Analysing delays and disruptions in Aircraft Heavy Maintenance

Leandro Julian Salazar Rosales[*], Jian-Bo Yang, Yu-Wang Chen

Decision and Cognitive Sciences Research Centre

The University of Manchester, Manchester M15 6PB, UK

Abstract

It is challenging to plan and manage heavy maintenance services in the aviation industry due to large amounts of resources involved and complex interactions between them. Furthermore, during the aircraft heavy maintenance process, unexpected damages and discrepancies may arise that must be solved by programming unscheduled tasks. The dynamism of the process and the uncertainty caused by unscheduled tasks require the adjustment of a maintenance service plan constantly, which might impact on delivery times, process costs and even the quality of the maintenance service. To address this problem, it is proposed to use System Dynamics as a tool to understand and analyse complex and dynamic systems. In this paper the interrelationship of scheduled and unscheduled tasks and its impact on delays and disruptions during aircraft heavy maintenance are explained and analysed designing a causal loop diagram. Additionally, the effect of occurrence and discovery of discrepancies and damages on unscheduled tasks is presented using a system dynamics model, which also highlights the relevance of workforce allocation for the project performance.

Key Words

System Dynamics, Aircraft maintenance, Heavy maintenance, Resources management, Uncertainty, Unscheduled activities, Non-routines.

1 Introduction

The maintenance of an aircraft and its components represents one of the main direct operating costs for an airline and it is an obligatory duty to ensure safety of air operations; therefore, it should be made at the lowest possible cost, with the highest quality standards and in compliance with the specified schedule. To accomplish these objectives, the maintenance is structured in a systematic and orderly programme. However, during its execution, unscheduled tasks are very common to arise, and most of the times they cause delays and interruptions during the process, delaying services and overrunning costs.

One of the most critical aircraft maintenance processes is heavy maintenance, which requires aircraft on ground for a long period of time ranging from 7 to 30 or more days. Moreover, during its execution, a large amount of resources in constant interaction are required (for instance, the highly

[*] Email: leandro.salazarrosales@mbs.ac.uk, Mobile: +44 (0) 7547 342 644

specialised and costly workforce). Additionally, due to uncertainty related to unscheduled tasks, managing heavy maintenance is complex and most of the times inaccurate.

Taking into account the main characteristics of the above problem and considering that System Dynamics is a tool for understanding and managing highly dynamic and complex systems, which has been successfully applied to project management due to its capabilities of analysing a whole project as a system and representing its dynamic behaviour; it is therefore proposed to use System Dynamics as a methodology to analyse the problem of delays and disruptions within the heavy maintenance process.

The rest of this paper is structured as follows. In the section two, a brief background of the problem is introduced, and then the heavy maintenance process and its main problems are explained. In the third section, a summary of the literature review is presented, with the aim to show how similar problems in the aviation maintenance field have been addressed and to propose System Dynamics as a suitable methodology to address the problem. Section four depicts the conceptual model using a casual loop diagram to explain the complexity of the problem and the interrelation between the variables. In section five, some preliminary results of the models built are discussed. Finally, in section six, the conclusions of this work are stated.

2 Research Problem

In order to better understand the aircraft heavy maintenance process and before explaining the research problem, it is important to first briefly describe the aim and relevance of aircraft maintenance, and also how it is generally structured. The complexity of heavy maintenance is then explained, and finally the research problem is presented.

2.1 Aircraft maintenance

Aircraft maintenance plays a significant role for airlines as it is an unavoidable, compulsory and strictly regulated activity to ensure the safety of aircraft and its operations. It also has relevant impact on costs, representing one of the main direct operating costs (DOC) for an airline (Friend, 1992) and (Doganis, 2009). Furthermore, it requires carefully planning and coordinating the availability of all resources (tools, equipment, parts, materials, trained workforce) and scheduling tasks in correct sequences. For this reason, aircraft maintenance management is one of fundamental strategies for cost optimization, whose basic aim is to perform maintenance at the lowest cost possible, with the highest level of service and offering competitive delivery times, without compromising quality and safety.

Radnoti (2002) points out that commercial aviation maintenance is structured as a systematic and orderly scheduled maintenance program that is jointly approved by the aeronautical authorities and manufacturers of aircraft and components. He also stresses that schedule maintenance checks can be grouped into services or categories which can be programmed from the smallest, and more frequent, to the heaviest that includes a major structural inspection of aircraft.

Furthermore, the Federal Aviation Administration (FAA), U.S. aviation authority, (2010) describes that schedule maintenance checks are based on a fixed number of flight hours and establishes that typically there are four levels of inspection, termed as A, B, C and D checks. The first two checks are generally considered part of line maintenance, whereas C and D checks are known as heavy maintenance. These intervals are based upon the guidelines of aircraft manufacturers and aviation authorities, and they are further customised by an airline.

Also, FAA explains that line maintenance consists of small and regular checks to ensure the airworthiness, troubleshooting, defect rectification and component replacement. These activities are generally grouped in three main categories: transit checks, daily/weekly checks and A, B-checks, which require the aircraft on ground from one hour up to two days. Besides, FAA defines that heavy maintenance consist of the detailed inspection and repair of airframe, components and accessories performed at specified time intervals. To carry it out, normally aircraft needs to be on ground from 7 up to 40 days. Friend (1992) adds that heavy maintenance must be performed inside a hangar using specialised equipment and also requiring a considerable amount of highly trained people. Hence these checks should be scheduled to maximise the use of aircraft but also maintenance facilities and resources (especially workforce).

2.2 Aircraft Heavy Maintenance Process

The high significance of a heavy maintenance process, in the eyes of management, is due to its operational and financial influence. From the operational standpoint, it has relevant impact on aircraft availability, and also demands the extensive use of resources. From the financial perspective it has an effect on both cost and revenue generation.

It can be claimed that difficulty and complexity in managing a heavy maintenance process has two main edges that are highly interrelated. The first is the complexity of a huge amount of resources involved in the process. And the second is the uncertainty of unscheduled tasks during the maintenance service.

2.2.1 Resources management complexity

During heavy maintenance several resources are in constant interaction: aircraft, ground facilities, tools and equipment, parts and materials, technical information and workforce. As a result of the massive amount of resources involved all along heavy maintenance, but above all, because of the complex interrelationship between them, the planning, supply and coordination of all resources must be carefully managed. A failure in the availability of these resources can affect the management of others and furthermore impact the whole maintenance service plan. This complexity in heavy maintenance might cause delays and disruptions in the process, having serious operational, technical and economic consequences. Figure 1 depicts the relation and interdependence between different resources involved in heavy maintenance checks.

If the delay at the end of a service is considerable (i.e. the duration of heavy maintenance check is more than planned), it will alter flying schedules, delaying or in the worst case cancelling flights. Additionally, as heavy maintenance services are programmed one after another, delays can affect subsequent maintenance checks. If the problem is recurrent, it will cause a domino effect, affecting both short and long term maintenance plans.

Furthermore, delays in a heavy maintenance process may have economic impact on an airline in two different ways: increasing costs and reducing revenues. About cost, for example, the pressure to reduce delays forces management to increase available workforce (hiring, boosting overtime or transferring from other areas), and to purchase parts and tools urgently (having a higher price than normal). Regarding revenue, if aircraft stays on ground for more time than expected, it will affect commercial itinerary and hence it will lower the number of seats available, which ultimately leads to a reduction of income-earning capacity.

Figure 1 Interrelationship of resources in heavy maintenance

2.2.2 Uncertainty of unscheduled maintenance tasks

Almost all maintenance scheduled tasks can be planned and programmed precisely, because they are specified in a maintenance service programme. However, even with such a rigorous maintenance system, unscheduled and unplanned activities arise during the operation of aircraft. Like in every machine, unexpected failures, damages and discrepancies in aircraft operation are common to occur but difficult to forecast (Friend, 1992). Resto (2005) points out that between forty and sixty per cent of all maintenance activities are non-routine, unplanned and unscheduled events, i.e. discrepancies, damages or something broken while maintenance managers do not have prior knowledge that they have happened. In the aviation maintenance field, these unplanned events are called “non-routine”.

Before the beginning of a heavy maintenance service, a detailed plan is designed, considering all the activities, resources and time required to accomplish a specified delivery time and budget, and to ensure the standards of quality and safety. Generally, heavy maintenance is performed following several stages that include opening access, cleaning, inspection, programmed tasks, non-routine tasks, tests, and closing access. Nonetheless, during heavy maintenance execution, mainly during the inspection stage, discrepancies and damages are discovered that need to be corrected by programming non-routine activities. Unscheduled tasks might require additional resources and activities, forcing to adjust and change an initial plan, causing delays and disruptions within a whole process. Managing non-routine resources and activities is a critical aspect in heavy maintenance services as they can affect costs and aircraft's return time; impacting also the supply chain (Resto, 2005). Figure 2 summarises the problem of unscheduled activities during aircraft maintenance execution.

Even when a heavy maintenance service can be planned and scheduled by using experience and statistical data and by taking advantage of informatics tools, due to the stochastic nature of unscheduled tasks, it is complex and most of the times inaccurate to manage it.

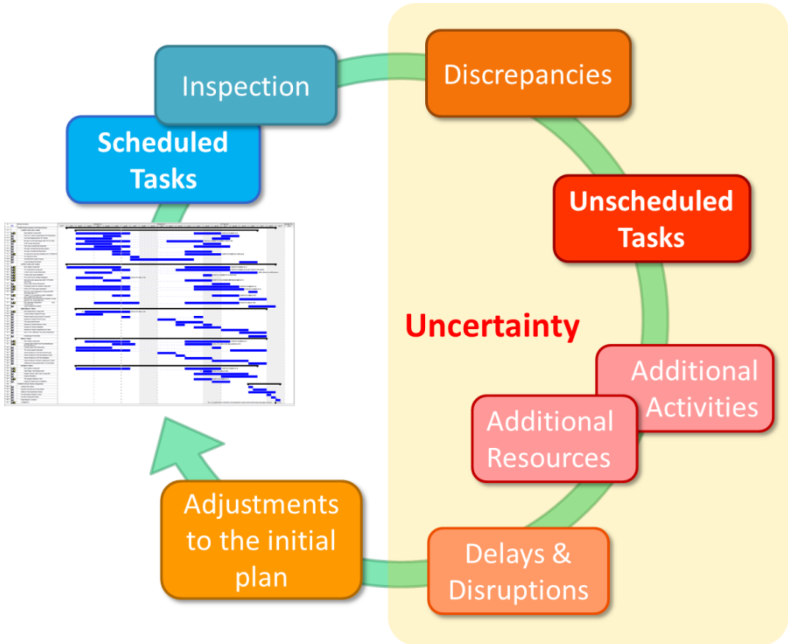

Figure 2 Delays and disruptions in the heavy maintenance process

2.3 Problem formulation

Williams (2002) describes that the main characteristics of a complex project are the large number of elements involved in the project, and the considerable interaction and interdependence between the elements, as well as uncertainty present in the project. Taking into account the features stated by Williams, and the two main problems of heavy maintenance, the process of heavy maintenance can be considered as a complex project.

Analysing the brief description of heavy maintenance process, the proposed research problems can be summarised as follows:

a) There is a lack of: i) understanding of the interaction between scheduled and unscheduled tasks and resources required to accomplish them; and ii) assessment of effects in delays and disruptions during a heavy maintenance process.
b) Planning unscheduled tasks and forecasting their required resources represent an important challenge for maintenance managers, mainly due to the stochastic nature of non-routine tasks.
c) As a result, adjusting an initial maintenance service plan and managing a whole process could be tortuous and complicated, which might impact delivery times, process costs and even the quality of maintenance service.

3 Literature review

A literature review in aircraft maintenance is performed to analyse relevant research in the aviation industry and aircraft maintenance and to examine system dynamics literature regarding similar problems.

3.1 Aviation Maintenance Studies

A review in the aviation industry and aircraft maintenance studies has two different purposes. On the one hand, it is for identifying if a proposed problem has been studied or analysed before, and if so, what methodology has been used to solve the problem and its results. On the other hand, it is for discovering the different perspectives applied to study and solve the most common problems in the aviation industry that could be strongly related with this research.

As an overall conclusion from this section, it can be pointed out that several approaches and techniques have been used to analyse aviation maintenance problems, providing different and valuable proposals to address these problems from different perspectives. However, it can be claimed that even though there are several studies in this field, most of them focus on the long-term planning (also called pre-planning) of resources, mainly manpower (e.g. Cobb (1995), Cheung et al. (2005), Hahn and Newman (2008), Yang et al. (2003) and Weckman et al. (2006)). Regarding short-term planning, most of the studies are focused on line maintenance processes and the re-routing of flights after the occurrence of unexpected events in operations (e.g. Papakostas et al. (2010), Sachon and Paté-Cornell (2000), Sarac et al. (2006), Sriram and Haghani (2003) and Yan et al. (2004)). Additionally, most of the reviewed approaches fail to consider the systemic understanding of a problem, not taking into account the relations and impact that each part has within a whole process. In a few studies that use systematic approaches, such as Lean or some IT developments, a deep cultural change is required in an organisation as well in the philosophy of thinking, and their implementation requires huge efforts.

Finally, despite the significance of non-scheduled activities and that experiences in aircraft maintenance suggest that delays and disruptions during a heavy maintenance process are a real problem in the aviation industry, none of the studies dealt specifically with this problem. Therefore, this research proposes to study and analyse the impact of non-scheduled activities in the delays and disruptions that might affect heavy maintenance goals.

3.2 System Dynamics and its applications

After analysing some of the most relevant literature in System Dynamics (SD) and reviewing its common applications, the following points are concluded:

(i) SD is a flexible methodology for designing, building and applying simulation models (qualitative and quantitative) to study and manage highly dynamic and complex systems. It is used for describing, understanding and learning how information feedback governs system behaviour, and for designing control policies through simulation (Coyle (1996), Ford et al. (2004) and Sterman (1992), (2000)). In addition, Richardson and Pugh III (1981) indicate that system dynamics simulation models are useful for managing processes with two main characteristics. Firstly, they change significantly over time and secondly, they have feedback loops where the information is transmitted.

(ii) SD has been successfully applied in the project management field. Lyneis and Ford (2007) stress that planning and managing projects is a challenge, because project conditions and performance evolve over the time as a result of feedback responses, principally involving nonlinear relationships and accumulation of project progress and resources. Furthermore, several studies have stressed that the traditional project management tools are inadequate for dealing with the dynamic of complex systems, as these tools conceive the project statically and focus only in a part of the project. These studies also suggest that given this inadequate management, most of the projects exceed time, cost and the allocated resources ((Lee and Peña-Mora, 2007), (Lyneis et al., 2001) and (Reichelt and Lyneis, 1999)). In contrast, Rodrigues and Bowers (1996), highlight that a holistic vision of the project rather than a sum of individual elements, the non-linear analysis of the feedbacks and the flexibility for modelling the project structure are some of the factors that motivate the application of SD in Project Management.

(iii) SD has been applied to wide range of areas, such as aerospace, construction, finance, health-care, Information Technologies, litigation, maintenance, military and defence, process management and supply chain among others. Some of the reviewed studies addressed problems with similar characteristics to the ones of this research problem (i.e. project overruns, delays and disruptions, etc.) (e.g. Lee and Peña-Mora (2007), Love et al. (2002), Madachy (1995), (Park and Peña-Mora, 2004), (Taylor and Ford, 2008) and Thompson and Bank (2010)).

Therefore, considering the previous points and bearing in mind the features of the proposed problem, it can be stated that System Dynamics is a suitable approach to address it.

4 Model Formulation

One of the challenges in understanding a complex system is to represent the complicated interrelationship between variables and their constant dynamism. One of the tools for system thinking that can help to overcome this challenge is causal loop diagrams. Sterman (2000) states that causal loop diagrams are helpful to capture hypotheses about the causes of dynamics, to elicit the mental models of individuals and teams, and to represent and communicate possible feedback responsible for a problem. Morecroft (2007) adds that causal loop diagrams can help to change the perspective of problems from simple cause-effect to a more complex structure full of feedback loops. For this reason, building a causal loop diagram that represents a problem, its dynamism and the interrelationship between variables, becomes a necessary and useful step.

The causal loop diagram, presented in Figure 3, is formed by fourteen feedback loops that depict the delays and disruptions in an aircraft heavy maintenance process, which are mainly caused by unscheduled tasks. It illustrates the interaction among resources and their impact on the completion of a project. The diagram includes perceptions, attitudes and delays in reacting during a project, which increase the variability and hinder the coordination of maintenance services. In order to facilitate the explanation of this model, it is separated in different sections as shown in Figure 4 to Figure 8.

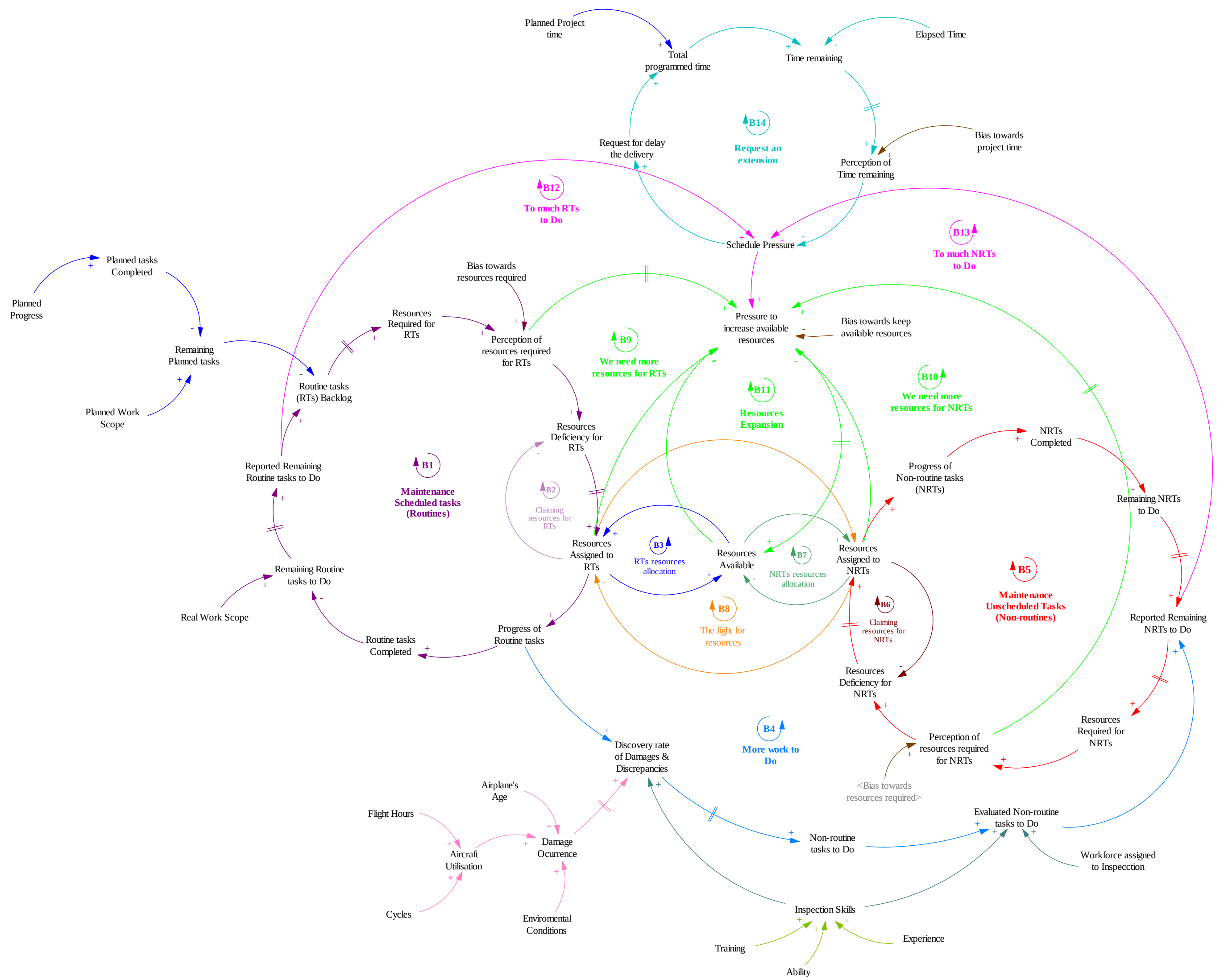

Figure 3 Causal loop diagram about delays in aircraft heavy maintenance process

The Figure 4 portrays one of the basic and common problems in project management, *the delays within the project*. In the upper left side, the project's plan is depicted. The planned progress leads to an increase in tasks completed, which in turn causes reduction in the remaining tasks according to the plan. Meanwhile, a rise in the work scope results in an increment in the planned remaining tasks.

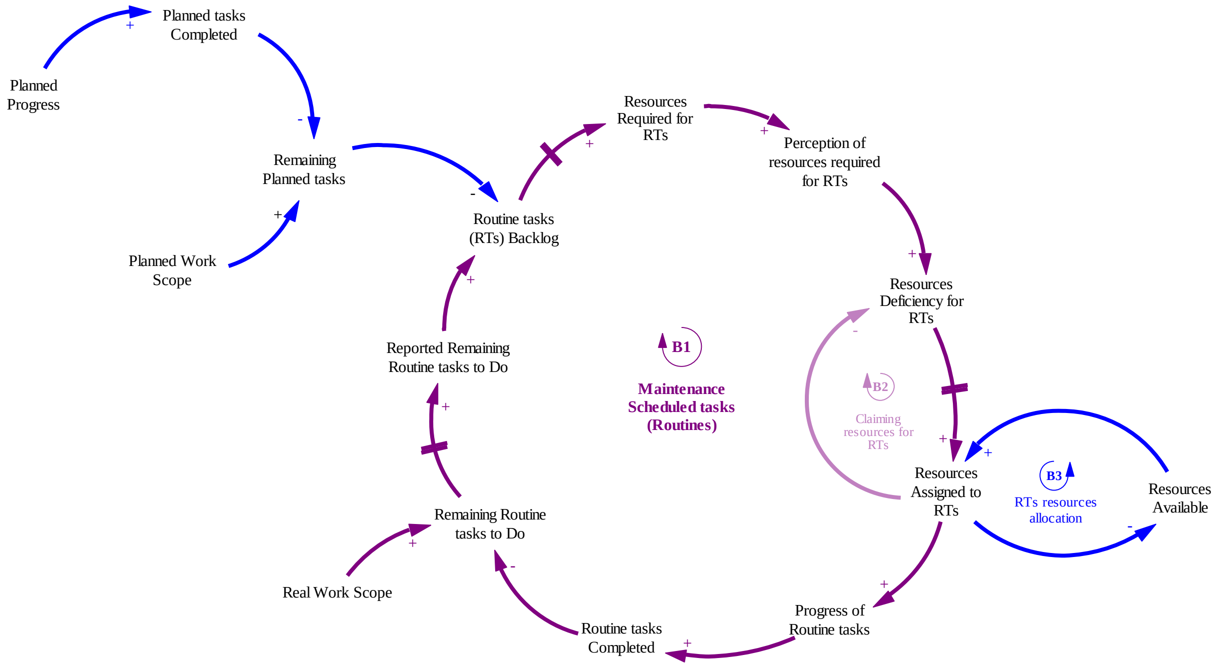

Figure 4 Scheduled tasks and resources allocation

Then the plan is compared against the status of the project. For this, the remaining tasks according to the plan are compared with the reported remaining routine tasks (RTs); if the latter is bigger than the former there is a backlog of tasks to do. In order to reduce this backlog more resources are required, though there is a delay in noticing this need. Additionally, there might be a difference between the real resources needed and the perception of this additional requirement, which is influenced by the attitude of management about the backlog of tasks.

Subsequently, the perception of resources required is compared with the resources already assigned to routine tasks. If the resources assigned are lower than needed, there is deficiency. Therefore it is required to allocate available resources to execute routine tasks with the aim to reduce the resources deficiency. Nevertheless this allocation of additional resources depletes the availability of resources for additional tasks.

If more resources are assigned to execute routine tasks, it is expected to have an increase in the routine progress that will result in more routine tasks completed. While a rise in the routine progress leads to a reduction in the remaining tasks to do, an increment in the real work scope upturns the remaining task to do. However, there is a delay reporting the remaining tasks to perform. Finally, if the remaining tasks drop, the routine backlog reduces too, closing in this way the balancing loop B1 of maintenance scheduled tasks.

Figure 5 adds the loop B4 called "*More work to do*" that represents uncertainty in the problem. During the progress of routine tasks, some damages and discrepancies can be found that must be corrected by programming non-routine tasks. Non-routines require to be evaluated to assess their severity and to estimate the necessary resources to execute them. In the diagram it can be seen that more discrepancies discovered leads to more non-routines, which need to be evaluated, and once assessed will increase the number of the remaining non-routine tasks.

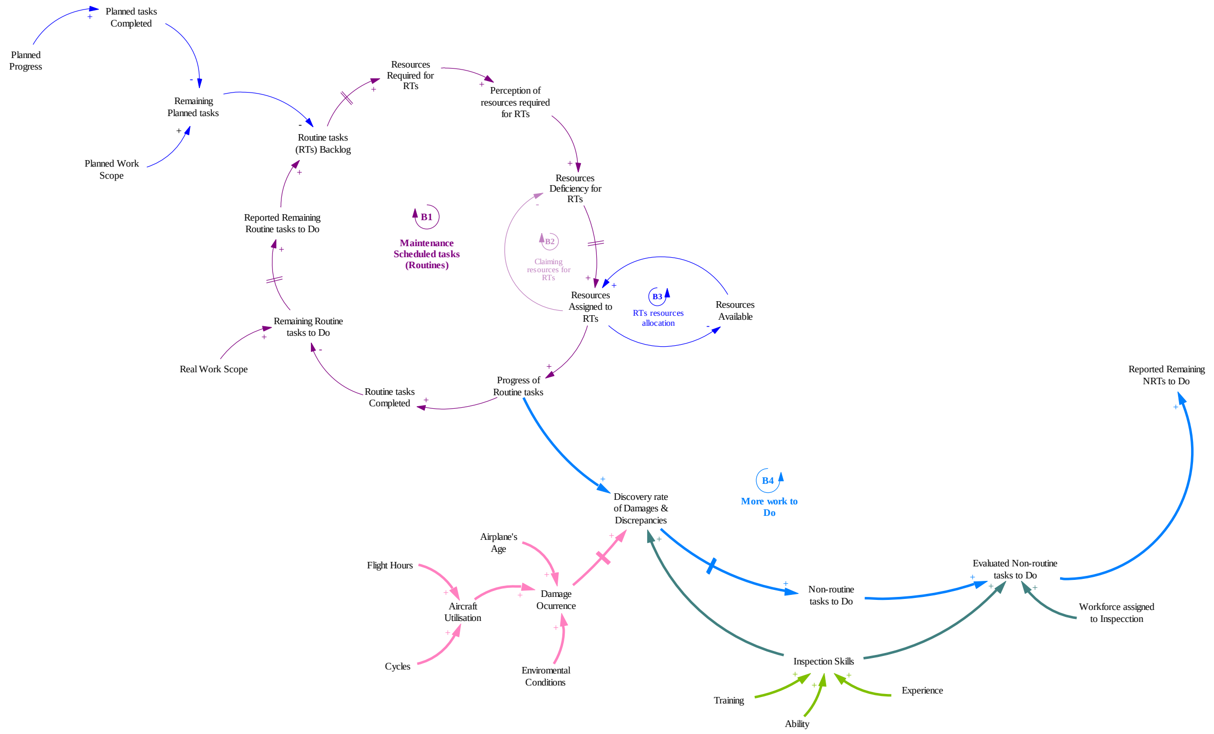

Figure 5 Occurrence and discovery of discrepancies

The question is where does uncertainty arise? The occurrence of damages and discrepancies is due to several external factors such as aircraft's age, utilisation and environmental conditions. The problem is that it is not possible to determine precisely the number of discrepancies, their type or when they may occur. Estimation about the number of damages is normally made by experts considering the external factors mentioned above. If the number of discrepancies is unknown and uncertain, the discrepancies discovery rate will also be uncertain, which may cause difficulty in the planning and coordination of non-routine tasks.

Moreover, the discrepancies' discovery rate and the evaluation of non-routine tasks are affected by the skills of workforce (mainly inspectors), as it is expected that people with higher skills can detect damages more easily and also evaluate them more accurately. The skills of workforce depend basically on the training, experience and ability of people.

The main loops in Figure 6 are B5 "*Maintenance unscheduled tasks*" and B8 "*The fight for resources*". B5 is very similar to the loop B1 as it shows that the more remaining non-routine tasks, the more resources are assigned in order to increase progress and to complete more unscheduled activities, so as to balance the loop with the number of remaining non-routines reduced.

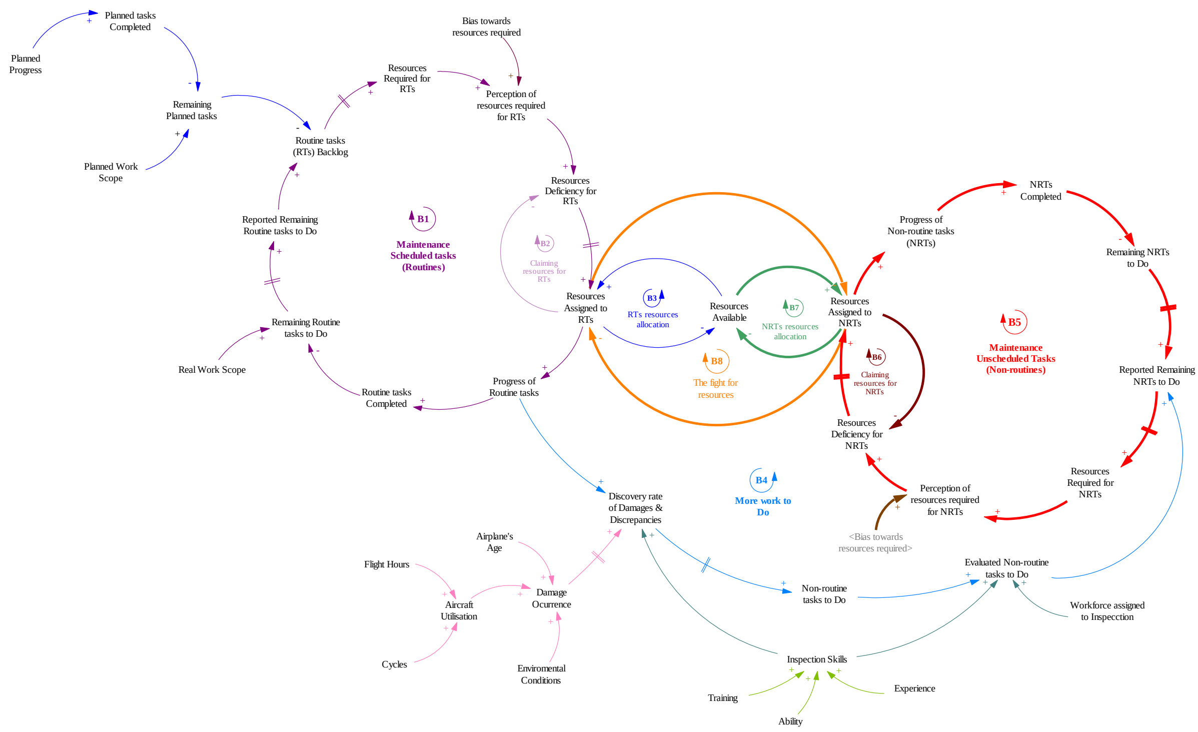

Figure 6 Unscheduled tasks and the fight for resources

On the other hand, the loop B8 illustrates constant fight for resources between scheduled and unscheduled tasks. If more resources are assigned to execute routine tasks, it is expected to have an increment in their progress and thus to complete them faster. However this causes a drop in available resources and affects the allocation of resources to perform unscheduled activities, leading to a negative effect in the progress of non-routines, thus delaying their completion. In contrast, when more resources are allocated to execute unscheduled activities, it will have positive impact on them, but negative impact on the progress of scheduled activities. Therefore finding the best resource allocation policy is fundamental to optimise the use of resources and to reduce project duration.

The loops B9, B10 and B11 illustrated in Figure 7 describe the growth of available resources. When the resources needed to perform scheduled and unscheduled tasks are greater than the resources available plus the ones already assigned, the pressure to expand the resources available increases, and later leads to an increase in the resources available, thereby closing the balancing loops and relaxing the pressure to expand the resources.

It is important to notice that there are delays and perceptions in these loops. First there is a delay to recognise that the resources available are not enough to overcome the need for additional resources; and second, the expansion of the available resources requires a considerable time to take effect, because it is not easy to get them. It is also important to mention the bias of management towards increasing the available resources. For example, at the beginning of a project, there is reluctance to increase resources, whereas at the end, when delay is too big the tendency is to increase them, even more than needed.

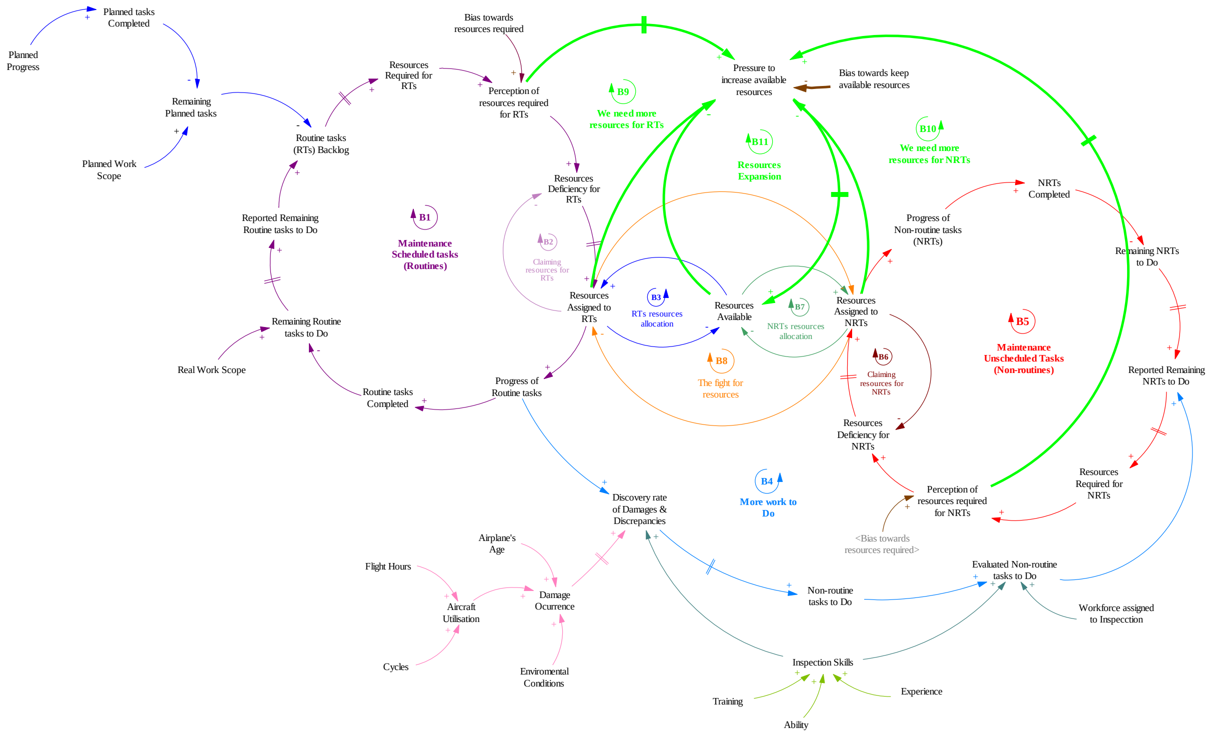

Figure 7 Increase of available resources

Figure 8 in loops B12, B13 and B14 illustrates the alternative of asking for maintenance service extension, thus reducing the pressure to finish a project on time. If the remaining routine and non-routine tasks increase, the pressure to finish the maintenance service on time starts rising. Additionally, if the time remaining is running out, the pressure to finish on time grows. Therefore if all other alternatives (explained in the previous loops) fail to complete the maintenance check on time, the last option is to ask for an extension to deliver an airplane after the expected date. Once the extension is approved, the total project time increases and hence the time remaining also increases, diminishing the time pressure as well.

It is important to mention that the loop diagram, presented in Figure 3 and explained in the previous paragraphs, considers resources in a general perspective. However, in real life this is not that simple. In heavy maintenance, three main and different types of resources are generally involved: workforce, parts and materials, and tools and equipment.

The *workforce* plays a key role in heavy maintenance, as labour is extensively used when a large number of maintenance tasks need to be executed. In the short term, the scheduling of workforce is critical to avoid shortages or excess of people. Meanwhile in the long term, it is also important to plan technical labour, as they are licensed, highly skilled and trained. Therefore a considerable investment in time and money is required to prepare these highly specialised resources. Regarding *parts and materials*, a large quantity of them are used in heavy maintenance and lead time for components and parts can be high. Thus their planning, replenishment and supply have to be managed carefully in order to ensure the availability of parts and materials without increasing costs unnecessarily. Finally, approved test *equipment and specialised tools* must be available to execute maintenance activities. The planning of these resources should be done months in advance, as it may take a long time to get them delivered. Besides, a large amount of money may be needed to have these resources available.

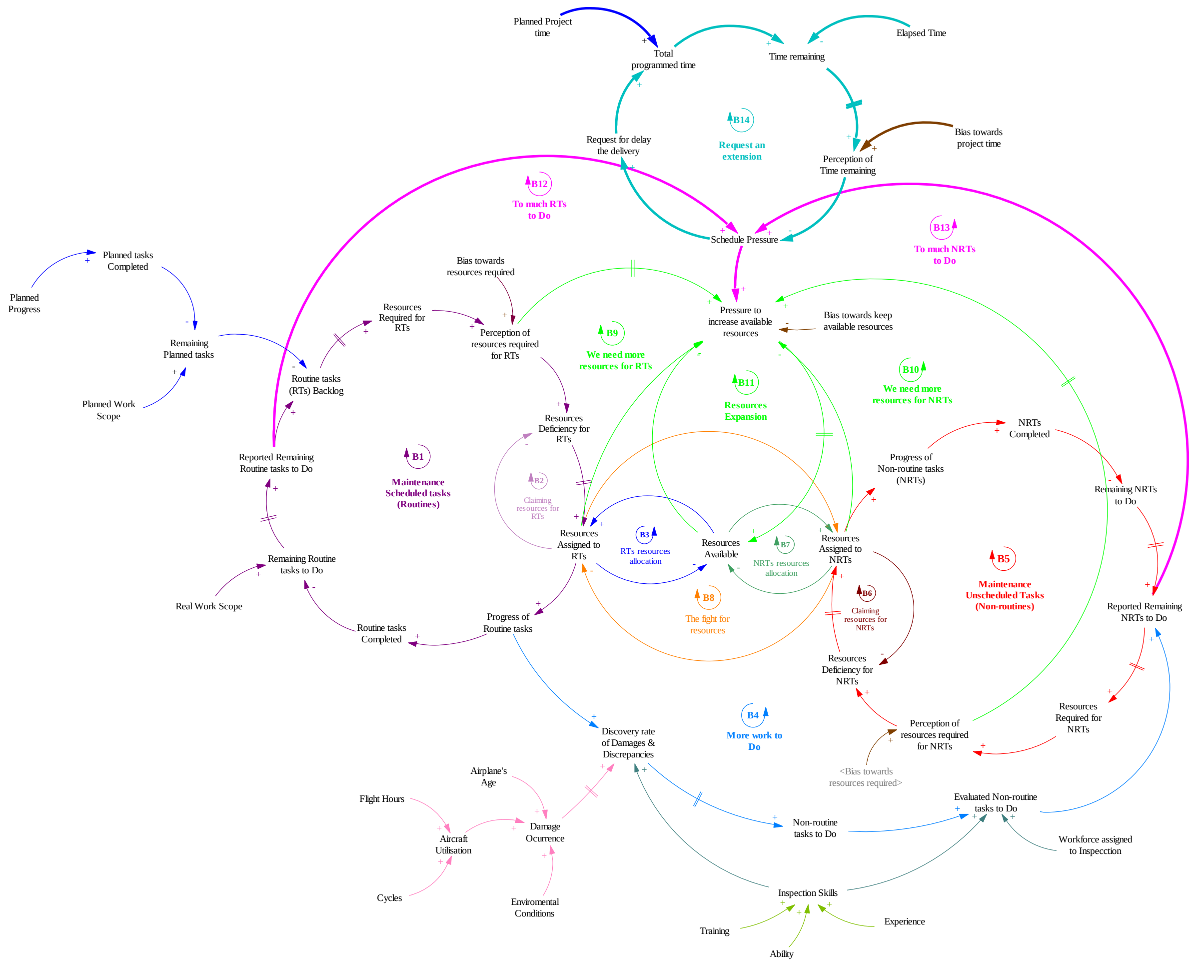

Figure 8 Extend the project deadline

5 Simulation and Preliminary Results

This section presents a preliminary model focused in simulating the workforce in heavy maintenance, and a brief discussion of its initial results. It is worth to mention that at this stage, some important assumptions have been considered that narrow the scope of this first model. The two main considerations, aiming to simplify the model and the simulation, are regarding the productivity and the task progress, assuming the former to be constant and the latter to follow a linear pattern, although in reality these variables might have more complex behaviours. Additionally, it is important to indicate that during the simulations hypothetical data have been used.

The model, displayed in Figure 9 and Figure 10, depicts the relation between routine (scheduled) and non-routine (unscheduled) tasks. The two major findings obtained from this model include how the arising of non-routines depends basically on two factors: the occurrence of discrepancies and the discovery of discrepancies. Secondly, the impact of workforce allocation between scheduled and non-scheduled tasks in the project performance, as was also stressed in the causal loop diagram.

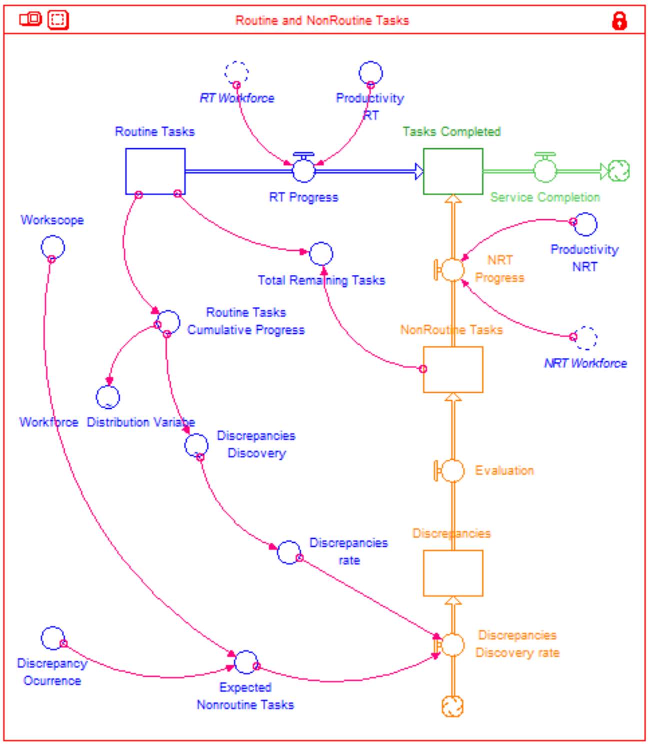

Figure 9 Occurrence and discovery of discrepancies

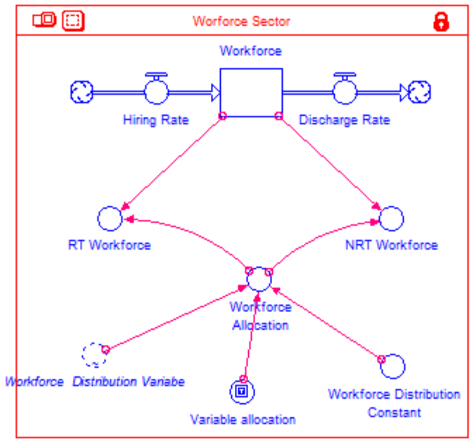

Figure 10 Workforce allocation

Regarding the arising of non-routines, on the one hand, the occurrence of discrepancies indicates the estimated number of non-routine tasks. This value is assigned considering different variables mainly related to the operation and usage of an airplane. However, as damages and discrepancies depend on several factors, it is difficult to accurately predict their quantity and severity. Furthermore, uncertainty in discrepancies and damages complicates the forecasting and planning of unscheduled activities. This rate is commonly estimated in terms of the number of non-routine tasks against the number of routine tasks, or non-routine man-hours against routine man hours. For instance, an occurrence rate of 1.2 expresses that for each routine task, 1.2 non-routine tasks might occur. The higher the rate, the greater the number of non-routines is.

On the other hand, the discovery of discrepancies is important, as it represents the rate in which damages and discrepancies are found during the progress of routine tasks. Generally, according with some experts in the industry, around 75% to 80% of non-routines should be found in the earliest 15% to 20% of the service duration, so as to have enough time to carry out the non-routines. Figure 11 illustrates a typical distribution of discovering non-routine tasks with respect to the routine progress, where, as can be seen, most of the discrepancies are found in the first quarter of the service.

It is expected that the later the discovery of discrepancies the greater the project duration. For instance, the discovery rate shown in Figure 11 is compared with the rate of Figure 12. In the first distribution, where approximately 95% of the discrepancies are discovered in the first half of the service, the maintenance check is completed in approximately 25 days. In the second distribution, where at the middle of the service only 30% of the discrepancies are found, the maintenance check requires approximately 30 days to be completed.

Figure 11 Discrepancies discovery distribution 1

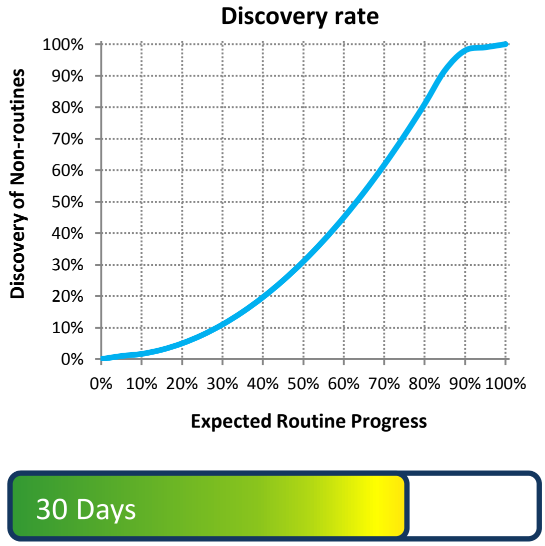

Figure 12 Discrepancies discovery distribution 2

Finally, the other point worth noting about this model is the significance of workforce allocation for completion of a maintenance service. In order to complete routine and non-routine tasks, workforce must be assigned to both activities. However, the difficulty lies in defining the number of people that should be allocated to complete scheduled and non-scheduled tasks. For example, as illustrated in Figure 13, if the majority of personnel is assigned to execute routine tasks (line 1), the routine activities will be finished rapidly and also most of the discrepancies (line 2) will be discovered early; however the progress of non-routine tasks (line 3) will be very slow, which has impact on the overall performance of the process and will delay the completion of the maintenance service (line 4). In contrast, as shown in Figure 14, if the majority of workforce is allocated to non-routines, the progress of routine tasks will be very slow and also will lag the discrepancies discovery, which will result in the late execution of non-routines. The consequence will be, as in the previous case, delay in completion of a project.

Figure 15 compares different workforce allocation values and their impact on the completion time of a maintenance service. The first line represents the allocation of 90% of the workforce to the routine, which leads to completing the project in more than 40 days. The second line depicts a distribution of 80% with a completion time of 30 days. Significantly allocating 60% of the workforce to the routine (line 4) means completing the project in approximately 21 days. However, the allocation of 50% (line 5) of the workforce increases again the duration of the project (25 days). All the previous alternatives consider a constant allocation of workforce; nevertheless it is possible to have a variable distribution of the labour during the maintenance service. Considering the variable workforce allocation shown in Figure 16, where at the beginning of the service most of the labour is assigned to the routine, but it gradually reduces until only 55% of the resources are left to the scheduled tasks; line 6 in Figure 15 shows a considerable reduction in project time, completing the maintenance service in less than 20 days. The results of Figure 15 depict the impact of workforce allocation on the maintenance service's performance, and emphasize the relevance of finding the best distribution of labour that reduces the project time.

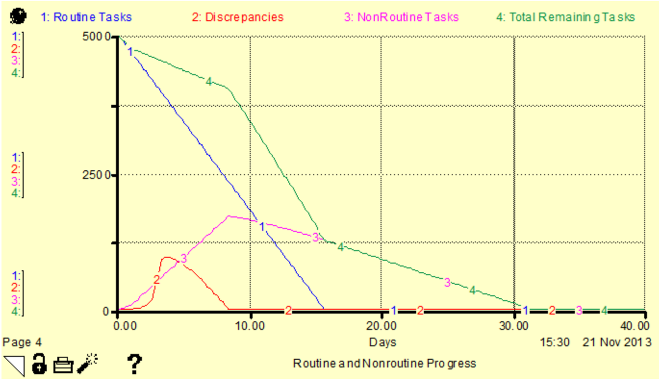

Figure 13 Routine and Non-routine tasks (80% workforce allocated to Routine)

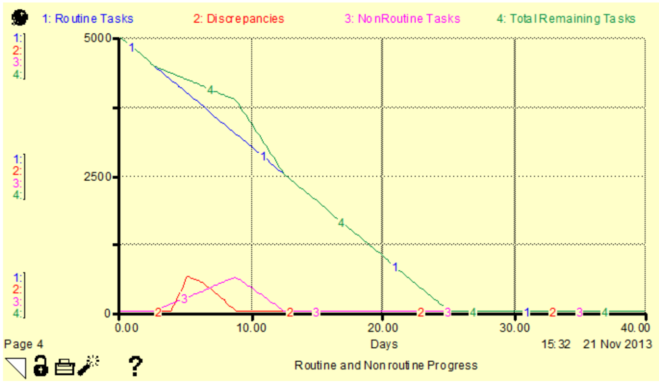

Figure 14 Routine and Non-routine tasks (50% workforce allocated to Routine)

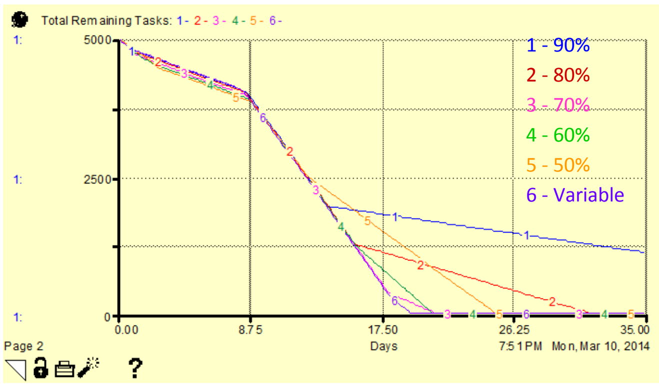

Figure 15 Remaining tasks and Project duration (Different Workforce allocation)

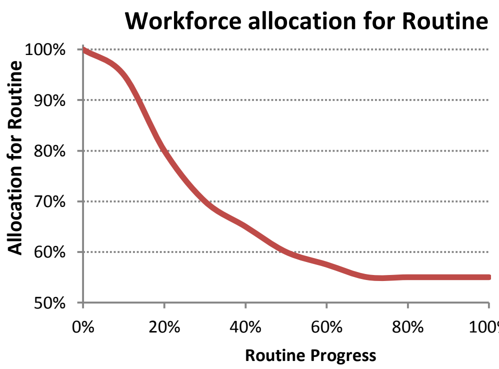

Figure 16 Variable workforce allocation for Routine tasks

6 Conclusions

Aircraft heavy maintenance services demand large amounts of specialised resources, which constantly interact between them. Nevertheless due to this complex relationship the planning, supply and coordination of all resources must be carefully managed. Furthermore, damages and discrepancies are commonly found during the execution of scheduled maintenance tasks. These unexpected events must be corrected by programming additional maintenance activities commonly known as non-routine. However, due to the uncertain nature of unscheduled tasks it is difficult to plan them in advance and moreover to forecast the required resources to perform them. As a result, they might cause delays and disruptions that might affect the costs, time and even quality of maintenance services.

System Dynamics is proposed for analysing delays and disruptions in aircraft heavy maintenance, as it is a flexible simulation methodology to study and manage highly dynamic and complex systems. Therefore it can be used to understand the relationship of routine and non-routine tasks and their impact on delays and disruptions within the process, and also to analyse the effects of uncertainty in unscheduled tasks on maintenance performance.

To understand the complex interaction of variables involved in a problem, a causal loop diagram was build. This also helped to depict the interrelation between scheduled and unscheduled tasks and to describe how the arising of unscheduled tasks depends on the occurrence but also on the discovery of damages and discrepancies. Additionally, it explains how the allocation of additional resources can help to reduce a backlog of activities. Finally it illustrates the continuous fight for resources between routine and non-routine tasks.

A stock and flow model was built in order to start simulating the dynamic and complex behaviour of aircraft heavy maintenance. Some of the preliminary results include the influence of discrepancy discovery rate on the duration of maintenance service, the effect of discrepancy occurrence rate on the estimated number of unscheduled tasks, and the impact of workforce allocation on the performance of maintenance service.

Despite the results and conclusions obtained so far using the stock and flow model, it is important to state the assumptions and limitations that may call into question the reliability of the research. First of all, productivity was assumed to be constant in the simulation, although in reality it is not. Secondly task progress was considered to be linear, but this behaviour is hardly the case. Finally, only workforce was modelled, whilst it is necessary to include the interaction of the two other main resources: parts and materials as well as tools and equipment.

Even though this research is focused on a particular problem in aviation maintenance, delays and disruptions caused by unscheduled tasks are a common problem in other areas, especially large scale projects. Thus, the models and results presented in this work can be applied to analyse problems with similar characteristics.

The results presented at this point are not conclusive, and it is necessary to improve the models to generate more robust and reliable results. In the future research, the initial assumptions will be reviewed and the other two main groups of resources will be taken into account. To model uncertainty caused by unscheduled tasks, it is important to achieve a deeply understanding of the most relevant variables involved in the occurrence and discovery of discrepancies. Finally, the validation of the model needs to be conducted as this is fundamental to gain confidence in using it to analyse the complex process of aircraft heavy maintenance.

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