHW: FLAPS LOCKED DUE TO TRANSMISSION OVERSPEED	13.00	2.00	Wing
15	ELECTRICAL POWER CUT	13.00	0.00	
	ACCESS/REMOVALS:			
1	ALL REQUIRED ACCESS PANELS AND FAIRINGS	39.00	5.00	All
2	ALL FUEL TANK ACCESS PANELS	26.00	3.00	Wing
	MAJOR INSPECTION:			

1	LHW AND RHW: DETAILED INSPECTION OF FLAP INTERCONNECTING STRUT AND ATTACHMENTS	13.00	0.30	Wing
2	ZONE 126: 1. GAIN ACCESS TO SKIN AIR OUTLET VALVE 2. CHECK PART NUMBER OF VALVE. 3A. REMOVE VALVE FOR OVERHAUL. 3B. REPLACE WITH A NEW VALVE	13.00	1.00	Nose Tail
3	HORIZONTAL STABILIZER - INSPECT INTEGRITY OF PRIMARY AND SECONDARY LOAD PATH AT THE LOWER ATTACHMENT	13.00	0.10	Nose Tail
4	ULTRASONIC THICKNESS MEASUREMENT OF THE FUSELAGE SKIN AROUND THE AFT LAVATORY (LAV) VENT OUTLET	13.00	2.50	Nose Tail
5	ENGINE #1; GENERAL VISUAL INSPECTION OF THE COMMON NOZZLE ASSEMBLY (CNA) FIRE PROOF BULKHEAD (ENGINE OR CNA REMOVED)	13.00	0.15	Engine
6	ENGINE#1 AND ENGINE #2: DETAILED INSPECTION OF INLET COWL ANTI-ICE SUPPLY DUCTS AND ASSOCIATED HARDWARE IN THE CORE COMPARTMENT.	13.00	0.45	Engine
7	ENGINE #1 AND ENGINE #2; IDV-T/R AFT CASCADE SUPPORT RING	13.00	0.25	Engine
8	LHW & RHW: INSPECTION OF THE INBOARD FLAP TRUNNION AND SLIDING PANEL	26.00	1.25	Wing
9	ZONE 145: DETAILED INSPECTION OF UPPER SURFACES OF PRESSURE DECK MEMBRANES AND SIDE BOXES, BETW FR 42-FR46	26.00	3.75	Nose Tail
10	LHW AND RHW: DETAILED INSPECTION OF PYLON TO WING ATTACHMENT FITTING LUGS AT RIB 4	13.00	0.52	Wing
11	LHW AND RHW: DETAILED INSPECTION OF PYLON TO WING FORWARD ATTACHMENT SHACKLES AT RIB 4	13.00	1.05	Wing
12	LHW AND RHW: DETAILED INSPECTION OF ENGINE PYLON FORWARD MOUNTING FITTING	13.00	0.55	Wing

13	LHW AND RHW: DETAILED VISUAL INSPECTION OF FORWARD CORNER FITTING OF PYLON AFT SECONDARY STRUCTURE	13.00	2.00	Wing
14	DETAILED INSPECTION OF CLEANLINESS INSIDE WASTE TANK.	13.00	1.00	Wing
15	AREA 3 INSPECTION OF RUDDER SHELLS FOR DISBOND (55-1035)	13.00	4.66	Nose Tail
16	LHW AND RHW: DETAILED INSPECTION FOR CRACKS OR CHAFFING ON THE LHW AND RHW WING OUTBOARD FLAP RIB 1 LOWER FLANGE	13.00	0.30	Wing
	NON DESTRUCTIVE TESTING (NDT):			
1	ENGINE #1, ENGINE #2; INSPECTION OF THE NUMBER 5 BEARING COMPARTMENT (OIL JET) AND OIL TUBES FOR COKING	13.00	7.00	Engine
2	ENGINE #1, ENGINE #2; LOW PRESSURE (LP) COMPRESSOR (FAN) SECTION AND FAN BLADE LUBRICATION - BOTH ENGINES	13.00	5.00	Engine
3	LHW AND RHW: SPECIAL DETAILED INSPECTION OF OUTER WING, TOP SKIN PANEL 2 OVERHANG BETWEEN RIB 4 - RIB 27	39.00	8.00	Wing
4	SPECIAL DETAILED INSPECTION OF CENTER WING BOX AT ENDS OF LOWER STIFFENERS 8 TO 15 LEFT HAND (LH) AND RIGHT HAND (RH)	39.00	1.50	Nose Tail
5	CHECK FOR LOOSE OR MISSING RIVETS AT RH OVERWING EMERGENCY EXIT CUT-OUT FRAME CORNERS INSPECTION AND REPAIR	39.00	2.90	Cabin
6	SPECIAL DETAILED INSPECTION (ROTO) OF CENTER WING	39.00	4.21	Nose Tail
7	SPECIAL DETAILED INSPECTION (US) OF OUTER WING BOX	39.00	0.80	Wing
8	SPECIAL DETAILED INSPECTION OF CENTER WING BOX AT ENDS OF LOWER SKIN STIFFENERS, 8 TO 15, LH/RH. PREPARATION: SEALANT REMOVED	39.00	4.00	Nose Tail

9	SPECIAL DETAILED INSPECTION (X-RAY) OF OUTER WING, BOTTOM SKIN RUNOUT OF BUTTSTRAP AT STRINGER 8, BETWEEN RIB 20 AND RIB 21, ADJACENT TO FRONT SPAR AND RUNOUT OF BUTTSTRAP AT STRINGER 11	52.00	0.80	Wing
10	LHW AND RHW: SPECIAL DETAILED INSPECTION (US) OF PYLON FORWARD MOUNT FITTING, END OF LOWER ARMS, AFT OF RIB 1, FORWARD AND AFT ATTACHMENT AND BOLT HOLES	13.00	0.52	Wing
11	LHW AND RHW: SPECIAL DETAILED INSPECTION (ROTO) OF PYLON FORWARD MOUNT FITTING AND SPIGOT FITTING	13.00	1.18	Wing
12	ZONE: 300 SPECIAL DETAILED INSPECTION OF THE HONEYCOMB CORE OF THE RUDDER LH AND RH SIDE PANELS	26.00	2.50	Nose Tail
13	PERFORM VACUUM LOSS INSPECTION OF RUDDER SHELLS FOR DISBOND (55-1035)	26.00	3.50	Nose Tail
14	SPECIAL DETAILED INSPECTION: CENTER WING BOX LH AND RH CRUCIFORM FITINGS	26.00	1.56	Nose Tail
15	LHW AND RHW: SPECIAL DETAILED INSPECTION OF PYLON TO WING FORWARD ATTACHMENT SHACKLES AT RIB 4	13.00	0.62	Wing
	COMPONENTS CHANGE:			
1	NOSE LANDING GEAR (NLG)/MAIN LANDING GEAR (MLG) DRIVE SELECTOR VALVES	13.00	3.00	LDG
2	REHEATER REPLACEMENT	13.00	2.30	Nose tail
3	NLG OLEO DYNAMIC SEAL REPLACEMENT	26.00	3.00	LDG
4	OFF WING SLIDE RESERVOIR OVER HEAD	26.00	0.60	Cabin

5	BATTERY CAPACITY INSPECTION; SLIDE OFFWING AND OVERHEAD	26.00	0.60	Cabin
6	PERFORM ENGINE REMOVAL/INSTALLATION.	39.00	16.00	Engine
7	PRIMARY AND MAIN HEAT EXCHANGERS REPLACEMENT	39.00	4.00	Nose tail
8	ZONE 200. 1. REPLACE FWD AND AFT WASTE TANK RINSE NOZZLE. 2. SEND REMOVED RINSE NOZZLES TO WORKSHOP.	52.00	1.00	Nose tail
9	AVIONICS - LAVATORY SMOKE DETECTORS	65.00	3.00	Nose tail
10	AVIONICS - COMMAND SENSOR UNIT	65.00	1.00	Nose tail
11	AVIONICS - AVIONICS COMPARTMENT SMOKE DETECTORS	65.00	2.00	Nose tail
12	AVIONICS - REPLCEMENT OF RADIO ALTIMETER ANTENNAS AND CABLES	65.00	12.00	Nose tail
13	AVIONICS - LIQUID LEVEL SENSOR REPLACEMENT	65.00	1.00	Nose tail
14	REMOVE ALL BUSINESS CLASS SEATS COVERS FOR LAUNDRY	65.00	4.00	Cabin
15	REMOVE ALL PASSENGER SEATS BOTTOM CUSHIONS	65.00	6.00	Cabin
16	REMOVE ALL ECONOMY CLASS SEATS COVERS FOR LAUNDRY	65.00	12.00	Cabin
17	POTABLE WATER EXTINGUISHER	26.00	2.00	Cabin
	WORKSHOP TRANSIT ITEMS:			
1	NLG TORQUE LINK APEX PIN FOR MAGNETIC PARTICAL INSPECTION (MPI)	13.00	2.00	LDG
2	PERFORM MPI OF INBOARD AND OUTBOARD ELEVATORS SERVOCONTROLS ROD EYE-ENDS	39.00	3.00	Nose tail
3	PORTABLE HALON FIRE EXTINGUISHERS FOR WEIGHT CHECK	65.00	2.00	Cabin

3	REMOVE LAVATORY "A", "E" "D" FIRE EXTINGUISHER BOTTLE FOR WEIGHT CHECK.	65.00	0.60	Cabin
4	FORWARD (FWD) AND AFT GALLEY DRAIN VALVE FOR CLEANING (IF APPLICABLE)	65.00	0.00	Cabin
5	FWD CABIN VACUUM TOILET RINSE VALVE FOR CLEANING	65.00	0.35	Cabin
6	FUNCTIONAL CHECK OF PRESSURE REDUCER FOR CARGO FIRE EXTINGUISHER SYSTEM.	65.00	2.00	Nose tail
8	ENGINE #1; CLEAN INTEGRATED DRIVE GENERATOR (IDG) OIL COOLER. NOTE: TASK TO BE PERFORMED AT OPPORTUNITY OF ENGINE SHOP VISIT	65.00	0.20	Engine
7	AVIONICS - CLEANING OF OXYGEN MASKS	65.00	0.10	Cabin
	MAJOR MODIFICATIONS:			
1	MOIFICATION (MOD): INTRODUCTION OF BEARING ASSEMBLY ON RETRACTION JACK	52.00	7.00	Wing
2	AVIONICS – MOD: INSTALL WIRING PROVISION FOR AIR TRAFFIC CONTROL (ATC) TRANSPONDER (XPDR)	91.00	3.50	Nose tail
3	AVI0NICS – MOD: INSTALL RS422 WIRING	91.00	3.50	Nose tail
4	AVI0NICS – MOD: INSTALL FLIGHT DATA INTERFACE UNIT (FDIMU) FROM TELEDYN	91.00	2.25	Nose tail
5	AVI0NICS - MOD: INTRODUCTION OF WIRING PROVISON FOR FDIU/DATA MANAGEMENT UNIT (DMU)	91.00	33.00	Nose tail
6	AVI0NICS – MOD: WIRE HARNESS INSTALLATION AT INTERFACE SECTION 19/19.1	91.00	2.00	Nose tail

7	WING: - INSTALL TRUNNION SLIDING PANEL WITH NEW ATTACHMENT	39.00	6.00	Wing
8	ENGINE #1 AND ENGINE #2; OVERWING MOD - REPLACE DEPLOY TUBE ADAPTOR O-RING	39.00	3.00	Engine
9	MOD: COCKPIT DOOR MODULE IMPROVEMENT	13.00	2.50	Nose tail
	MAJOR RESTORATION:			
1	ALL REQUIRED ACCESS PANELS AND FAIRINGS	52.00	5.00	Nose tail
2	ALL FUEL TANK ACCESS PANELS	52.00	3.00	Wing
3	ELECTRICAL POWER ON	13.00	0.00	
	FUNCTIONAL:			
1	SYSTEM FUNCTIONALS	26.00	8.00	All
2	LANDING GEARS (LG) RETRACTION TEST	13.00	4.00	Nose tail
	FINALS:			
1	REFUEL AND LEAK CHECK	13.00	4.00	Wing
2	ENGINE WASH AND ENGINE RUN	13.00	3.00	Engine
3	AIRCRAFT HANDOVER	13.00	0.00	

The planners in response to question 5 of their questionnaire (Table 2) stated that they were not used to create a work breakdown structure (WBS) and Gantt chat, generally. Similarly, some critical tasks included in maintenance schedule (Table 1) were not analysed by the engineers. As there was no priority set in task execution, any delay in carrying out a critical task could not be monitored. Therefore, the plan was not effective in dealing with uncertainty and variations in critical tasks. Besides, reply to question 3 of the planner questionnaire (Table 2) shows that 9 of the 10 planners did not allocate resources in planning phase of the project. It was found by field observation that resources were allocated during execution without any resource levelling and conflict resolution system in place. Investigation of the maintenance schedule and result of question 4 of the planner questionnaire (Table 2) signal an inadequate progress and resources utilisation tracking of the project.

A project plan using CCPM system was designed in view of issues identified by the survey, and a field observation was also done to validate various elements of this study. The heavy maintenance check is divided into different phases known as pre-check, defuel and dock, access facilitation, inspection and modification, component replacement, close up, refuelling and aircraft system tests (Fig.7) to tackle problems of task interdependency. For example, all panels are opened before starting the inspection.

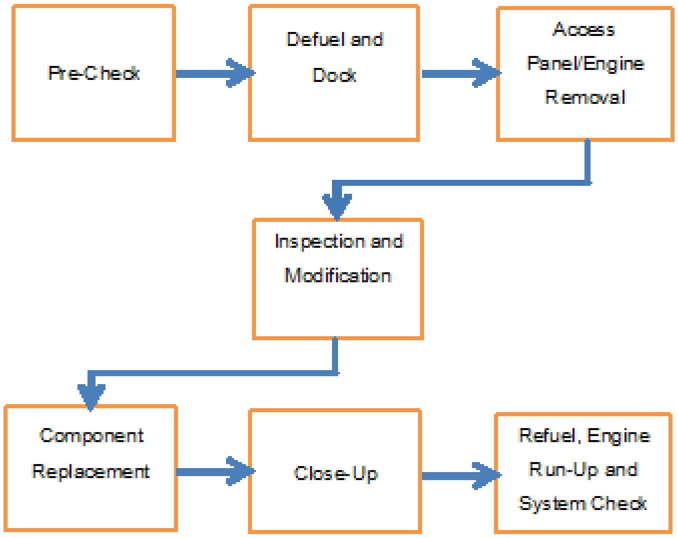


Figure 7 Maintenance process flow

In addition, a WBS is created as shown in Fig.8. Likewise, an estimation of duration as presented by Table 3 is derived using MPD. The duration is significantly aggressive with a probability of 50% principle discussed above in this study. In order to reduce Student syndrome and Parkinson law effect, work packages are created by grouping the tasks according to the phase, work area, and work team. Table 4 outlines the work packages related to various tasks and the duration of each package is estimated by adding individual task durations as presented in the table. This method simplifies the allocation and it also reduces resource interdependency. The plan resolves resource and task conflicts using a critical chain.

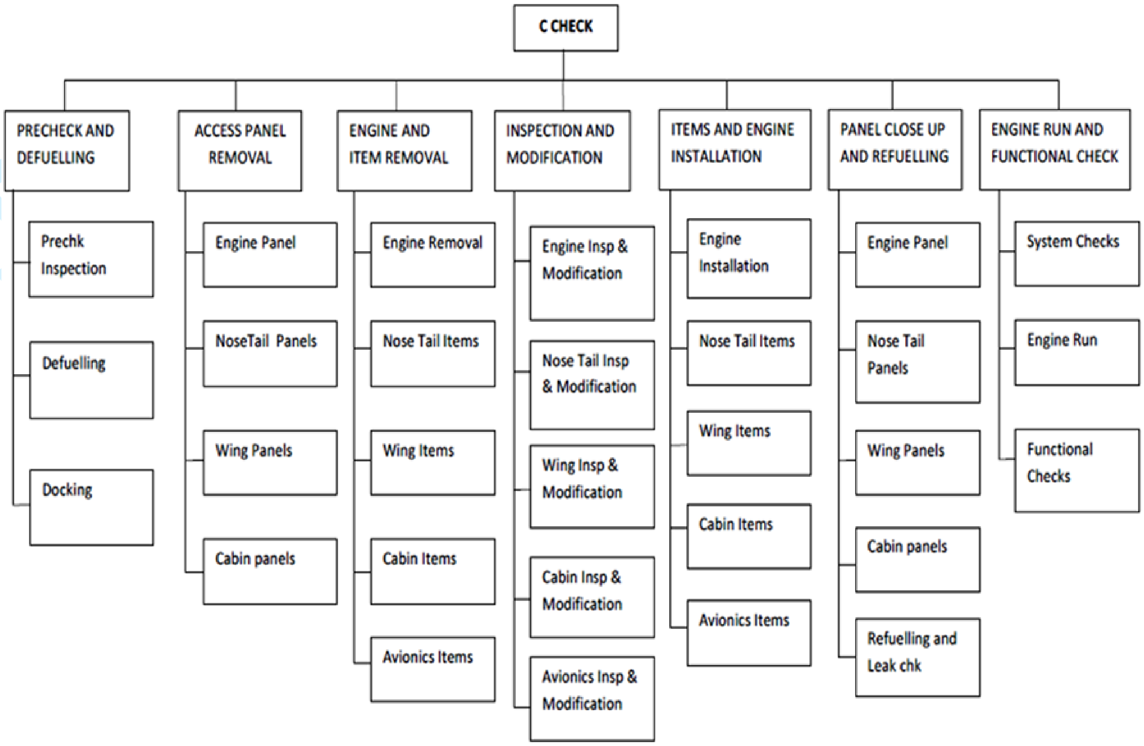


Figure 8 Work breakdown structure

Table 4 A sample of work packages

Item replacement
Work package: CAB_AF_COMP_REPL
Phase: ITEM REPLACEMENT
Area: CABIN
Total Duration (DUR) in hours :13.55
Team: CAB_AF
TASK :
1. OVERWING SLIDE RESERVOIR DUR=.60 BCI, SLIDE OFFWING RH DUR=.60
2. INSTALL ALL BUSINESS CLASS AND ECONOMY SEATS COVERS DUR=6.0

3. INSTALL ALL PASSENGER SEATS BOTTOM CUSHIONS. DUR= 2.00
4.. POTABLE WATER EXTINGUISHER DUR=2.0
5. PORTABLE HALON FIRE EXTINGUISHERS DUR=2.0
6. LAVATORY FIRE EXTINGUISHER BOTTLE DUR=.60
7. FWD CABIN VACUUM TOILET RINSE VALVE DUR=.35
Work package: NT_AF_COMP_REPL
Phase: ITEM REPLACEMENT
Area: NOSE_TAIL
Total Duration in hours: 0 (each side)
Team: NT_AF
TASK :
1.NLG AND MLG DRIVE SELECTOR VALVES DUR=3.00
2.NLG OLEO DYNAMIC SEAL REPLACEMENT DUR=3.00
3. NLG TORQUE LINK APEX PIN DUR = 2.00
4. REHEATER REPLACEMENT DUR = 2.30
5. PRIMARY AND MAIN HEAT EXCHANGERS REPLACEMENT DUR=4.00
6. ZONE: 200 1. REPLACE FWD & AFT WASTE TANK RINSE NOZZLE. DUR = 3.00
7. PERFORM MPI OF THE ELEVATOR INBOARD AND OUTBD SERVOCONTROLS ROD EYE-ENDS DUR= 3.0
8. FUNCTIONAL CHECK OF PRESSURE REDUCER FOR CARGO FIRE EXTINGUISHER SYSTEM. DUR=3.0
9. ZONE: 126 1. GAIN ACCESS TO SKIN AIR OUTLET VALVE. CHECK PART NUMBER OF VALVE. REPLACE WITH

A NEW VALVE, IF REQUIRED DUR=1.00
Work package: AVIO_COMP_REPL
Phase: ITEM REPLACEMENT
Area: AVIO
Total Duration in hours:19
Team: AVIO1, AVIO2
TASK :
1. CLEANING OF OXYGEN MASKS DUR=.10
2. LAVATORYSMOKE DETECTORS DUR= 3.00
3. COMMAND SENSOR UNIT DUR= 1.00
4. AVIONICS COMPARTMENT SMOKE DETECTORS DUR=2.00
5. REPLCEMENT OF RADIO ALT ANTENNAS AND CABLES DUR=12
6. LIQUID LEVEL SENSOR REPLACEMENT DUR=1.0
Close-up and engine installation
Work package: L_ENG_REPL, R_ENG_REPL
Phase: CLOSEUP
Area: ENGINE
Total Duration in hours:.8.0(each side)
Team: L_ENG,R_ENG
TASK :

PERFORM ENGINE INSTALLATION DUR=8 .0
Work package: NT_AF_CLOSE
Phase: CLOSEUP
Area: NOSE-TAIL
Total Duration in hours: 5.00
Team: NT_AF
TASK :
ALL REQUIRED ACCESS PANELS & FAIRINGS DUR=5.00
Work package: W_LH_CLOSE, W_RH_CLSEUP
Phase: CLOSEUP
Area: WINGS
Total Duration in hours(DUR) :.3(each side)
Team: LW_AF,RW_AF
TASK :
ALL FUEL TANK ACCESS PANELS DUR = 3.00

Fig.9 presents the critical chain designed using specialised software. The chain alleviates the problem of multitasking, because only one task at a time is performed by one team and the tasks are started after ensuring relevant resource availability. A project buffer equal to 50% of the critical chain duration is added in the plan for this study (Fig.9). Actual duration of the buffer is 3 days. In addition, feeding buffers are inserted between the last task on a feeding path and the critical chain to absorb delays. The feeding buffer is equal to half of the size of safety time taken out of the feeding path as shown in Fig.9. This resolves the issues of uncertainty and variation in task duration.

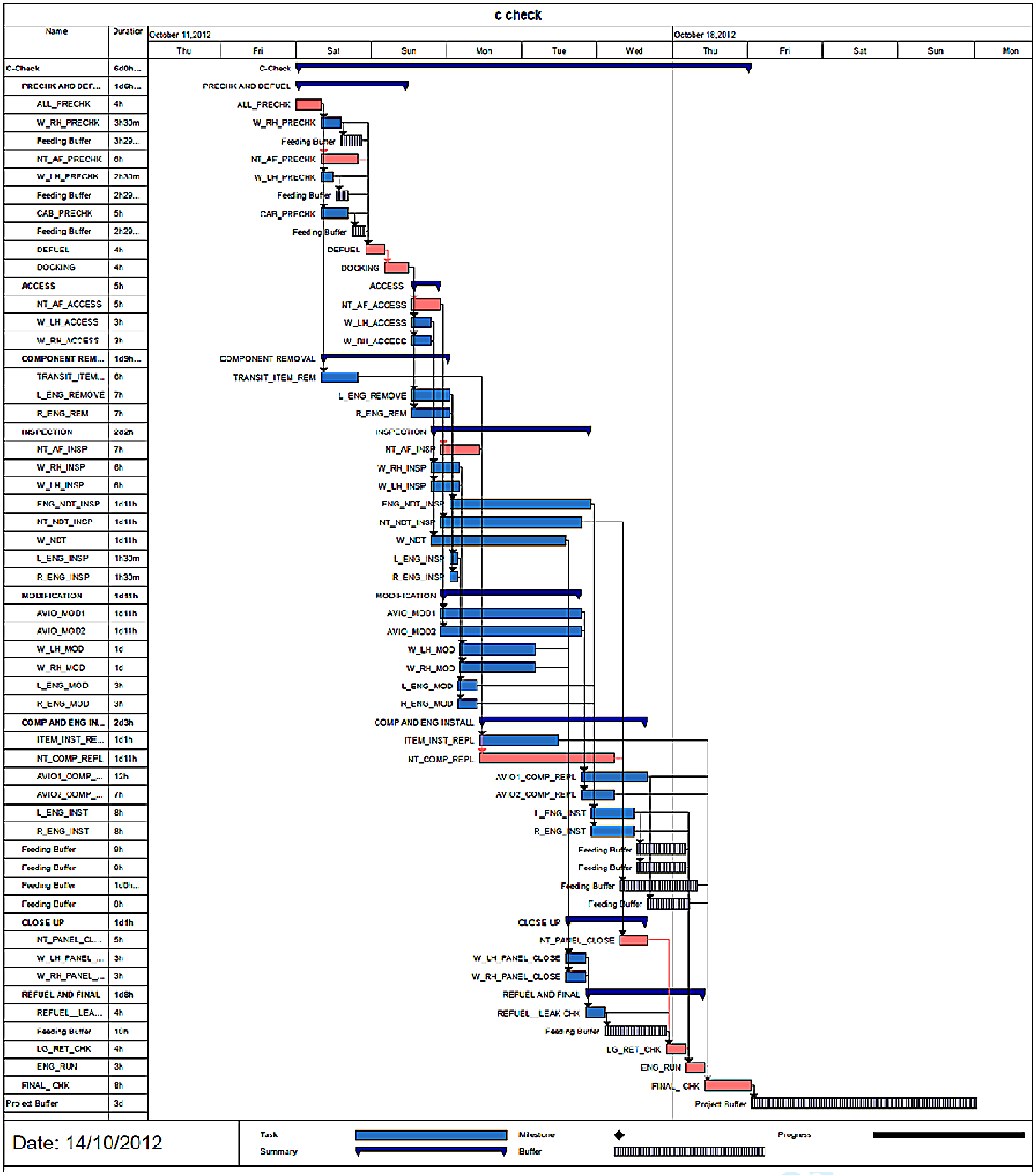


Fig.9. Critical chain with safety buffers

Finally, progress tracking of the project is carried out using a buffer consumption chart presented by Fig.6. As a result, this study demonstrates that the maintenance check plan designed in accordance with critical chain principle is able to reduce the check completion duration from 11 days to 6 days by tackling uncertainty and variation in task durations, multitasking, wastage of safety buffers happenings due to Student syndrome and Parkinson law effect, deadline, and milestone issues.

Conclusion

Maintaining an aircraft to meet mandated airworthiness standard is a costly affair for an airline and it also amounts to a significant revenue loss for the airline when the aircraft is taken out of service for maintenance. Therefore, innovative maintenance management methods are required to keep the cost within an acceptable limit. Aircraft maintenance tasks are divided into various categories according to depth of the required maintenance and to reduce out of service period of the aircraft as a consequence of the maintenance. Considering the heavy maintenance checks as individual projects, this study was focused on a typical check C carried out on an Airbus 320 aircraft at a major aircraft maintenance facility. The paper compares the traditional project management method with critical chain project management method in view of reducing the aircraft down time duration for carrying out the check C. It is argued that length of a critical path and total duration of the check can be reduced using critical chain method. The typical check C planned by this study repositions buffers using aggressive estimation along with other techniques in order to shorten the chain path. As a result it manages to reduce the duration of the project by 5 days, which is around 8.92% of the total.

The paper explores a possibility of using CCPM method in view of reducing the duration of a heavy maintenance check. The study observes that the duration is affected by long term strategic and tactical issues, such as available qualified personnel, aircraft spare parts, project value, and planned schedule. Therefore, a survey on the personnel involved in the maintenance along with necessary field observations is carried out as a part of this study. Analysis of the survey and observations has identified a number of issues affecting the duration, such as task and resource interdependency, variation and overestimation of task duration, wastage of buffers during execution, managing by milestones and deadlines, multitasking, critical path identification, and project progress tracking using the traditional critical path method. Consequently, an attempt has been made to minimise or prevent these issues by applying the CCPM principle for the heavy maintenance project. Foremost solution explored is adding project and feeding and buffers at strategic points on the critical chain to reduce uncertainty, variation in task duration, and wastage of safety buffer caused by student syndrome and Parkinson law effect. Typically, the feeding and project buffers are calculated as 50% of the size of safety-time taken out of the feeding path and 50% of the critical chain duration, respectively. Consequently, the duration required to complete a task is estimated at 50% level confidence using aggressive task duration estimation, because the feeding buffers are available at strategic location to complement the duration, if required. Similarly, the issue of multitasking is resolved by creating a critical chain based on resource and task constraints. Likewise, the process of managing by deadlines and milestones is replaced by a system of monitoring progress of the project using buffer consumption.

In conclusion, the traditional tools, such as CPM, PERT and bar chart do not totally address deviations of task duration in a heavy aviation maintenance project. Conversely, a critical chain of CCPM is the longest chain of dependent events that consider both task and resource dependencies in managing the duration. The chain differs from the CPM, which considers task dependencies, but ignores resource dependencies while calculating the duration. It can therefore be argued that application of the CCPM principles can reduce the duration of a heavy aircraft maintenance check, but uncertainty and variation of tasks remain an issue. However, this study has been carried out in a single project situation focusing on project planning and execution. Hence, further investigation may be required to analyse the effects of a multi project environment. Moreover, the method presented in this study is not considered as a substitute for effective project management skills.

.

References

Adams, C. (2012). “Project management technology: Keeps critical chain bright”. Retrieved September 20, 2012, from Realization: http://www.realization.com/pdf/articles/Aviation-Maintenance-PM-Technology-Keeps-CC-Bright.pdf.

Airbus.(2012). “A318/A319/A320/A321 maintenance planning document”. Toulouse: Airbus Industrie.

Goldratt, E. M. (1997). “Critical chain”. Massachusetts: The North River Press.

Hamad, A., Potter, A., Naim, M. (2007). “An outsourcing decision model for airlines' MRO activities”, Journal of Quality in Maintenance Engineering, 13(3), 217-227.

Herreraa, I.,Nordskag, A., Myhre, G., & Halvorsen, K. (2009). “Aviation safety and maintenance under major organizational changes, investigating non-existing accidents”, Accident Analysis and Prevention, 41(2009), 1155-1163.

Karadzic, R., Petkovic, D., & Sabic, M. (2012): A model for the maintenance of old aircraft, *Aviation*, *16*(1), 16-24.

Kerzner, H. (2006). “Project management: A systems approach to planning, scheduling, and controlling (9th ed.)”. New Jersey: John Wiley & Sons, Inc.

Knotts, R. M. H. (1999). “Civil aircraft maintenance and support fault diagnosis from a business perspective”, Journal of Quality in Maintenance Engineering, 5(4), 335-348.

Leach, L. P. (2000). “Critical chain project management”. Boston: Artech House Inc.

Marya, V., Parkins, M., Sachs, K., & Shaw, C. (2013). “Excellence in cost management: A new era for aerospace”. San Francisco: McKinsey & Company.

Masmoudi M, H. A. (2010). “A tactical model under uncertainty for helicopter maintenance planning”. *Proceedings of 8th ENIM IFAC International Conference of Modeling and Simulation*. Tunisia: MOSIM.

Pandit, P. N. (2007, December). “Tenets of MRO strategy for airlines”. Bangalore: Infosys Limited.

Papakostas, N., Papachatzakis, P., Xanthakis, V., Mourtzis, D., & Chryssolouris, G. (2009). “An approach to operational aircraft maintenance planning”, Decision Support Systems, 48(2010), 604-612.

Samaranayake, P. (2006). “Current practices and problem areas in aircraft maintenance planning and scheduling: Interfaced/integrated system”. *Proceedings of the 7th Asia Pacific Industrial Engineering and Management Systems Conference.* Bangkok: Asian Institute of Technology.

Srinivasan, M. M., Best, W. D., & Chandrasekaran, S. (2007). “Warner Robins air logistics Center streamlines aircraft repair and overhaul”, *Interfaces, 37*(1), 7-21.

Srinivasan, M., & Best, W. D. (2006, March). “Back on the runway: The United States air force meets critical chain project management”. *APICS Magazine,* 20-23.

The TOC Centre of Australia Pty Ltd. (2006). “White paper: the transition to a constraint based maintenance organisation in the airline industry”. Retrieved September 16, 2012, from TOC Centre of Australia:http://www.tocca.com.au/Documents/ConstraintBasedMaintenance.pdf.

Biographical Details

Anand Kulkarni holds a master degree in management and he is associated with Singapore International Airlines and National University of Singapore. In addition to the academic qualifications, he also holds an aircraft engineer license on wide-body Airbus and Boeing aircraft. His research interests include aeronautical engineering, avionics, project engineering, and aviation management.

Devinder Kumar Yadav holds a doctorate degree in engineering and he is associated with Shenyang Aerospace University, China. In addition to the academic qualifications, he also holds an aircraft engineer license with several ratings starting from Cessna 152 to wide-body Airbus and Boeing aircraft, and a pilot license. His research interests include aeronautical engineering, airport engineering, aviation regulations, multidisciplinary engineering, flight safety, and aviation management.

Hamid Nikraz holds a doctorate degree in engineering and he is associated with Curtin University, Australia. His research interests include civil engineering, aviation engineering, transportation and airport engineering, and multidisciplinary engineering.