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Procedure structuring for programming aircraft maintenance activities

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Abstract

Purpose – This paper aims to exemplify the use of project management tools in the scheduling of aircraft maintenance activities. This process is known as maintenance, repair and overhaul and it has gained importance within the aeronautical sector due to its expected growth in the coming years; however, it also faces increasing competitiveness in its market. This fact gives rise to the need of acting in maintenance management and seeking lower costs while maintaining the quality of the service provided. The purpose of this paper is to propose the structuring of a procedure that aims to reduce the total maintenance time (downtime) and guarantee the delivery of the aircraft on time.
Design/methodology/approach – The paper, through a case study at a Brazilian aircraft maintenance center, used critical path method and critical chain project management, the latter being derived from the theory of constraints, with the purpose of analyzing resources systematically and synchronizing the activities in the precedence network.
Findings – As a result, it is shown that downtime can be reduced from 11 to 5 days and improvements are proposed to achieve greater market competitiveness.
Originality/value – This paper demonstrates the competitive advantage that resulted from the application of project management tools in the aircraft maintenance planning and execution.

Keywords MRO, Project management, TOC, Aircraft maintenance, Critical chain project management, Critical path method

Paper type Case study

1. Introduction

Nowadays the Brazilian aeronautical sector is among the four largest aircraft manufacturers in the world. This sector is characterized by its strong growth potential, a positive contribution to the trade balance and the generation of jobs and income because of the high technology and added value of its products. These achievements are due to, among other reasons, the decision taken by the Brazilian Government to define the domain of aeronautical technology as a strategy and to invest in the development of this industry (Gomes, 2012; Montoro and Migon, 2009).

However, there is a high competitiveness in the aeronautical market generated by the organizations that started to operate at a global level and by the dynamism of the sector, which can be confirmed by the increasing level of customers' requirements for safety, efficiency and product costs. In order to remain competitive in the international market, companies in this sector began to diversify their activities to other segments and to

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incorporate technological innovations, which is the main competitive factor of the worldwide aeronautical industry (Ferreira, 2009).

According to Lucinda (2012), another critical factor for international competitiveness is the company's strategy. Business strategies such as offering modern and efficient aircraft or having a global system of maintenance, as well as the strategy of serving different market niches, can determine important advantages in competitiveness.

In addition, in order to maintain the levels of customer satisfaction and, consequently, competitiveness in the global market, representatives of the Brazilian aeronautical industry have been trying to obtain a prominence in customer service. Moreover, the expected revenue from maintenance over an aircraft's lifespan is high. Thus, these companies offer customer support and after-sales services, which include parts repair and aircraft maintenance services, to ensure the safety of operations (Silva *et al.*, 2011).

It is important to highlight that aircraft maintenance plays an important role in the aviation industry. This service aims to maintain the airworthiness and reliability previewed in civil, executive and military aircraft projects throughout their operational lives. According to Marais and Robichaud (2012), in the absence of maintenance, systems parts deteriorate due to usage or age, which can cause component failure and compromise system security, reinforcing the importance of maintenance service and repairs.

Nevertheless, the activity called maintenance, repair and overhaul (MRO) is extremely affected by fluctuations in the financial market and new competitors. Therefore, it is imperative that these companies seek low and predictable costs, while ensuring a competitive total maintenance time. In this way, aircraft maintenance and component repairs centers must guarantee a fast, quality service with competitive cost in the market (Reményi and Staudacher, 2014).

This paper presents a case study carried out in an aircraft maintenance center that composes the Brazilian aeronautical sector. The objective of the study is to analyze and propose a sequencing method for maintenance activities in order to reduce the total downtime. Once the sequencing aims to increase the aircraft availability, it has a strong influence on delivering the service in a competitive time (Reményi and Staudacher, 2014).

In recent years, some tools used in project management, such as critical path method (CPM) and critical chain project management (CCPM), have been applied successfully in the management of MRO activities. Summers (1965) described the concepts of the traditional project management method CPM applied in aircraft maintenance. Srinivasan *et al.* (2004) applied tools derived from TOC and lean thinking at a US Navy equipment maintenance center. Zhang *et al.* (2010) applied CCPM method in ship maintenance. Kulkarni *et al.* (2017) applied CCPM method to aircraft maintenance checks classified as heavy maintenance. This paper aims to apply such project management tools, but jointly, in the aircraft maintenance process. The object of this study is an aircraft maintenance type classified as light maintenance, where no structural modifications or tasks that require the disassembly of critical parts of the aircraft are executed. These tools provide an assertive scheduling of activities, leading to a detailed activity planning, with deadlines and resources clearly defined. Therefore, there is a great probability of completing the maintenance on the due date.

The rest of the paper is organized as follows: Section 2 provides the general theoretical context of maintenance, aircraft maintenance and the tools that will be applied in this study. In Section 3, we present the case study and the systematic application of CPM and CCPM to the problem studied. Finally, Section 4 discusses the results and points directions for future research.

2. Theoretical contextualization

2.1 Maintenance

Maintenance can be described as a combination of technical and administrative actions with the objective of keeping an item working according to the specifications of its project or restoring it to those conditions, thus avoiding failures and ensuring operation within predefined specifications. This wide concept of maintenance includes routine activities, periodic inspections and preventive replacements, among others (Barlow and Proschan, 1965; Rausand and Høyland, 2004; Fogliato and Ribeiro, 2009; Paschoal *et al.*, 2009).

Maintenance, according to Rausand and Høyland (2004) and Otani and Machado (2008), can be classified into three types:

(1) corrective – maintenance is performed after a breakdown occurs;

(2) preventive – maintenance is performed at predetermined intervals to reduce the likelihood of failure or degradation; and

(3) predictive –maintenance is performed based on the systematic application of analysis techniques in order to reduce preventive maintenance to a minimum and reduce corrective maintenance.

In recent years, the operation of maintenance industry has been modified due to changes in the way companies see the strategic importance of this sector. Market-leading companies are replacing corrective and preventive maintenance with predictive maintenance techniques to predict system failures, ensure great availability for use and reduce the number of interventions during operation. Another reason why this change is occurring is the cost generated by the different types of maintenance. The average cost of corrective maintenance is twice in comparison with the average cost of predictive maintenance and the cost of predictive maintenance is on average 50 percent lower than that of preventive maintenance (Otani and Machado, 2008).

Hence, it is a worldwide trend in the maintenance industry to increase data analyses and plan interventions effectively in order to maximize the element availability and maintain continuous operation, similarly to aircraft maintenance, which will be discussed below (Reményi and Staudacher, 2014).

2.2 Aircraft maintenance

Aircraft maintenance, which aims to maintain airworthiness of the aircraft and the reliability expected in its design during its operational life, has undergone changes over the last few years. With an increasing flow of people flying, the demand for aircraft availability has also increased. In this way, companies in the MRO industry need to invest in their skills and qualifications to ensure high quality work and remain competitive in the market.

Another change affecting the maintenance industry is the increase in demand for aircraft. In addition to the increase already occurred to date, it is projected that aircraft production will increase by 25 percent over the next ten years. These new aircrafts, with new technologies, should receive a maintenance plan for their entire operational life, which will bring new challenges for companies in this sector (Deal, 2016).

In addition to the changes already addressed, according to Hazelwood (2016), the most significant prediction for the MRO industry for the next ten years is the change in the composition of the fleets. Currently, only 10 percent of the operating fleet is classified as the "new generation" aircraft. However, in the next ten years that number will rise to 50 percent. Such a change will have a profound impact on how MRO firms work.

Furthermore, aircraft maintenance is the main reduction source in the airlines' high operating cost, since the two largest cost holders (fuel and wages), which account for 49 percent of the revenue of a flight, do not have large margin for reduction. Thus, maintenance, one of the few areas that can help these companies to increase their profits and that accounts for an average of 11 percent of a flight's revenue, when converted into an efficient and effective business, can increase the value of investments in this industry (Deal, 2016).

Therefore, the maintenance sector in the aviation industry, as well as in industry in general, is a sector of great importance for the return generated when improvements are applied. Moreover, due to major changes that are occurring in world aviation, this industry is also surrounded by challenges and opportunities. Because of this dynamism, in addition to investments in skilled labor, infrastructure and capability, MRO companies must combine these investments with an effective management method.

2.3 Maintenance management tools

The main goal of maintenance management is to provide the highest equipment availability and the lowest product cost. Among the main tools used in industrial maintenance management for this purpose are failure analysis and total productive maintenance (TPM). Failure analysis aims to address the root causes of the most critical problems to eliminate the causes of maintenance problems and not just their symptoms, thus preventing them from occurring again. An important feature of this method is data analysis, which is used to discover the cause of the problem, whereas managing using TPM acts preventively, improving the processes and encouraging people involved to participate in this continuous improvement. Unlike failure analysis, this tool is not intended to address problems but to avoid their occurrences (Piechnicki, 2011).

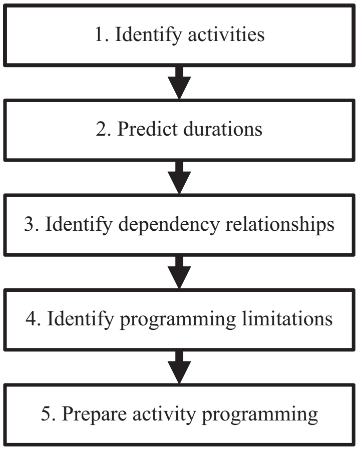
Similar to industrial maintenance, aircraft maintenance also utilizes tools that support maintenance management and data analysis. Tools commonly used in project management can also be applied in aircraft maintenance management. In this context, the maintenance of an aircraft can be classified as a project. As in aeronautical maintenance, according to Carvalho *et al.* (2005), a project is characterized as a set of coordinated activities that have start and end dates and time, resources and cost limitations. In this way, two concepts that are widely used in the management of the aeronautical industry will be described, specifically in its maintenance: CPM and CCPM.

2.3.1 Critical path method. CPM is a method used in activity sequencing that was successfully applied and improved by the US Navy during the Polaris program to reduce a project completion time. As aircraft maintenance centers aim to ensure great availability for their customers, and for this purpose it is necessary to decrease the maintenance check total time, this tool is commonly used in this sector. It can be used to define the activity flow to be performed, including the precedence between tasks, and calculate the best starting and finishing time for each task (Summers, 1965).

CPM method consists in the creation of an activity network with well-defined deadlines and sufficient time for completing each one of them, which makes the probability of finalizing the project on time be 90 percent (TOCCA, 2006, p. 3). If the interdependence between tasks and their durations is known, this tool allows finding the longest path in the project (critical path), which will determine the project duration. In addition, when finding the tasks that are on the critical path, which cannot have start or end dates changed, it is possible to prioritize the management of these tasks to ensure that there are no delays in their execution and that the project will be finalized on time. The Gantt diagram, a bar chart that aims to represent a process in a system of axes, is also commonly used jointly with this network diagram. The list of activities that are part of the project is arranged in the axis of ordinates and their durations in the abscissa axis (Santos *et al.*, 2010). Both can be implemented with Microsoft Project software, which will be used to develop this study.

In order to operationalize the implementation of CPM, Miranda and Almeida (2002) presented a five-step scheme that can be used to manage large projects as shown in Figure 1.

In this scheme, the first step consists in identifying the activities that compose the project, i.e., the operations that consume time and resources, as breaking the project in smaller parts generates a greater understanding of the project. Subsequently, the time



Source: Adapted from Miranda and Almeida (2002)

Figure 1.
Five-step scheme for large project management

required to perform these tasks is estimated, which can be done with the support of probabilistic tools or historical data analysis. The third step consists in identifying the dependency relations between tasks, that is, the activity precedence network. These relationships may be of technical origin or dependent on the logic of the project, and they are fundamental in the project planning development. In the fourth step, the project's limitations are identified, which are related to resources and time availability. After passing through all the four previous steps, in the last step, the activities are scheduled indeed.

Although the CPM method is one of the most widely used sequencing techniques, it is not the most suitable one for managing projects in the MRO industry, because it does not consider resource unavailability when these resources are allocated to perform tasks in another project. It assumes that resources are always available (Zhang *et al.*, 2010). In addition, if an activity is finalized in advance the next task will not be initialized immediately because it is scheduled to start on its original start date (TOCCA, 2006). Therefore, this method should not be used exclusively, but combined with a tool that meets these needs, such as the critical chain method, which is described in the next subsection (Zhang *et al.*, 2010; TOCCA, 2006).

2.3.2 Critical chain project management and theory of constraints (TOC). Managing projects using CCPM is a concept based on TOC and it can be allied to more traditional tools such as CPM to support time management. This methodology is an expansion of critical path concept, since besides defining a critical path, it also determines where buffers should be placed to avoid delays in project delivery (Srinivasan *et al.*, 2004).

Projects involve uncertainties and deal with three different commitments: delivery date, cost and quality. At the same time, in most organizations they occur concurrently, which is denominated a multitasking environment, and human resources cannot determine which tasks are priorities (The Goldratt Institute, 2001). In this scenario, TOC defines an organization as a system that can be compared to a chain composed of several links, as processes present in the organization are interdependent and must be analyzed jointly. Additionally, TOC admits that there will always be a weaker link, the system constraint, which should be strengthened so that the overall performance is optimized (Noguchi, 2006). Thus, TOC can be defined as a management philosophy that assists organizations to improve their performance by focusing on their constraints (BearingPoint, 2003).

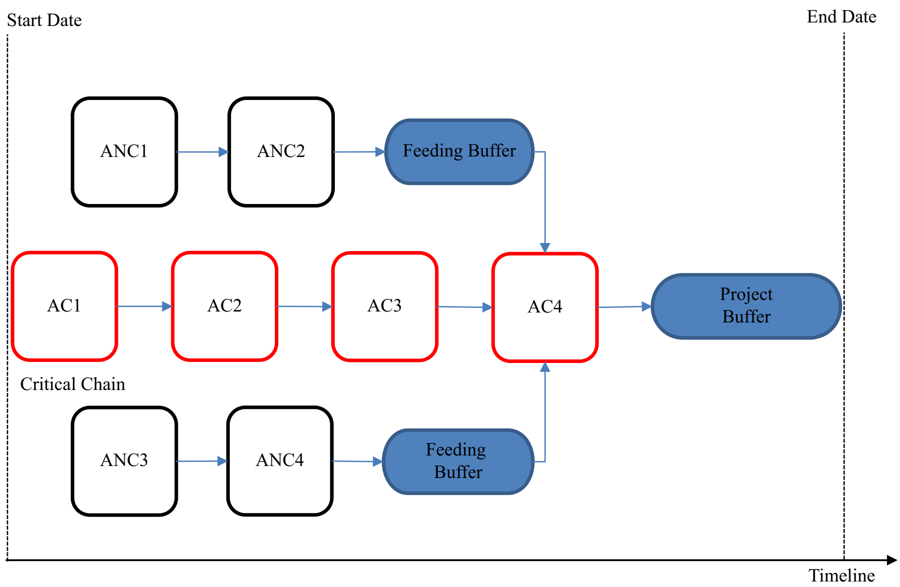
When TOC is applied in project management in order to reduce its duration and improve resources usage, it is noticed that the project constraint is usually a resource divided among several projects or several critical and non-critical paths within the same project. To solve this issue, CCPM network diagram is employed, in which all activity paths are analyzed systemically, in order to synchronize tasks that share the same resource and define priorities (Barcaui and Quelhas, 2004).

According to Barcaui and Quelhas (2004), critical chain method suggests a reduction in task durations and the removal of safety margins placed naturally when durations are estimated. The purpose of this method is to reduce the critical chain size and place part or the entire safety margin in a buffer at the end of the critical chain (project buffer)or at the end of non-critical paths (feeding buffer) to ensure that they do not become critical. Project total time will be estimated by adding the project buffer to the critical chain, as it can be seen in Figure 2.

The project buffer is the responsible for protecting the project from the effects of variability during critical tasks performance. This buffer can be calculated as the sum of reductions in critical activities durations, the same way as buffers of non-critical chains are calculated. The duration reduction is defined as the difference between an aggressive, although achievable completion time and a completion time with high probability of being reached. It should be noticed that these buffers are reservations of time rather than resources (Srinivasan *et al.*, 2004; The Goldratt Institute, 2001).

In order to operationalize the CCPM tool implementation, Noguchi (2006) describes four steps to be followed. The first step is to create the project task network, what can be done by applying the CPM tool described previously. A schedule created using CPM is shown in a form of Gantt Chart in Figure 3.

Still during the task network creation phase, CCPM methodology recommends that activity durations be reduced to an aggressive value to decrease the total project time. As it



Note: AC1, AC2, AC3 and AC4 represent the activities of the critical chain and ANC1, ANC2, ANC3 and ANC4 represent the activities of non-critical chains
Source: Prepared by the authors based on Srinivasan *et al.* (2004)

Figure 2.
Critical chain concept

is presented by Figure 4, activity durations were reduced by 50 percent of their initial values, however, this percentage may vary according to each project manager's strategy.

The second step is described as the critical chain identification. In this step, all resources that are running more than one task at the same time are identified and the tasks are synchronized in order to extinguish the multitasking environment, as it is known to reduce resource efficiency. In the example given in Figure 4, resources A and B are overloaded. After synchronization, the critical chain will be the longest path in the CCPM network, considering the dependencies between tasks and resources, as shown in Figure 5.

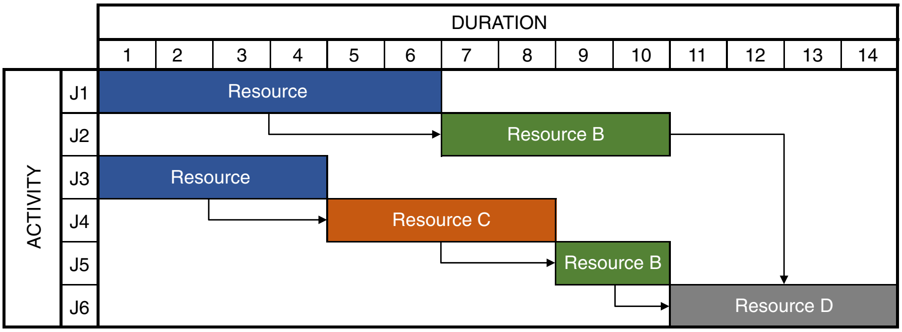


Figure 3. Gantt chart: Initial schedule of activities (critical path method)

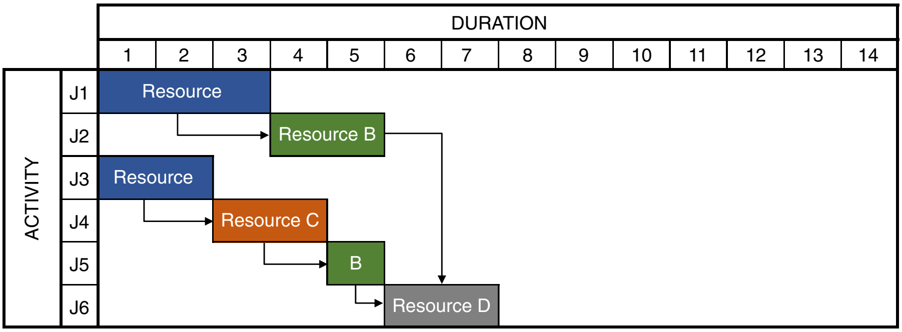


Figure 4. Schedule of activities with reduced durations

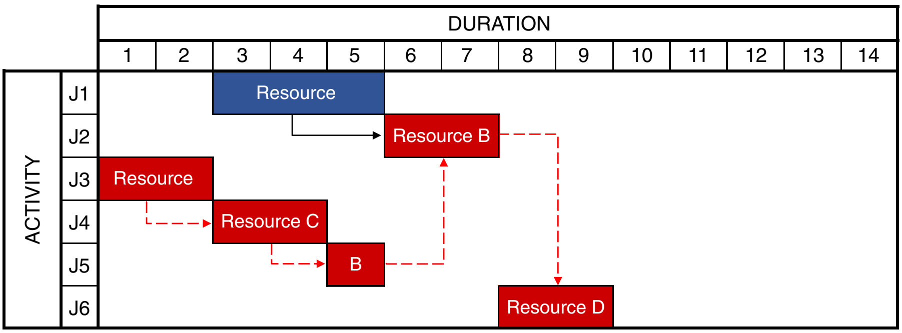


Figure 5. Schedule of activities with synchronized resources (A and B) and critical chain identification

In the third step, that is called protecting the critical chain, buffers are inserted to protect the project against variability during task executions. The project buffer inserted after the critical chain and the feeding buffers inserted after the non-critical paths that converge into the critical chain are usually calculated through the sum of the duration reductions made on tasks in the path preceding the specific buffer. However, instead of the total sum, it is also possible to use about half of this value, as shown in Figure 6.

Finally, the fourth step can be described as an increase in the critical chain performance if it is necessary, which means a reduction in the project total time. It may be necessary to add new resources for the project execution.

Therefore, the application of CCPM tool in project management differs from the application of CPM and at the same time complements it, because besides defining the precedence network it also synchronizes the resources. The resource analysis has the objective to develop a systemic view of all projects running in the company and eliminate the multitasking environment, which means eliminating the time needed to reposition the resource between tasks (The Goldratt Institute, 2001).

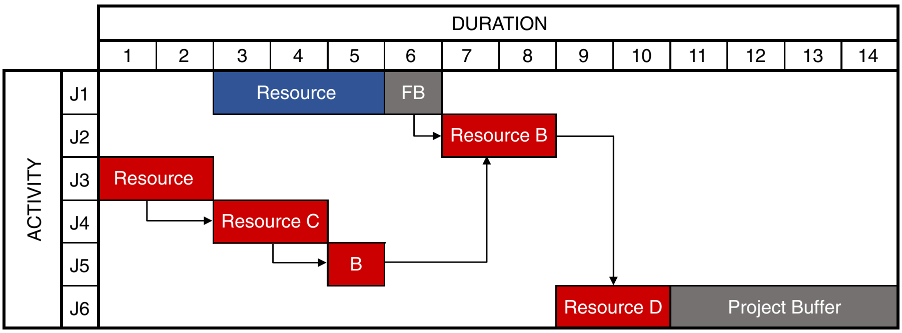
In project progress control managed by CCPM methodology some tools may be used to manage buffers, such as a buffer consumption chart known as fever chart or even monitoring the critical chain progress. It should be stressed that the project buffers management is done by knowing that when there is some delay in carrying out critical tasks the buffer is consumed and when they are finished ahead of schedule, time is added to the buffer (The Goldratt Institute, 2001).

To conclude, CCPM methodology and TOC, on which the tool is based, suggest that it is essential to have a change in the behavior of people involved in the project. In summary, a work assigned to a human resource should be started as soon as it is assigned, there should be no interruptions in its execution to avoid wasting time in repositioning the resource and, when the task is completed, there should be an immediate notification of completion (The Goldratt Institute, 2001).

3. Results

3.1 Methodology

The case study was adopted as a research approach for this study. According to Miguel (2007), the case study has an empirical nature that produces an in-depth analysis of a subject. The purpose of the case study is to clarify the reasons that justify the decision making, the way the implementations are made and the respective results obtained. Its goal is to deepen the knowledge about a particular problem to stimulate understanding about the topic. Thus, the procedure performed and the results obtained from data analysis in this



Note: FB represents the feeding buffer

Figure 6. Schedule of activities with buffers

study can be used to evaluate similar problems that affect project duration and to assist the search for better results. In addition, this methodology was chosen due to the lack of public domain data related to maintenance checks.

Besides this typology, this research is classified as: a unique case, because it deals with a single project planning and execution; exploratory rather than conclusive, as it seeks to better define a problem and proposes considerations to reach a solution; qualitative, because it portrays real data in a descriptive way and the treatment of this data is directly related to the researcher's ability to analyze the project environment and the available information (Stefanovitz, 2006); longitudinal, since it investigates data from the present moment (Miguel, 2007).

3.2 Case study characterization

The case study was carried out at an aircraft maintenance center located in Brazil during 2016. The company has an infrastructure capable of receiving up to six aircrafts for maintenance concomitantly; highly qualified personnel, around 80 technicians of various specialties divided into two work shifts, and are certified by several aviation regulatory bodies.

The object of this study is an aircraft maintenance type classified as scheduled maintenance, also called preventive maintenance, which is mandatory and required by aviation regulatory bodies (Yan *et al.*, 2011). Scheduled maintenance varies in scope, duration and frequency according to the age of the aircraft and the number of hours flown (Bergh *et al.*, 2013). For this study, the chosen maintenance is performed every six months or 450 flight hours on aircraft classified as low-use, that is, operated for up to 1,400 flight hours per year. Maintenance was conducted on an Embraer Legacy aircraft model. The choice of maintenance check was made based on the fact that it has the highest frequency among the mandatory maintenance performed during the aircraft life. The historical average duration of such maintenance at this service center is 11 days and the scope is classified as light maintenance, since no structural modifications or tasks that require disassembly of critical parts of the aircraft are executed.

In order to obtain information about the scope of maintenance activities under study, the average duration of tasks and the technical precedence between them, data from this maintenance category operated in the last two years at the site were analyzed and the aircraft maintenance manual was consulted. In addition, direct observation was used to document the experience of the team involved in the programming activity.

From the data collection, CPM and CCPM methods were combined to overcome their individual limitations and were applied in the creation of maintenance activities scheduling and of a procedure that adapts to the MRO environment.

3.3 Critical path (CPM)

In this subsection, it will be demonstrated that how the five steps proposed by Miranda and Almeida (2002) for the CPM tool implementation were applied.

3.3.1 Step 1: Identify activities. During the development of this study, macro activities involved in the maintenance check were first identified and later on they were broke into smaller activities in order to analyze the dependency relation between them. The maintenance check under analysis can be divided into seven macro activities, which encompass the maintenance tasks contained in the maintenance manual of the aircraft under study and the supporting activities required to perform these mandatory tasks.

The first macro activity (receiving and operational tests) refers to the inspections that must be performed at the beginning of maintenance in order to identify discrepancies as soon as possible and to the mandatory operational tests presented in the aircraft maintenance manual. These inspections should ensure that all materials and components necessary to carry out unplanned activities are available on the need date (Samaranayake and Kiridena, 2012). This macro activity is carried out in the company, outside the hangar, until the aircraft is defueled (fuel tank drainage) and the second macro activity is initiated hangaring the aircraft. Furthermore, during the second macro activity it also conducted the access openings in the aircraft fuselage, which are necessary to access regions that will be inspected during the execution of other maintenance tasks, besides the installation of protections on the furniture and wing edges.

During the third macro activity (operational checks and component removals), the maintenance manual mandatory operational tasks are performed, such as landing gear lubrication, windshield film inspection and engine and air conditioning routines. In this macro activity, the components that need to be sent for repair in a specialized workshop are also removed, which are batteries in this case study. Already in the fourth macro activity of this maintenance check, discrepancies found in the first macro activity are executed and, in case the customer has reported any damage or irregularity during the aircraft arrival, the client's reports will also be executed at this moment.

The fifth macro activity is composed by the repaired components return, installation and test by the opened accesses closing and the removal of installed protections. After the fifth phase, the aircraft returns to the courtyard and the sixth macro activity begins with the aircraft fueling procedure, followed by final inspections and pre-flight procedure, a group of activities that must be performed before a flight. The last macro activity (aircraft delivery) consists of the customer receiving procedure, a compliance check list application and the maintenance flight, which ensures that all systems are functioning properly.

All macro activities can be visualized in Table I, which are italicized and listed from 1 to 7.

3.3.2 Step 2: Predict durations. As the critical path determines project duration, it is necessary to determine the activities belonging to the project and their durations. For this reason, a historical data analysis was performed to estimate the average duration of non-scheduled activities, since the duration of planned tasks are already known by the maintenance manual. According to Samaranayake and Kiridena (2012), unplanned activities encountered during maintenance inspection can add up to 50 percent of the total hours spent on the aircraft maintenance. In this case study, it is accepted that possible discrepancies to be found will add up to 45 percent of the total hours spent with planned activities, a value obtained by historical database analysis composed by the aircraft maintenance type under study.

The fourth macro activity duration can be estimated based on the data analysis of the last two years. This phase is composed only of activities that could not be predicted in advance, which are named discrepancy correction and discrepancies reported by the customer, and the Activity 6.6 (discrepancy correction during final inspections). As shown in Table I, the activities presented in the fourth macro activity were estimated according to the personnel specialty used in their executions and the frequency and duration that these activities occurred during maintenance in the historical data sample analyzed. The service center personnel are stratified in mechanics, avionics, painting, sealant, interior and structure. This classification refers to technologies that an aircraft technician can specialize in order to ensure operational safety (Yan *et al.*, 2011). To complement, it was calculated that on average discrepancies related to mechanical tasks add up to 32 percent of the total discrepancies, avionics 21 percent, painting 16 percent, sealant 13 percent, interior 11 percent and structure 7 percent, with respective durations presented on the list of tasks in Table I.

3.3.3 Step 3: Identify dependency relationships. In this step, predecessor activities, which must be performed before a certain task for technical reasons or logic of execution, were defined based on the knowledge about the activities in the project, their estimated durations and how these activities are interrelated during maintenance execution. With the support of

ID	Task identification	Precedence	Duration (h)
1	*1. Receiving and operational tests*		*21.3*
2	1.1 Loose items removal		4
3	1.2 Mechanics receiving and operational tests	2	2.7
4	1.3 Avionics receiving and operational tests (data collection)	2	11.85
5	1.4 Composite material receiving	2	2
6	1.5 Structure receiving	2	5
7	1.6 Painting receiving	2	4
8	1.7 Interior receiving	2	5
9	1.8 QTU/QTA (reservoir drain)	8	1.5
10	1.9 Engine run	6; 3; 7; 5; 9	2
11	1.10 Opening of discrepancy documents	3; 4; 5; 6; 7; 8; 12	1.5
12	1.11 Troubleshooting	10	4
13	1.12 Fuel test		0.8
14	1.13 Compressor washing	10; 13	3
15	1.14 Landing gear washing	10; 13	4
16	1.15 Defueling	13; 15; 14; 11	1.5
17	*2. Hangaring and access openings*	*1*	*18*
18	2.1 Hangaring	16	1
19	2.2 Wing edge protection installation	18	0.5
20	2.3 Furniture protection installation	18	2
21	2.4 Internal access openings	19; 20	12
22	2.5 External access openings	19; 20	15
23	*3. Operational checks and component removals*	*17*	*11*
24	3.1 Electric hangar check	18	2.1
25	3.2 Removal/ship components to workshop	21; 24; 22	1
26	3.3 Lubrification	22	1.8
27	3.4 Engine and air conditioning routines	21; 22	4.5
28	3.5 Electric routine	21; 22	0.5
29	3.6 Interior routine	18	3
30	3.7 Inspection (sealing/films)	18	0.3
31	3.8 Out-of-phase	21; 22	11
32	*4. Discrepancy correction*	*23*	*28*
33	4.1 Discrepancy – mechanics	21; 22	28
34	4.2 Discrepancy – avionics	21; 22	18
35	4.3 Discrepancy – painting	18	14
36	4.4 Discrepancy – sealing	18	12
37	4.5 Discrepancy – interior	21; 22	10
38	4.6 Discrepancy – structure	21; 22	7
39	4.7 Client’s reports – interior	21	17
40	4.8 Client's reports – avionics	21; 22	10
41	4.9 Client's reports – mechanics	21; 22	6
42	4.10 Client's reports – painting and sealing	18	7
43	*5. Components installation and accesses closing*	*32*	*54*
44	5.1 Installation of repaired components	25	1
45	5.2 Components operational tests	44	4
46	5.3 Internal accesses closing	44II	30
47	5.4 External accesses closing	44II	36
48	5.5 Sealant application	47TT+1 hrd	12
49	5.6 Painting of sealing threads	48	15
50	5.7 Wing edge and furniture protections removal	49	1
51	5.8 Taxiing aircraft to courtyard	50	1
52	*6. Pre-flight and Final Inspections*	*43*	*19.85*
53	6.1 Fueling		1
54	6.2 Engine run	53	2
55	6.3 Final inspection – mechanics	54	2
56	6.4 Final inspection – avionics	54	4
57	6.5 Final inspection – Interior	54	5
58	6.6 Corrections post final inspection	55; 56; 57	5.85
59	6.7 QTU/QTA	57	1.5
60	6.8 Dry clean (internal and external)	59; 58	4
61	6.9 Pre-flight procedure	60	2
62	6.10 Prepare release and documentation	58	5
63	*7. Aircraft delivery*	*52*	*7*
64	7.1 Customer delivery	61	5
65	7.2 Maintenance flight	64	2

Table I.
Precedence network of the activities

Microsoft Project software, it was possible to determine the project total downtime, which is equivalent to 11 working days. The dependence relationships between the tasks are seen in Table I (see column titled "Predecessors").

3.3.4 Step 4: Identify programming limitations. From the identification of dependence relationships, it was also possible to identify some limitations of the project, such as tasks 1.12, 5.1 and 5.6, which have time and technical limitations. The fuel test, for example, should be the first task of the day to be performed, thus it cannot be executed in advance and it becomes the first critical task (with technical limitation rather than predecessor tasks). Besides that, the installation of components repaired in the workshop will only happen after three days from the removal of these components and shipping for repair, due to the workshop lead time. Finally, the task of painting the sealing threads must comply with the sealant curing time, in other words, painting can only carried out after 12 h where the sealant was applied.

3.3.5 Step 5: Preparation for programming. After the four previous steps, the schedule of activities is obtained according to CPM method, in which the critical path determines project total duration and requires special management in order to avoid delays in delivery. However, in this study the programming will be refined with the CCPM method application, a combined use of the methods already discussed, which is described in the next section.

3.4 Critical chain (CCPM)

Based on TOC, in an MRO environment it is essential to analyze the availability of resources used during performing tasks. It is known that a maintenance requirement is that the maintenance hangar is properly equipped with specialized tools and instruments for a given aircraft fleet and that consumable materials and components are always available for use (Sriram and Haghani, 2003). Since this study assumes that all tools and materials will be available for use, only the analysis of personnel resource is required.

After developing a task precedence network through CPM method, the next steps in creating a critical chain for the implementation of CCPM method, by Noguchi (2006), are: reduction in task duration aggressively, and at the same time attainably; synchronization of tasks with critical resources; insertion of buffers that will protect the project from variability; if necessary, an increase in the critical chain performance.

3.4.1 Step 1: Task duration reduction. In order to define the reduction percentage in the durations of maintenance tasks, a benchmarking was carried out with a service center located in France, which is becoming a reference in the CCPM implementation A, 30 percent reduction in these activities durations was determined. The precedence network with reduced durations and the required human resources is presented in Figure 7.

3.4.2 Step 2: Critical tasks synchronization. After the insertion of the resources, it was necessary, as expected, to synchronize the tasks, since some resources were over-allocated, thus avoiding multitasking. For example, it was necessary to insert two specialists in avionics, because there was more than one task requiring this specialty concurrently, such as tasks 3.1 and 3.5 (electric hangar check and electric routine) in Figure 7. The same happened with mechanics and interior specialties. In the case of painting specialty, two technicians were allocated due to the high workload in the same working day. Therefore, because of tasks concomitance and maximum workload that each employee can receive daily, the necessary team to perform the activities of this maintenance, which can be distributed in two shifts, should be composed of three mechanics, two avionics, two interior specialists, two painters, a sealer and a specialist in structure. It can also be noticed that painting, sealing and structure technicians only perform their functions in the phases of receiving, correcting discrepancies and closing accesses, which means that these resources can be shared between different projects.

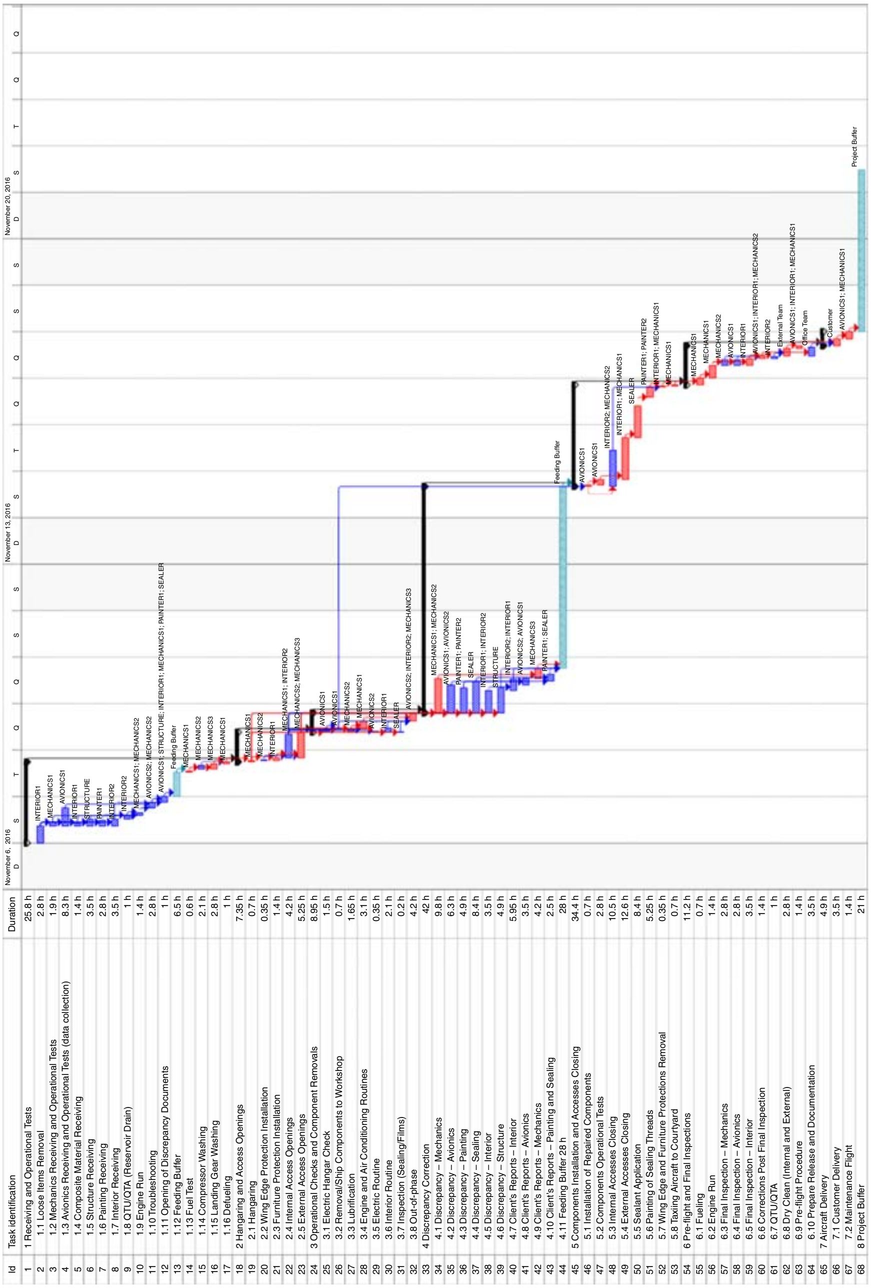


Figure 7.
Durations reduction and activities synchronization

3.4.3 Step 3: Protection buffers insertion. The next step in the application of critical chain method is characterized by the insertion of buffers into the activity network in order to protect the project delivery date from variations during the execution of the tasks. In this case, two feeding buffers were inserted after paths that converged to the critical tasks "fuel test" and "installation of repaired components," besides the project buffer, which was inserted at the end of the project after the critical chain. The calculation of these buffers was made based on the duration reductions of the tasks contained in the pathway that precedes the buffer and it is defined as half of the sum of these reductions, as is shown in Figure 7.

3.4.4 Step 4: Critical chain performance elevation. The last step of the procedure used in the study for the CCPM tool application is the elevation of critical chain performance. After benchmarking against other service centers that work with the same type of aircraft and getting information from the developers of the aircraft maintenance plan, it was found out that this type of maintenance check should ideally be carried out in five business days. Therefore, it is necessary to have a six-day reduction in the project total time, thus the maintenance center under study becomes competitive in rendering maintenance services.

Among the possible actions to increase critical chain performance and reduce maintenance downtime is the addition of new resources (Barcaui and Quelhas, 2004). Figure 7 shows that tasks such as "internal and external accesses closing", "sealing of accesses" and "sealant application" (activities 5.3, 5.4 and 5.5, respectively) have high durations. Because it is technically possible to increase the number of people performing these tasks, this action suggests adding an extra person to each activity, decreasing the duration of macro activity 5, as presented in Figure 8.

In Figure 7 it is also possible to observe that the activity "painting of sealing threads," the successor of activity 5.5, can be initiated only after 12 h from the beginning of its predecessor task execution. This is due to the technical characteristic of curing time of the material used in the sealing. Therefore, the second possible action is the alteration of the sealant used in the activity by another type available in the market with shorter curing time (7 h). Even with the considerable reduction in the duration of activity 5.5 after the insertion of new resources, the use of the new sealant allows this activity not to wait more time to be initialized, as shown in Figure 8.

Another important action that can be taken and will effectively help to reduce maintenance downtime is the better phasing of aircraft maintenance checks. Phasing a maintenance check means to allocate tasks called "out-of-phase," which have maintenance intervals that do not fit into the scheduled maintenance, to maintenance checks that comport the number of accesses required by these tasks (Delmas, 2015). Since the six-month check has an extremely small number of access openings, it is necessary to assign out-of-phase activities to long-term maintenance checks, in which the aircraft may be kept out of operation for a longer period of time. With the phasing action, the execution of out-of-phase activities (activity 3.8) stops happening in checks considered small, such as the maintenance check under study.

One more action identified that could be applied in this step of the procedure can be described as increasing customers and employees awareness not to perform long duration tasks or a big number of access openings in short-term maintenance checks. Thus, the number and duration of customer reports and corrected discrepancies should be reduced in accordance with these limitations by planning those activities for maintenance checks that comport them. In this case study, activities in the fourth macro activity (discrepancy correction) had their durations additionally reduced with the estimate of 30 percent to meet these limitations (Figure 8).

As a consequence of better phasing "out-of-phase" activities and discrepancies reported by the customer, the hours spent opening and closing accesses will also be reduced. For this

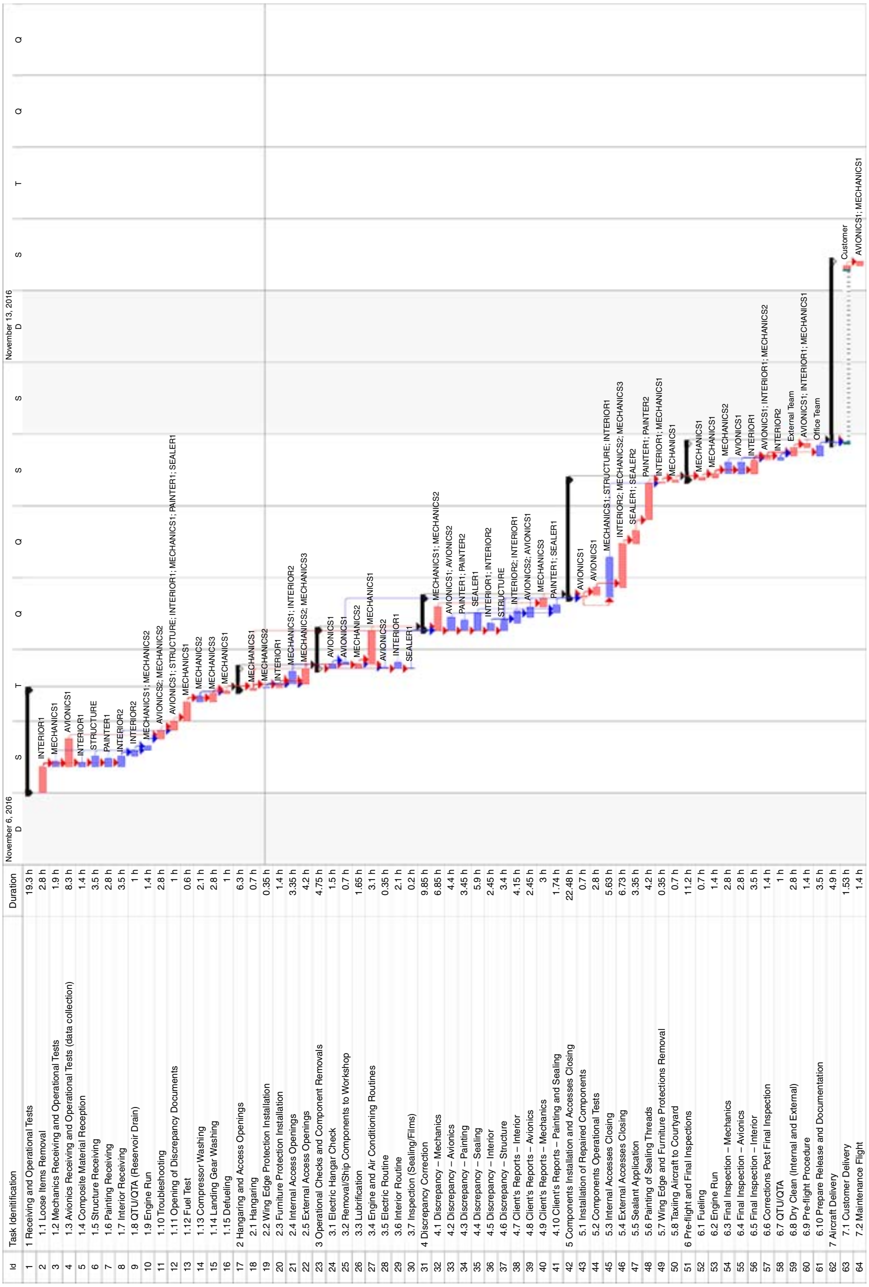


Figure 8.
Reduced downtime after the improvement actions implementation

reason, activities related to accesses (activities 5.3-5.6) had 20 percent of additional reduction in their respective total durations (Figure 8).

Finally, the critical chain performance will be elevated if the workshop three-week lead time is reduced, because the components to be repaired are removed in the activity 3.2 and reinstalled in the activity 5.1 and these activities are part of the critical path. One possible action would be to keep these components (batteries) in stock, as they are currently sent for repair only when maintenance has already been started. Considering the existence of this component in stock, the time gap between these two activities goes from three to one day.

In order to demonstrate visually a decrease in the project total duration, buffers were removed from the activity flow provisionally. Figure 8 shows the possibility of completing the maintenance in five working days, as it was found during benchmarking. Another considered point is that customers receive the aircraft on the sixth business day, since activity 7.1 (customer delivery) cannot be divided into different days. Critical tasks were also kept in red font color to signal the critical path obtained with the CPM method application, even though the leveling of critical resources has already been done through CCPM method.

4. Discussion and final considerations

Maintenance execution time is an important factor when choosing a service center, since the unavailability of an aircraft can generate high costs for the customer. Therefore, it is important that MRO companies seek to reduce maintenance downtime to remain competitive. As discussed previously, the application of the traditional project management tool, CPM, combined with CCPM method can help to reduce project duration and delays in aircraft deliveries, as these tools can reduce activities duration and increase the adherence to project completion date, due to the protection that buffers offer against the variability in maintenance activities execution.

After reducing activity durations to aggressive but still realistic times, synchronizing activities that share the same resources, and inserting safety buffers that will protect the project from variability, the maintenance downtime has not been increased. In addition, after the application of many actions to increase critical chain performance, it has been identified that it is possible to reduce the project downtime to a competitive number, from 11 to 5 working days, which demonstrates the advantage in using the methods addressed in this study.

These results were also observed by the authors Kulkarni *et al.* (2017) with the application of CCPM tool in maintenance checks classified as heavy maintenance. The results obtained by these authors, added to the practical results obtained by this case study, prove the relevance of applying these tools in the MRO sector. As a result, most maintenance checks performed at the maintenance center under study every six months on low-use aircraft are being executed in five working days and delays in aircraft deliveries being reduced. Another advantage of the exemplified procedure is programming automation, since according to Yan *et al.* (2011), aircraft maintenance scheduling is often based on employee experience, which is time consuming and not highly effective.

As large investments are not necessary to adopt the practices studied in this paper and the procedures performed during maintenance checks are regulated by a national civil aviation agency, which creates a similarity between maintenance performed by different companies, this procedure has great applicability by other maintenance centers.

As downtime decreases, there is also an increase in aircraft availability and in service center capability, since the faster the maintenance process is completed, the sooner another aircraft will be able to occupy a slot in the hangar and the sooner another customer will have its maintenance started. This availability will result in increased customer satisfaction and improvement of the company’s financial results.

It is important to emphasize that, in order to reach the results proposed by these tools, it is necessary to monitor the critical chain progress by using a buffer consumption chart or another method chosen by the project manager. This monitoring will indicate the best time for action to be taken and the priorities in relation to concomitant projects.

Another great impact derived from the application of these methods refers to the satisfaction and involvement of the employees in the maintenance project. When the personnel share the on-time delivery goal, and not just those who have direct contact with the customer, they become more motivated to achieve that goal. This change in organizational culture may also contribute to deliveries on time, increasing the likelihood of tasks completion without extrapolating the time allocated in the project buffer.

With the objective of creating a procedure that could allow a greater understanding of the theme and propose ways of improvement, existing methods were used in a new application. However, this study was directed to a single project, so in future research, it is important to carry out an analysis in a multiproject environment in order to ensure the suitability of the procedure for MRO processes. In addition, in this study, the availability of all tools and materials to perform maintenance activities was taken as an assumption. As a suggestion for further research, in order to make the case more real, one can rule out this premise.

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