Vizyoner Dergisi

Süleyman Demirel Üniversitesi Vizyoner Dergisi, Yıl: 2024, Cilt: 15, Sayı: 42, 368-381.
Süleyman Demirel University Visionary Journal, Year: 2024, Volume: 15, No: 42, 368-381.

ISSN: 1308-9552

ARAŞTIRMA MAKALESİ / RESEARCH ARTICLE

A NOVEL ROLLING HORIZON BASED SOLUTION FRAMEWORK FOR SCHEDULING AIRPLANE MAINTENANCE[*]

UÇAK BAKIMININ PLANLANMASI İÇİN YENİ BİR KAYAN UFUK TABANLI ÇÖZÜM ÇERÇEVESİ

Prof. Dr. Mehmet Güray GÜLER[1]

ABSTRACT

Maintenance, Repair and Overhaul (MRO) activities on aircraft and systems in aviation is a service sector that relies heavily on skilled workforce. The output of MRO activities is basically bringing the system reliability values, which decrease because of the use of aircraft and systems in certain flight times and landing and take-off numbers, to the default levels determined during the design phase. MRO companies are accountable to the civil aviation authorities who directly authorize them to ensure the required levels of reliability of their products. Airline companies request MRO services at the most convenient time and cost. However, the maintenance of an aircraft is a process that can take up to five weeks, includes plenty of jobs some of which may have stochastic durations, and many over-costed qualified technicians spend thousands of man-hours. In addition, each MRO company is involved in the maintenance of several airplanes arriving at different time intervals. In the study such a problem faced by an MRO company is addressed. The company's aim is to schedule several incoming airplane maintenance projects. A framework that employs an integer programming (IP) model working on a rolling horizon (RH) setting is used.

Keywords: Integer Programming, Rolling Horizon, Scheduling.

JEL Classification Codes: C02, C44, C61.

ÖZ

Havacılıkta uçak ve sistemler üzerindeki Bakım, Onarım ve Revizyon (MRO) faaliyetleri, ağırlıklı olarak kalifiye işgücüne dayanan bir hizmet sektörüdür. MRO faaliyetlerinin çıktısı temel olarak uçak ve sistemlerin belirli uçuş saatlerinde ve iniş kalkış sayılarında kullanılması nedeniyle azalan sistem güvenilirlik değerlerinin tasarım aşamasında belirlenen varsayılan seviyelere getirilmesidir. MRO şirketleri, ürünlerinin gerekli güvenilirlik düzeylerini sağlama konusunda kendilerine doğrudan yetki veren sivil havacılık yetkililerine karşı sorumludur. Havayolu şirketleri MRO hizmetlerini en uygun zaman ve maliyetle talep etmektedir. Bununla birlikte, bir uçağın bakımı beş haftaya kadar sürebilen bir süreçtir, bazıları stokastik sürelere sahip olabilen çok sayıda işi içerir ve bakım için birçok kalifiye teknisyen, binlerce adam-saat harcar. Ek olarak, her MRO şirketi, farklı zaman aralıklarında gelen birkaç uçağın bakımıyla ilgilenmektedir. Bu çalışmada bir MRO şirketinin karşılaştığı böyle bir sorunu ele alıyoruz. Şirketin amacı, gelen birkaç uçak bakım projesini planlamaktır. Kayan ufuk (RH) üzerinde çalışan bir tamsayılı programlama (IP) modeli kullanan bir çerçeve sunuyoruz.

Anahtar Kelimeler: Tam Sayılı Programlama, Kayan Ufuk, Çizelgeleme.

JEL Sınıflandırma Kodları: C02, C44, C61.

---

[*] The study is supported by TEYDEB 1507 Project (Project No: 7161160).

[1] İstanbul Technical University, Faculty of Management, Department of Industrial Engineering, mguler@itu.edu.tr

Makale Geliş Tarihi / Received : 24.07.2023
Makale Kabul Tarihi / Accepted : 06.03.2024

https://doi.org/10.21076/vizyoner.1332082

GENİŞLETİLMİŞ ÖZET

Amaç ve Kapsam:

Bu çalışmada, farklı uçak tipleri için bakım yapan bir bakım, onarım ve yenileme (MRO) firmasının bakım-onarım çizelgesi oluşturma problemi incelenmiştir. Bakım projelerinde deterministik süreli işler olabileceği gibi stokastik süreli bazı işler olabilir. Stokastik süreye sahip işlerin doğası gereği oluşturulan çizelgenin yeni uçak geldiğinde güncellenmesi ihtiyacı ortaya çıkmaktadır. Bu kapsamda, bu çalışmada birden çok uçağın bakım çizelgelerini dinamik olarak üreten bir çözüm önerisi sunulmaktadır.

Yöntem:

Uçak bakım süreçlerinde işler sürelerine ve meydana gelmelerine göre ikiye ayrılır: Rutin işler deterministik süreye sahiptir. Neredeyse tüm denetimle ilgili işler rutin işlerdir. Rutin olmayan işler, stokastik süreleri olan, yani süresi önceden bilinmeyen işlerdir. Bilinmese de bu işler için tarihsel veriler mevcuttur, teknisyenlerin birçoğu bu işler hakkında çok detaylı bilgiye sahiptir. Olayların sırası, gelen ve bakıma ihtiyacı olan bir uçakla başlar. Uçakla ilişkili iş setinde hem rutin hem de rutin olmayan işler olabilir. Bu çalışmada birden fazla uçağın bakım sürecini çizelgelemek için bir tamsayılı model (IP) geliştirilmiş ve kayan ufuk bazlı bir yöntem önerilmiştir. MRO şirketi, gelen herhangi bir uçağın işlerini geliştirilen IP modeli ile çizelgeler. Bu çizelgeyi hazırlarken sistemde mevcut diğer uçakların çizelgelenmiş işlerini de hesaba katar, bir başka deyişle yeni gelen uçağını bakımını bu işlerden artan kaynaklar ile oluşturur. Rutin olmayan işler için önceden bilinen bir dağılım olduğu varsayılır. Planlama yaparken bu dağılıma ait olası en büyük rakam alınır. Böylece gerçekleşecek sürenin planlanandan daha düşük olması garantilenmiş olur. Dolayısıyla mevcut çizelge tamir edilmeden de kullanılabilir halde kalır. Tekrar çizelgeleme sayısının düşük olması da sistemde çok sık plan değiştirmekten kaynaklanan gerginliğin düşürülmesini de sağlamaktadır. Bakımın ilk gününde uçakta herhangi bir sorun olup olmadığı kontrol edilir ve ilk günün sonunda rutin olmayan işlerin süresi belirlenmiş olur. Döngü bu şekilde devam eder. GANTT şeması kullanılarak iki uçağa ait bakım onarım çizelgeleri görselleştirilmiştir. IP modelleri çözebilmek için ticari çözücü olarak Gurobi V10.0.2, modelin ve GANTT şemalarının kodlanması için de Python 3.9.13 kullanılmıştır. Problemler i5 2.40GHz işlemcili ve 8 GB RAM'a sahip bir bilgisayarda koşturulmuştur.

Bulgular:

Oluşturulan IP model bazlı kayan ufuk yöntemi, iki uçak ve iki kaynaktan oluşan bir örnek ile çalıştırılarak sonuçlar analiz edilmiştir. Örnekte yer alan her iki uçağın da bakım süreçlerinin tamamlanabilmesi için sekiz iş yer almaktadır. Her iki uçak için de rutin olmayan iki iş vardır. Sistemin eldeki kaynaklara göre davranışını belirleyebilmek için kaynak seviyesine bir duyarlılık analizi yapılmış ve farklı kaynak seviyelerine göre her iki uçağa ait işlerin ve genel olarak tüm bakım işleminin bitiş zamanları incelenmiştir. Elde edilen sonuçlar incelendiğinde beklendiği gibi, mevcut kaynak seviyesi azaldıkça ilk gelen uçağın bitirme süresinin azalmadığı görülmektedir. Ancak ikinci uçağın bakım planlaması beklenenin aksine kaynak seviyesi azaldıkça azalmaktadır. Buna sebep olarak da iki etmen belirlenmiştir. Birincisi, sistem her iki uçak için de aynı anda optimize edilememektedir çünkü uçakların geliş süreleri farklıdır. Bu nedenle önce birinci uçak, sonra ikinci uçak için bakım planlama optimizasyonu çalıştırılmaktadır. İkincisi ise kullanılan IP modelinin amaç fonksiyonu son işin tamamlanma süresini en aza indirmektir. Bu nedenle ilk uçak geldiğinde IP modelinin önceliği son iş olduğu için diğer işlere odaklanmamakta, ilk uçak için bu durum herhangi bir probleme yol açmasa da yeni gelen uçak var olan işlerin üzerine çizelgelendiğinden ikinci uçağın bakım planı gecikebilmektedir. Bir diğer deyişle son işi hariç diğer işlerin sırası amaç fonksiyonunu değiştirmemektedir çünkü amaç fonksiyonu tüm projenin bitiş zamanı olan son işe bakmaktadır. Uçakların gelişi önceden bilinmediği için tüm problemin aynı anda çözülmesi mümkün değildir. Bu nedenle amaç fonksiyonu üzerinde bir güncelleme yapılarak son iş dışındaki diğer tüm işlerin de bitiş zamanlarının minimize edilmesi sağlanmıştır. Önerilen bu çözümün bahsedilen problemi ortadan kaldırdığı sayısal örnekte gözlemlenmiştir.

Sonuç ve Tartışma:

Uçak bakımları birçok farklı tipte iş barındıran, bir kısım işlerin stokastik sürelere sahip olduğu kısıtlı kaynaklar altında dinamik olarak çözülmesi gereken bir çoklu proje problemidir. Bu çalışmada, bu sorunu çözmek için bir IP modeli kullanan kayan ufuk bazlı bir çözüm çerçevesi öneriyoruz. IP modelleri yöneylem araştırmalarında çizelgeleme problemlerinin çözümünde kullanılan bir tekniktir. Geliştirilen sistem çok fazla çizelgelemenin getirdiği gerginliğin önlemek için tamamlama süresini azaltmak için temel programlardan her sapmada değil, sadece yeni uçakların gelişlerinde çizelgeler oluşturmakta ve bunu yaparken de stokastik sürelerin en büyüğüyle planlama yapmaktadır. Oluşturulan bu yöntem bir örnekle açıklanmıştır. IP modelin amaç fonksiyonunun yapısı gereği etkisiz sonuçlar verebileceği ortaya çıkmış, bu nedenle çalışma kapsamında amaç fonksiyonunda daha iyi sonuçların elde edilmesi için değişiklik önerilmiştir.

1. INTRODUCTION

Long-lasting complex equipment has characteristics of complex structures, numerous components, and sophisticated manufacturing technology, and they require customized maintenance, repair, and overhaul (MRO) services throughout their lifecycles (Zhao et al., 2022). Aviation equipment, military equipment, engineering machinery, and large complex products are some examples that require MRO services (Boukas et al., 1996; Cheng et al., 2010).

Airlines and MRO organizations mainly have two types of aircraft maintenance capabilities defined based on maintenance work scopes and resource requirements: *line maintenance* and *base maintenance* (Chandola et al., 2022). Line maintenance is primarily *light* in nature and takes care of minor inspections, line replaceable unit replacements, and basic troubleshooting of defects. On the other hand, base maintenance takes all the major load related to aircraft maintenance. Specifically, outsourcing airline's MRO operations regarding the base maintenance to an independent maintenance service company has become an economical and attractive operating mode (den Bergh et al., 2013; Deng et al., 2020) since it reduces fixed-asset and operational investments on fleet maintenance management significantly (Qin & Ng, 2023).

In recent years, the MRO sector has been growing rapidly, with airline companies transferring up to 50-60% of their total maintenance operations to third-party MRO companies. The MRO markets of transport jet and turboprop in 2017 have exceeded $61B and will surpass $100B by 2025 (Choi, 2017; ElSaid et al., 2018). Moreover, it's shown that a collaboration between the MRO firms and the airline companies enhances the benefit of both sides (Qin & Ng, 2023). On the other hand, concerning base maintenance, it's one of the major cost components of an airline company. Hence the aim of airlines is to retain or restore the inherent levels of reliability of aircraft to keep them airworthy at a minimum cost. However, the objective of MRO companies is to achieve high service levels and to maximize profit through service efficiency and costs reduction (Dinis et al., 2019). In addition, unexpected malfunctions and findings that may occur during routine maintenance are also problems that need to be solved within the scope of maintenance planning and optimization. Such contingencies require that the maintenance plan be reconfigured quickly, in line with the new conditions, without affecting the maintenance completion time as much as possible, without increasing costs and impairing the quality of service. However, the number of resources and the complexity of inter-resource relationships in the aviation industry pose a great challenge in planning MRO activities. If delays in the maintenance process are unavoidable, this may affect flight plans and even cause flight cancellations which is extremely costly.

In this study the problem of an MRO firm which is performing base maintenance for different types of airplanes is investigated. Maintenance projects arrive at different times and may have some jobs with stochastic durations. This is a dynamic scheduling problem and generating dynamic schedules is not addressed in the literature. We provide a solution framework that generates schedules at arrival epochs of the incoming airplanes over the existing schedules of the previous airplanes. The paper is structured as follows: the next section gives the literature review, the problem definition, modelling and results are given in Section 3 and Section 4 is for conclusion.

2. LITERATURE REVIEW

The efficient scheduling of MRO operations for the airplanes is important for flight performance. The supporting operations and maintenance processes of MRO operations involve multiple support resources, complex scheduling process, and multiple constraints; the efficient coordination of these processes can be considered as a special case of resource capacitated project scheduling problem which is first introduced by J.E. (1963), and its solution with an IP model is first given by Pritsker et al. (1969). MRO problems, on the other hand, are considered as a multi-resource constrained multi-project scheduling problem under uncertain environments (Yuan et al., 2018) .

The most important goal in project scheduling is to prepare a schedule that provides precedence relationships and is appropriate for the use of resources before the project starts. This schedule is called the *baseline schedule* or the *predictive schedule* (de Vonder, Demeulemeester, et al., 2007). This is very important in allocating resources to different activities, requesting spare parts or materials from suppliers, and connecting with other elements of the supply chain. According to this basic schedule, agreements are made with suppliers, worker requirements are determined, and most importantly, a *due date* and a *price quote* are given to customers (de Vonder, Demeulemeester, et al., 2007; Herroelen & Leus, 2004b). This offer covers the completion of airplane maintenance within a certain period of time. If the due date is missed (i.e., the project is late), serious penalty payments are incurred by the MRO firm. Therefore, it is important for the process to create a *flexible* and high-quality baseline schedule, i.e., schedules can easily be adapted to changes and repaired.

The problem instances in the literature are generally solved offline, and the input data for those instances is known in advance. On the other hand, the input for these problems in practice is stochastic and the solution algorithm learns about the input piece by piece, reacting to the new requests with only a partial knowledge of the input (Leung, 2004). Hence, the basic schedules created never stay as they are due to the randomness in the problem. That is, it is not a process where all time and resources are fixed like an exam scheduling problem. For this reason, much variability may occur during the execution of the project. The uncertainty in such a complex problem is addressed with different approaches. First, a baseline schedule can be generated by incorporating the statistical knowledge of random durations of the jobs. Such baseline schedules are called *proactive schedules* (Lambrechts et al., 2008). The purpose of proactive scheduling is to prepare a robust baseline schedule that is insensitive to disruptions by incorporating future uncertainties. The durations of some jobs are stochastic and not known exactly in advance. In proactive scheduling, the duration of this type of work is incorporated into the baseline schedule by looking at the previous records (Ashtiani et al., 2011). Some studies, for example, introduce the use buffers in such setting (de Vonder et al., 2005). In general, two approaches can be employed: *quality robust* and *solution robust*. In quality robust approach, rescheduling ensures that execution is performed in accordance with the basic schedule as much as possible. The solution robust approach, on the other hand, prevents deviation from the first determined objective function target. Otherwise, the firm is subject to serious penalties (de Vonder, Demeulemeester, et al., 2007). Therefore, proactive schedules try to build a schedule that is as safe as possible against the disruptions that may occur during the implementation of the project (Herroelen & Leus, 2004a). The consideration of uncertainty information is used to make the baseline schedule more robust, i.e., insensitive to disruptions (Fu et al., 2015). Second way is revising or re-optimizing a schedule when an unexpected event occurs. This process is called *reactive scheduling* (Deblaere et al., 2011). There are many different reactive scheduling methods (de Vonder, Ballestin, et al., 2007). These methods can be positioned between the two extreme points. The first one is not doing any scheduling at all. All jobs are shifted to the right during rescheduling just because one job takes longer than expected. At the other extreme, things are rescheduled from scratch. Too frequent scheduling causes nervousness in the system (Herroelen & Leus, 2005). That is, in each scheduling process, jobs are reassigned to different people and at different times. This causes people to change their plans very often and therefore it's not convenient at all. Hence there is a tradeoff between finishing the project (i.e., the line maintenance of an airplane) on time for not to pay a serious penalty cost and system nervousness (de Vonder et al., 2005).

The available data in MRO for aircraft maintenance has some limitations. Dinis et al. (2019) address the limitations of real maintenance data and propose a framework for the qualitative and quantitative characterization of maintenance work to support MRO organizations in performing capacity planning and scheduling. That seems to be the main reason of very limited work for scheduling MRO operations in airline maintenance. Among this limited work, den Bergh et al. (2013) propose a rolling horizon (RH) approach for the line maintenance department of an airline maintenance company at Brussels airport. Such a framework is widely used in production management (Nahmias & Cheng, 2009). The main idea is to schedule the jobs in a long horizon (for example 12 days) but fix the schedules of earlier days (for example, 3 days). They show that by incorporating an RH to partially account for stochasticity and a dynamic environment, they better succeed in capturing reality in the scheduling process. (Bruecker et al., 2018) is another work that studies MRO operations of airplanes but addresses line maintenance. They present a three-stage mixed integer programming (MIP) approach for optimizing the skill mix and training schedule at an aircraft maintenance company. They focus on the line maintenance which takes place at the gate or parking ramp between the arrival and departure of an aircraft. Yuan et al. (2018) focus on MRO operations of airplanes but their focus is on carrier-based aircrafts. In particular they study dynamic scheduling of carrier-based aircraft support scheduling. They use an IP model (and use a genetic algorithm to enhance to computation time) and a RH approach and show that the RH approach reduces the solving time significantly. Later Zhang et al. (2023) improve the genetic algorithm for the same problem. As stated, MRO service is also available for other complex systems. Li et al. (2020), for example, studies a scheduling optimization method for the MRO service resources of a large vertical mill. They solve a single project deterministic problem with three objectives and introduce a genetic algorithm to enhance the solution. A recent review on resource-constrained project scheduling problem is given by Snauwaert and Vanhoucke (2023).

The studies that deal with scheduling MRO operations on airlines are Yuan et al. (2018) and Zhang et al. (2023) only. Their IP models solve all incoming projects (i.e., MRO operations of aircrafts) *simultaneously* and introduce genetic algorithms to solve the problem in a reactive fashion. In this study, we address the problem of an MRO firm that can start maintenance of an airplane before finishing its ongoing project(s), i.e., the aim is to schedule *newcomers* while keeping current projects rolling on. We propose an IP model which runs over an RH framework. Our proposed framework can address the scheduling problem of several projects with jobs having stochastic durations. There are a few numbers of studies dealing with project scheduling of several airplanes in MRO systems. Among those, ours is the only study that can schedule a dynamic system, i.e., schedule the newcomers over an existing system.

3. PROBLEM DEFINITION, MATHEMATICAL MODEL AND THE RH FRAMEWORK

3.1. Problem Definition

In this section, first, the problem structure and assumptions are given. Then, the RH based framework and the IP model are introduced. We will illustrate the problem with an example problem where two airplanes arrive at different days.

Jobs in scheduling problems are items those need to be scheduled and are designated as task or task cards in aircraft maintenance taxonomy. Every job has a duration and a resource requirement. In aircraft maintenance processes, jobs are divided into two according to their duration and occurrence: *Routine jobs* have deterministic duration. All audit-related jobs are routine jobs. *Non-routine jobs* are the jobs who have stochastic durations, i.e., their duration is not known in advance. Although they are unknown, there is historical data for these jobs, and many of the technicians are very experienced and have detailed knowledge about these jobs. The order of events starts with an incoming airplane that needs maintenance. The job set associated with the airplane may have both routine and non-routine jobs. We assume that the durations of non-routine jobs have a known distribution which can be derived from the past data. The MRO company schedules the jobs of this incoming airplane. In the first day of the maintenance the airplane is inspected to identify any further problems and the duration of the non-routine jobs are identified at the end of the first day. Therefore, the durations of the non-routine jobs that are used in the scheduling phase can be different than the realized durations during execution. At the end of day, (possibly different) durations of non-routine jobs are identified. At the beginning of day 3, airplane 2 arrives. Like the first airplane, it has routine and non-routine jobs. The jobs of the second airplane are scheduled at the time of arrival. The difference between two airplanes is that there are jobs of the first airplane in the system during the scheduling process of those of the second airplane. Therefore, the capacity of the system should be considered with respect to both airplanes. Like the first airplane, the real durations of non-routine jobs of the second airplane are realized at the end of the day of the arrival, in this case it’s at the end of day 3. The order of events can be extended to more than two airplanes. In the next section the proposed framework is explained in detail.

3.2. The RH Based Framework

An RH framework is a widely used concept in production planning (Nahmias & Cheng, 2009). In RH framework, the data associated with the planning horizon is fed to the planning model as if one plans the full horizon. This data consists of approved customer orders, sales forecasts, etc. For example, if the planning period is 12 weeks, a production plan is carried out for 12 weeks. When it comes to execution, only the production plan for the first few weeks are executed (one or two weeks, for example). The intuition is that a plan should cover as much period as possible to be smooth since the processes are continuous in factories. On the other hand, the data regarding the future is more volatile than the data of early periods since early periods consists of approved orders in general but future periods have forecasts which may change with time.

In this study we propose an RH based framework to solve the dynamic resource constrained multi project scheduling problem with random durations of an MRO. Our aim is to create a proactive schedule that incorporates statistical knowledge of the random durations and then revise the schedule whenever needed. We will use the above two airplane examples to illustrate the framework and give the details step by step.

Durations for non-routines: For non-routine jobs (i.e., jobs having random durations) there are several ways to incorporate the statistical knowledge of the durations into the schedule (Ashtiani et al., 2011; de Vonder et al., 2005). Our motivation is to prepare a baseline schedule that is prepared for the worst scenario in terms of the durations and get the best schedule in the worst scenario. Therefore, we use the *maximum* value of these durations during scheduling to prevent any delays during the execution since any delay in the due date of the maintenance schedule is extremely costly.

Reschedule policy – non-routine realizations: A baseline schedule of a single airplane may need rescheduling if the real durations are different than the planned ones. In our case we assume that the durations of the non-routine jobs are identified at the end of the first day. The completion time of the maintenance can be improved with rescheduling since we use the *maximum* of possible durations. Therefore, there are two possible policies in terms of non-routines duration realization: (i) don't reschedule or (ii) reschedule. There is a trade-off between the two policies. If rescheduled, then the project is completed earlier, however this will not affect the company's profit since the due date and price quotes are given at the start of the project. But such a rescheduling increases the nervousness of the system. In terms of robustness, both policies are solution robust since there is no change in terms of penalties incurred or revenues accrued, however a rescheduling will have less robustness in terms of quality. In MRO companies, technicians are the main driving force of the maintenance. Therefore, in this study our focus is to reduce nervousness. Hence, for this case we do not reschedule at the realization of the non-routine durations.

Reschedule policy – New airplane arrivals: There are two policies when a second airplane comes to the MRO company over an existing maintenance project: (i) keep the existing plan of the first project with the *realized durations* and schedule the second airplane, (ii) schedule the second airplane and uncompleted jobs of the first airplane *simultaneously*. The same trade off applies here. The second policy may give a shorter completion time for the second airplane; however, it increases the nervousness of the system. Again, like the case above, we schedule the second plane while keeping the schedule of the first plane fixed with realized durations.

To conclude, the RH framework can be summarized as follows: *Schedule jobs of an arriving airplane using the largest possible durations of the non-routine jobs. If there are any existing airplane maintenance projects in the system, use their executed times to calculate remaining available times of the resources.* In the next section we give the IP model that is used for scheduling:

3.3. The IP Model

In the following we give the IP model of our proposed framework. IP is an operations research technique to solve optimization problems like scheduling, production planning, vehicle routing, etc. It consists of a function to be optimized, called the objective function, and sets of functions to be satisfied, called constraints. All functions should be linear. In this problem, the decision variables are denoted by X_{ujt}. It shows the completion time of job j of airplane u. It assumes value 1 if job j of airplane u is completed at time t, otherwise 0. Such variables are called binary variables, i.e., they are constrained to take only values of $\{0,1\}$. The sets and parameters are presented in Table 1 and Table 2, respectively.

Table 1. The Sets

Sets	Definition
u, U	Index and set of the jobs
c	Index of the *last* arriving airplane, i.e., the airplane whose jobs to be scheduled
j, J_u	Index and set of the jobs of airplane *u*
j_u^*	Index of the last job of airplane *u*
t, T	Index and set of the time horizon
r, R	Index and set of the resources

Table 2. The Parameters

Parameters	Definition
EFT_{uj}	The earliest finish time of job j of airplane u
LFT_{uj}	The latest finish time of job j of airplane u
d_{uj}	The required time to complete job j of airplane u
A_r	Availability of the resource r
k_{ujr}	The amount of the resource r required to complete job j of airplane u
P_{uj}	Predecessor list of job j of airplane u

In scheduling problems, in addition to the existing jobs, two auxiliary jobs are defined that have no duration, hence do not consume any resources. One of them is the *first job* which precedes all jobs and the other one is the *last job* which has all jobs as its predecessor. j_u^* is the index of the last job. There can be limits in finishing (or starting) time of jobs. The earliest (and latest) finish time of a job is used to address such limits. For example, if an airplane arrives at $t = 15$, then the earliest finish time can be the sum of 15 and its duration. To schedule the jobs with an IP model, the durations of the jobs (d_{uj}) are needed. Durations are clear for routine jobs. For the non-routine jobs, on the other hand, the duration is random, and we pick the largest possible time to reduce any delays. Resources can be renewable or non-renewable. They are necessary for the execution of the project. Resources that can be reused in each period are called *renewable resources*. Technicians or equipment are examples. *Non-renewable resources,* on the other hand*, are* those which are depleted as they are used such as paint, nails, money. A_r denotes the quantity of resource *r*. For a renewable resource like technician, this number is the same at each period, i.e., they are not consumed by jobs. For example, if there are five technicians in the company, the value of A_r is five at every period. For non-renewable resources, A_r denotes total value throughout the periods and each operations consumes the resources. Hence the company should purchase any non-renewable resources whenever needed.

In the following, the IP model for generating the schedules is given:

$$\sum_{t=EFT_{c\,j_c^*}}^{LFT_{c\,j_c^*}} t\,X_{cj_c^*t} \tag{1}$$

Subject to

$$\sum_{t=EFT_{u^*j}}^{LFT_{u^*j}} X_{u^*jt} = 1 \qquad j \in J \tag{2}$$

$$\sum_{t=EFT_{ci}}^{LFT_{ci}} t\,X_{1it} \leq \sum_{t=EFT_{cj}}^{LFT_{cj}} (t - d_j)\,X_{cjt} \qquad j \in J, i \in P_{cj} \tag{3}$$

$$\sum_{u\in\{U/u_a\}} \sum_{j\in J_u} k_{ujr} \sum_{e=t}^{t+d_j-1} \hat{X}_{uje} + \sum_{j\in J_c} k_{cjr} \sum_{e=t}^{t+d_j-1} X_{u_aje} \leq A_r \qquad u \in U, r \in R, t \in T \tag{4}$$

$$X_{1jt} \in \{0,1\} \qquad j \in J, t \in T \tag{5}$$

The objective function, given in eq. (1), minimizes the total duration of the project by minimizing the completion time of the last task $\boldsymbol{j_c^*}$**.** The objective function minimizes completion time of this last job. Constraint in eq. (2) states that each job must finish at a time t between the earliest finish time and the latest finish time. Constraint in eq. (3) states that to finish any job, all its predecessors should be completed. In other words, the constraint gives the predecessor-successor relationship. Constraint in eq. (4) is the availability constraint for renewable resources. It states that, in every period, total resource consumption in each period should not exceed total capacity. The first part of the left-hand side gives the total consumption of the resources which have been already scheduled and exist in the system. Here, $\hat{X}_{uje}$ shows the ending time of these jobs and are calculated using the real execution time. Note that $\hat{X}_{uje}$ is *not* a decision variable but it's an input to the model. If there are no jobs in the system during scheduling, then this part of the left-hand side is zero. The second part of the left-hand side gives the total resource consumed by the jobs to be scheduled. The right-hand side is the total available amount of renewable resource *r*. Technicians are the costliest items in MRO systems. Unlike normal technicians, they work for very high wages. Therefore, their effective scheduling is also extremely important in terms of reducing the costs of technicians. Hence, we don't employ any constraint regarding non-renewable resources. The last constraint is called the non-negativity constraint and shows the values that the variable X_{ujt} can take.

4. NUMERICAL ILLUSTRATIONS

In this section we will provide a numerical illustration for the RH framework. There are two airplanes and two resources. Both airplanes have eight jobs. Two of these jobs are auxiliary jobs; J1 is the first job and J8 is the last job. There are two non-routine jobs for both airplanes. The data is given in Table 3. The first and the second column respectively gives the airplane and job IDs. The third column shows whether the job is routine or non-routine and gives the distribution of the durations if it's a non-route job. We assume that the durations are uniformly distributed. For example [4-7] shows the set of {4, 5, 6, 7}. Columns 4 and 5 give the processing time and the execution time, respectively. If a job is a routine one, then both values are the same. However, if it's a non-route job, then the planning time is the maximum of its possible durations and the execution time is the realization among these values. Columns 6 and 7 show the consumption of the resources by each resource which are R1 and R2. The available amount of resource is six for both resource type. The last column gives the priority list of each job. J1 is a predecessor of all jobs for both planes and J8 has all jobs at its predecessor. We assume that each day has eight hours, and the second airplane arrives at the third day or at the beginning of hour 17. We use Python 3.9.13 to code the IP model and generate GANTT charts and use the state-of-the-art commercial solver Gurobi V10.0.2 to solve the problem. The problems are solved in a i5 2.40GHz 8 GB-RAM computer and the solution times are almost negligible (less than 10 seconds).

Table 3. Parameters of the Illustrative Example

AirPlane	Job	Routine	PT	ET	R1	R2	Priority
U1	J1	R	0	0	0	0	-
U1	J2	R	6	6	3	1	J1
U1	J3	N [4-7]	7	5	1	1	J1; J2
U1	J4	R	6	6	1	1	J1; J2; J3
U1	J5	R	7	7	3	1	J1
U1	J6	R	8	8	3	1	J1
U1	J7	N [2-9]	9	4	2	1	J1; J4
U1	J8	R	0	0	0	0	J1; J2; J3; J4; J5; J6; J7
U2	J1	R	0	0	0	0	-
U2	J2	N [5-9]	9	6	2	1	J1
U2	J3	R	5	5	1	1	J1; J2
U2	J4	R	6	6	1	1	J1
U2	J5	R	7	7	1	1	J1; J4
U2	J6	N [6-10]	10	7	1	1	J1; J5
U2	J7	R	9	10	2	1	J1; J4
U2	J8	R	0	0	0	0	J1; J2; J3; J4; J5; J6; J7

The resulting schedule is given in Figure 1. There are several points in the figure. First, since J2 and J5 have precedence relationship, they start simultaneously. Second, J3 ends earlier than planned, however since re-scheduling after realization of random durations is not our policy, J4 still starts at its planned time ($t = 13$). Third, the second airplane arrives at $t = 17$ and it starts immediately since the resource is available. The last point is that J7 has lasted less than planned, and this is used by J5 of the second airplane. The total execution time turns out to be 39 hours.

Figure 1. GANTT Chart with Resource Levels at Six

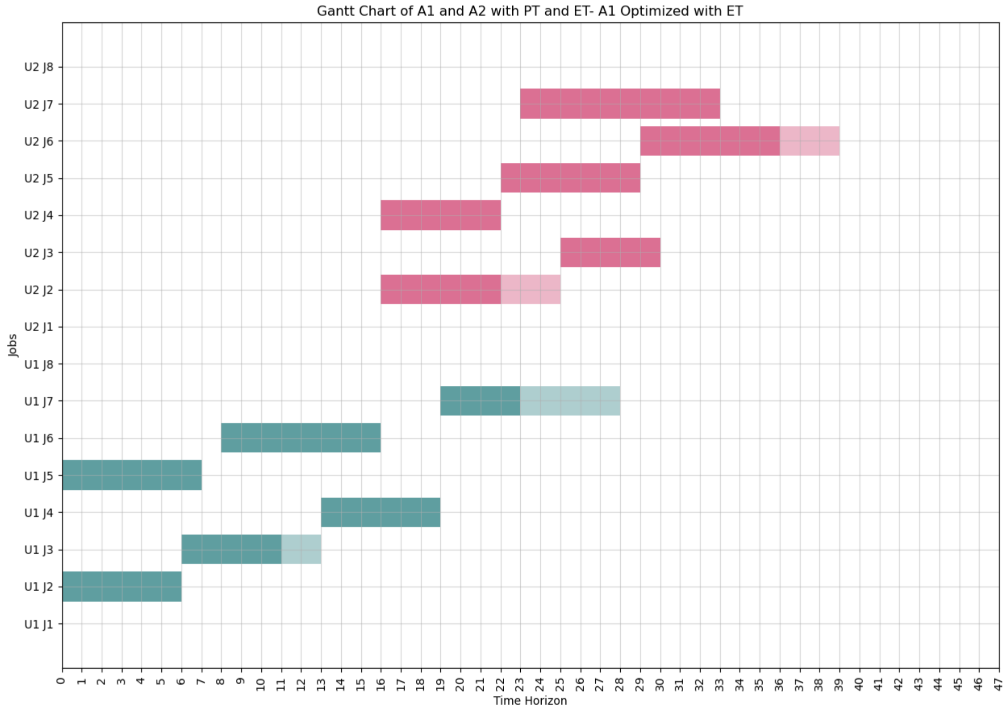


Figure 2 and Figure 3 show the results of the same problem with the available resource levels at five and four, respectively. It can be said that similar observations to the points raised above is observed. One remark is that, as expected, the time to finish both airplanes increase as the available level of resources reduce (46 for level 5 and 44 for level 4). It's counter-intuitive to observe such a result since a higher level or resource yields in a longer completion time. The causing effect can be identified when the GANTT charts are analyzed carefully. The completion time of the first airplane is respectively 28 and 30 for resource levels five and four, which is expected. However, the second airplane is finished later when resource level is five. This can be explained by two facts. First, the optimization model schedules the maintenance of airplanes *individually*, rather than doing it *simultaneously*. Second, the objective function of the optimization problem is to minimize the completion time of *the last job*. The result of this can be observed in J5 and J6 of the first airplane. Although there are enough resources in Figure 2, these jobs' ending time is later than those in the schedule of Figure 3. This is because the only important thing in the objective function is the finishing time of the last job, i.e., the finishing time of other jobs does not change the value of the objective function. Note that, simultaneous optimization of two problems at the same time is always better than optimizing them individually, hence if maintenance of both airplanes is scheduled *at the same time*, the ending time will be shorter (i.e., not longer) in the case where the resource level is higher.

The problem raised by the first issue cannot be intervened since arrival of airplanes cannot be known in advance. However, the latter problem can be solved by modifying the objective function of the IP model. The modified version of the objective function is given in the following:

$$\sum_{t=EFT_{c\,j_c^*}}^{LFT_{c\,j_c^*}} \lambda\ tX_{c j_c^* t} + \sum_{t=EFT_{cj}}^{LFT_{cj}} \sum_{j\in J\setminus j_c^*} t\, X_{cjt} \tag{6}$$

The modified objective function given in eq. (6) minimizes the finishing times of the other jobs in addition to the last job. However, since the last job is more important in terms of the total duration time of the project, it has a weight of λ. In our case we set it to 20. The resulting runs are given in Figure 4 and Figure 5. Now, it turns out that in both schedules the finishing time of the second airplane is $t = 44$.

Figure 2. GANTT Chart with Resource Levels at Five

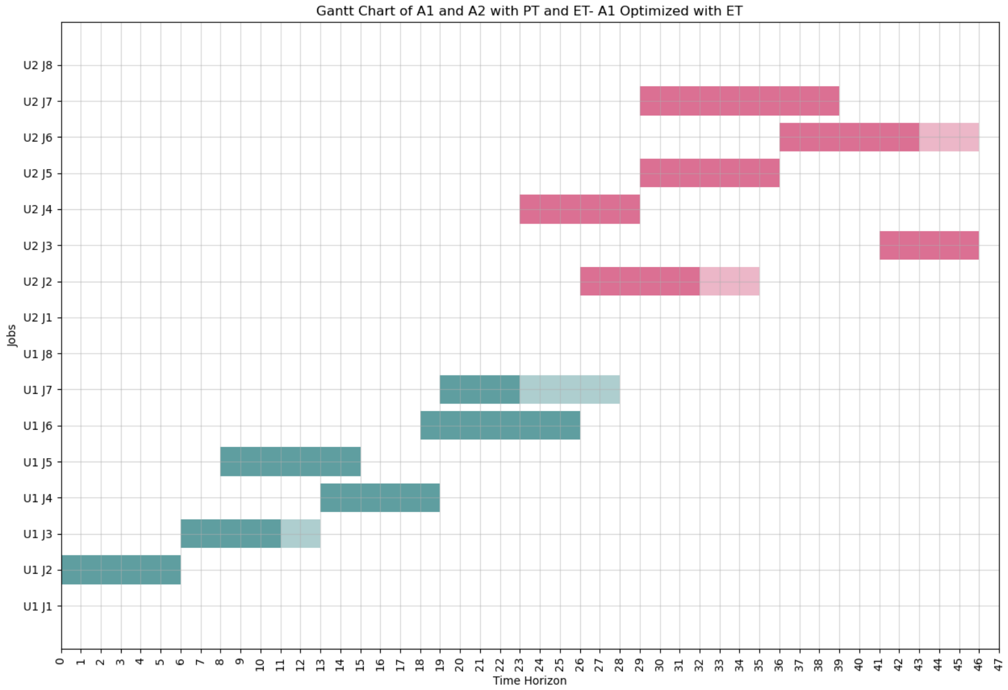


Figure 3. GANTT Chart with Resource Levels at Four

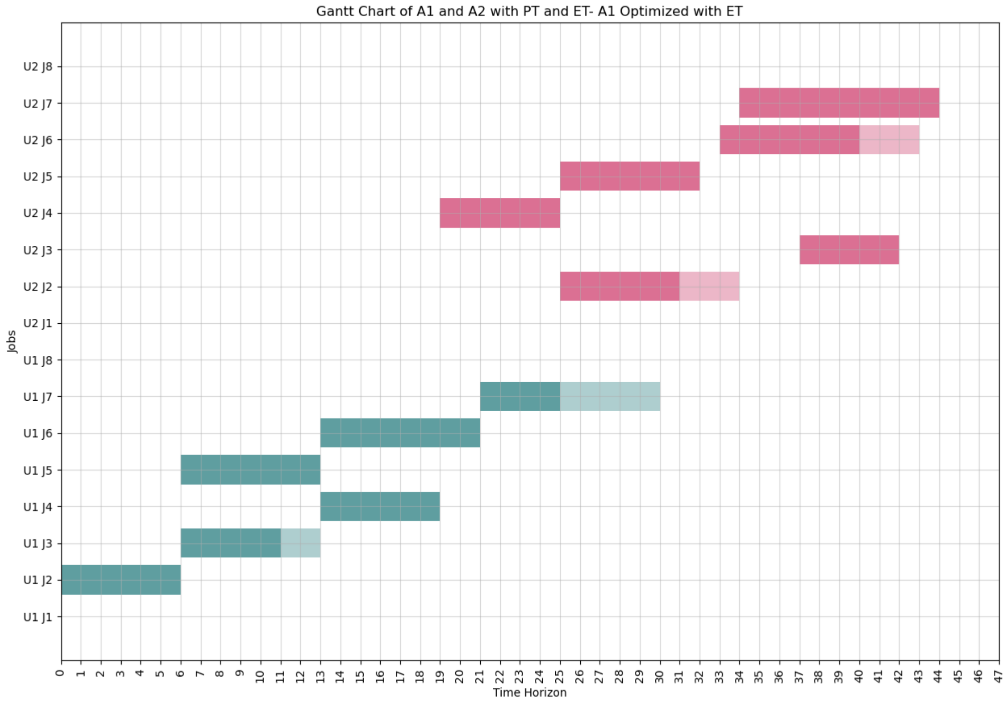


Figure 4. GANTT Chart with Resource Levels at Five with Modified Objective Function

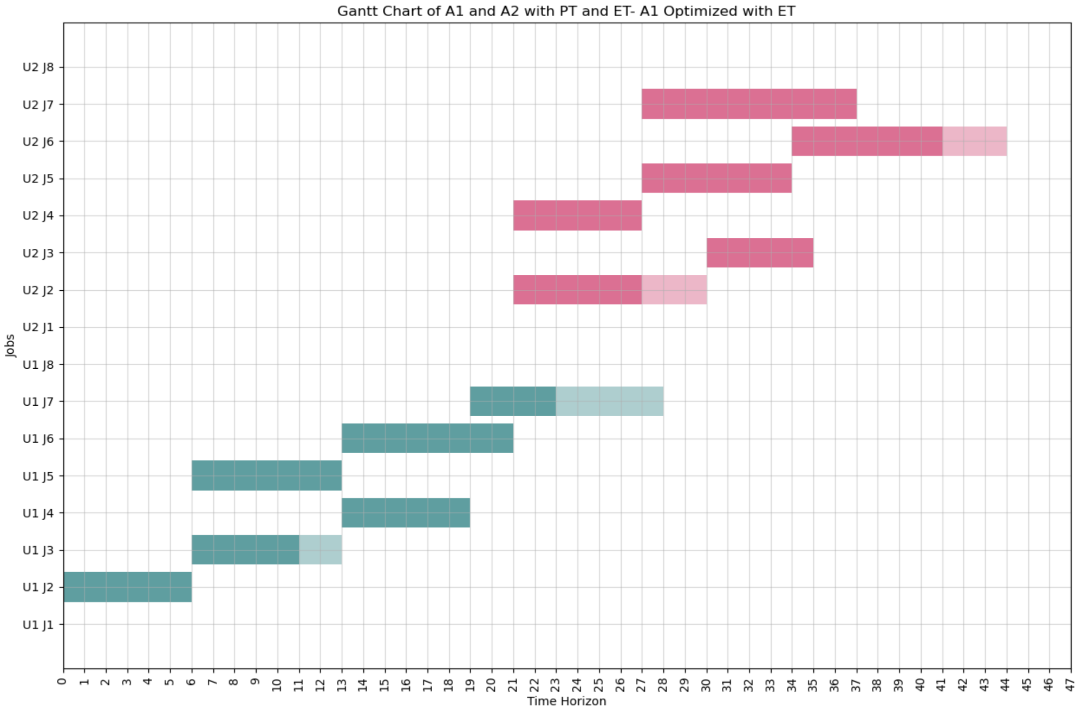
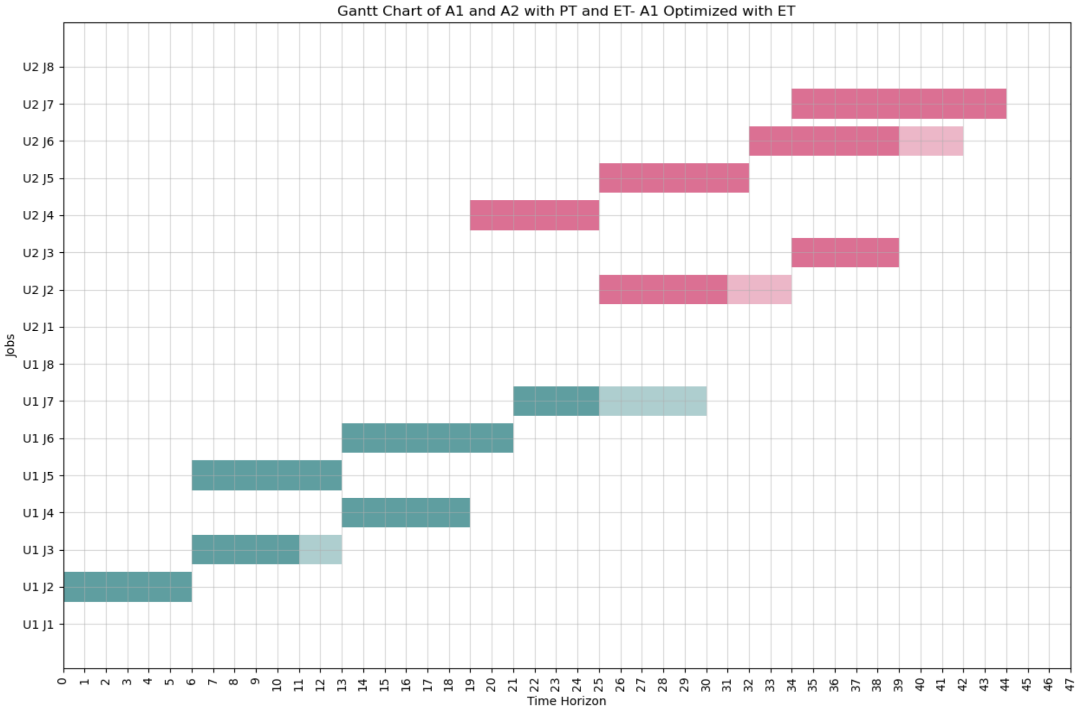


Figure 5. GANTT Chart with Resource Levels at Four with Modified Objective Function



5. CONCLUSION

MRO companies face problems in scheduling the jobs of maintenance of airplanes arriving at different time intervals. Jobs can have deterministic durations as well as random durations. In this study, we propose an RH framework that employs an IP model to solve such a problem. We use the largest of the possible task durations to create proactive baseline schedules. We reschedule at the arrival of airplanes to reduce the completion time and don't reschedule at each deviation from baseline schedules to prevent system nervousness. We illustrate our framework with an example. It turns out that the structure of the IP objective function may yield ineffective results, hence we propose a modification in the objective function that yields better results.

Our study has some limitations: First, illustrative examples with more airplanes may yield different results. Second, another objective function which makes a trade-off between the nervousness and a better schedule in terms of the existing jobs is worth examining. A natural extension of this study to develop a heuristic algorithm instead of an IP model since the model may fail to give results with many jobs. Genetic algorithm, which is a widely used in similar scheduling problems, is a good candidate for such a heuristic. Another future work avenue is to introduce chance constraints or stochastic programming to deal with the stochasticity of the durations.

DECLARATION OF THE AUTHOR

Declaration of Contribution Rate: The author contributes the study on his own.

Declaration of Support and Thanksgiving: The study is supported by TEYDEB 1507 Project (Project No: 7161160).

Declaration of Conflict: There is no potential conflict of interest in the study.

REFERENCES

Ashtiani, B., Leus, R., & Aryanezhad, M.-B. (2011). New competitive results for the stochastic resource-constrained project scheduling problem: Exploring the benefits of pre-processing. *Journal of Scheduling*, *14*, 157–171.

Boukas, E. K., Yang, J., Zhang, Q., & Yin, G. (1996). Periodic Maintenance and Repair Rate Control in Stochastic Manufacturing Systems. *Journal of Optimization Theory and Applications*, *91*(2), 347–361. https://doi.org/10.1007/BF02190100/METRICS

Bruecker, P. De, Beliën, J., den Bergh, J., & Demeulemeester, E. (2018). A three-stage mixed integer programming approach for optimizing the skill mix and training schedules for aircraft maintenance. *European Journal of Operational Research*, *267*(2), 439–452.

Chandola, D. C., Jaiswal, K., Verma, S., & Singh, B. (2022). Aviation MRO: A comprehensive review of factors affecting productivity of Aircraft Maintenance Organization. *2022 Advances in Science and Engineering Technology International Conferences (ASET)*, 1–7.

Cheng, Y.-A., Zhang, L., Liu, Y.-B., & Mo, X.-N. (2010). Solution of MRO support system for large complex equipment. *Computer Integrated Manufacturing System*, *16*(10), 0.

Choi, S. (2017). A study on aviation MRO industries and growth strategy in korean MRO. *Journal of the Aviation Management Society of Korea*, *15*(2), 3–19.

de Vonder, S. Van, Ballestin, F., Demeulemeester, E., & Herroelen, W. (2007). Heuristic procedures for reactive project scheduling. *Computers & Industrial Engineering*, *52*(1), 11–28.

de Vonder, S. Van, Demeulemeester, E., & Herroelen, W. (2007). A classification of predictive-reactive project scheduling procedures. *Journal of Scheduling*, *10*, 195–207.

de Vonder, S. Van, Demeulemeester, E., Herroelen, W., & Leus, R. (2005). The use of buffers in project management: The trade-off between stability and makespan. *International Journal of Production Economics*, *97*(2), 227–240.

Deblaere, F., Demeulemeester, E., & Herroelen, W. (2011). Reactive scheduling in the multi-mode RCPSP. *Computers & Operations Research*, *38*(1), 63–74.

den Bergh, J. Van, Bruecker, P. De, Belien, J., Boeck, L. De, & Demeulemeester, E. (2013). A rolling horizon algorithm for an airline line maintenance scheduling problem. *HUB Research Paper 2013/11*.

Deng, Q., Santos, B. F., & Curran, R. (2020). A practical dynamic programming based methodology for aircraft maintenance check scheduling optimization. *European Journal of Operational Research*, *281*(2), 256–273.

Dinis, D., Barbosa-Póvoa, A., & Teixeira, Â. P. (2019). A supporting framework for maintenance capacity planning and scheduling: Development and application in the aircraft MRO industry. *International Journal of Production Economics*, *218*, 1–15.

ElSaid, A., Reza, H., Adhikari, D., & Jamiy, F. El. (2018). A General Model Based Engineering Approach To MRO Business Software Applications Using Acme. *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC)*, 1–10.

Fu, N., Lau, H. C., & Varakantham, P. (2015). Robust execution strategies for project scheduling with unreliable resources and stochastic durations. *Journal of Scheduling*, *18*(6), 607–622.

Herroelen, W., & Leus, R. (2004a). Robust and reactive project scheduling: a review and classification of procedures. *International Journal of Production Research*, *42*(8), 1599–1620.

Herroelen, W., & Leus, R. (2004b). The construction of stable project baseline schedules. *European Journal of Operational Research*, *156*(3), 550–565.

Herroelen, W., & Leus, R. (2005). Project scheduling under uncertainty: Survey and research potentials. *European Journal of Operational Research*, *165*(2), 289–306.

J.E., K. J. (1963). The critical path method: resources planning and scheduling. In J. F. Muth & G. L. Thompson (Ed.), *Industrial Scheduling* (p. 347–365). Prentice-Hall.

Lambrechts, O., Demeulemeester, E., & Herroelen, W. (2008). Proactive and reactive strategies for resource-constrained project scheduling with uncertain resource availabilities. *Journal of Scheduling*, *11*(2), 121–136.

Leung, J. Y. T. (2004). *Handbook of scheduling: algorithms, models, and performance analysis*. CRC press.

Li, H., Mi, S., Li, Q., Wen, X., Qiao, D., & Luo, G. (2020). A scheduling optimization method for maintenance, repair and operations service resources of complex products. *Journal of Intelligent Manufacturing*, *31*(7), 1673–1691. https://doi.org/10.1007/S10845-018-1400-4

Nahmias, S., & Cheng, Y. (2009). *Production and operations analysis* (Vol. 6). McGraw-hill New York.

Pritsker, A. A. B., Waiters, L. J., & Wolfe, P. M. (1969). Multiproject scheduling with limited resources: A zero-one programming approach. *Management Science*, *16*(1), 93–108.

Qin, Y., & Ng, K. K. H. (2023). Analysing the impact of collaborations between airlines and maintenance service company under MRO outsourcing mode: Perspective from airline's operations. *Journal of Air Transport Management*, *109*, 102396.

Snauwaert, J., & Vanhoucke, M. (2023). A classification and new benchmark instances for the multi-skilled resource-constrained project scheduling problem. *European Journal of Operational Research*, *307*(1), 1–19.

Yuan, P., Han, W., Su, X., Liu, J., & Song, J. (2018). A dynamic scheduling method for carrier aircraft support operation under uncertain conditions based on rolling horizon strategy. *Applied Sciences*, *8*(9), 1546.

Zhang, Y., Li, C., Su, X., Cui, R., & Wan, B. (2023). A baseline-reactive scheduling method for carrier-based aircraft maintenance tasks. *Complex & Intelligent Systems*, *9*(1), 367–397.

Zhao, X., Deng, Q., Liu, X., Zhang, L., Wu, S., & Jiang, C. (2022). Integrated scheduling of distributed service resources for complex equipment considering multiple on-site MRO tasks. *International Journal of Production Research*, *60*(10), 3219–3236.