A scenario-based stochastic programming approach for aircraft expendable and rotable spare parts planning in MRO provider

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Abstract

Purpose – This paper aims to build a novel model and approach that assist an aircraft MRO procurement and overhaul management problems from the perspective of aircraft maintenance service provider, in order to ensure its smoothness maintenance activities implementation. The mathematical model utilizes the data related to warehouse inventory management, incoming customer service planning as well as risk forecast and control management at the decision-making stage, which facilitates to alleviate the negative impact of the uncertain maintenance demands on the MRO spare parts inventory management operations.

Design/methodology/approach – A stochastic model is proposed to formulate the problem to minimize the impact of uncertain maintenance demands, which provides flexible procurement and overhaul strategies. A Benders decomposition algorithm is proposed to solve large-scale problem instances given the structure of the mathematical model.

Findings – Compared with the default branch-and-bound algorithm, the computational results suggest that the proposed Benders decomposition algorithm increases convergence speed.

Research limitations/implications – The results among the same group of problem instances suggest the robustness of Benders decomposition in tackling instances with different number of stochastic scenarios involved.

Practical implications – Extending the proposed model and algorithm to a decision support system is possible, which utilizes the databases from enterprise's service planning and management information systems.

Originality/value – A novel decision-making model for the integrated rotable and expendable MRO spare parts planning problem under uncertain environment is developed, which is formulated as a two-stage stochastic programming model.

Keywords Rotable MRO spare Parts, Stochastic programming, Aircraft maintenance, Bender's decomposition algorithm

Paper type Research paper

1. Introduction

Outsourcing aircraft's MRO operations to a professional maintenance service provider has become a trend in aviation industry, as such practice enables airline companies to focus on their profitable passenger and cargo transportation service operations and fulfill compulsory

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aircraft MRO requirements (Qin *et al.*, 2018; Li *et al.*, 2019). It is estimated by Marcontell (2013) that there is a 45% increase of MRO outsource rose from the mid-1990s to 2012. Receiving increasing MRO service demands associated with heterogeneous aircraft configurations, aircraft maintenance service company is faced with great challenge in fulfilling incoming demands and coordinating its limited maintenance resources. Having sufficient aircraft MRO spare parts is one of the perquisites for aircraft maintenance tasks implementations, as maintenance capacity partially replies on spare parts' inventory levels (Dinis *et al.*, 2019). According to the complexity of aircraft structure and specification of MRO spare parts (as shown in Figure 1), aircraft's MRO spare parts can be classified into expendable and rotable parts on the basis of its service life cycle. Procurement of expendable MRO parts with one-time use on single aircraft can lead to high inventory holding costs, and the overhaul process of rotable MRO spare parts with multiple-time service cycles involves long lead times. Specifically, some MRO spare parts are expensive with long service life, which can be rotated among different aircraft after overhauling. On the other hand, some spare parts are for one-time use on single aircraft and its service life ends after being taken down from aircraft. In this regard, maintaining sufficient MRO parts and minimizing inventory cost are critical for aircraft maintenance company. A combination of MRO spare part procurement and rotable overhaul practice is adopted in aircraft MRO industry as the service life cycle of spare parts is different. In addition, the uncertain maintenance demands may interrupt the original MRO spare parts' plan in the progress of practical implementation. In real situations, maintenance demands from different clients (i.e. airline companies seeking MRO service) are difficult to predict since each airline carries out its own fleet's flight and maintenance plan (Eltoukhy *et al.* 2017, 2018). In addition, the stability of the MRO supply chain can be affected by uncertain productions and transportation processes (Chan and Chan, 2010; Nakandala *et al.*, 2014), especially in global supply chains nowadays (Choi *et al.*, 2019). Therefore, it is essential to have an advancement estimation on order fulfillment performance under uncertainty (Ng *et al.*, 2017; Liu *et al.*, 2019). Therefore, the consideration of risk and uncertainty in modeling can enhance the solution robustness on inventory management (Zheng and Wu, 2017; Wen *et al.*, 2019). Managing Business and Inventory Management (BIM) for aircraft MRO operations is challenging as MRO demand is stochastic for accurate predication with single scenario (Mcarthur *et al.*, 2018; Gao and Pishdad-Bozorgi, 2019).

Given the sophisticated physical structure of aircraft, the overhaul process on aircraft involves consumptions of necessary spare parts that support the airworthiness of aircraft. As mentioned above, spare parts for aircraft MRO operations can be differentiated into two types according to the number of service life cycles times on aircraft. For some costly core spare parts with multiple service life cycles, they are classified as rotable spare parts, which require compulsory periodic

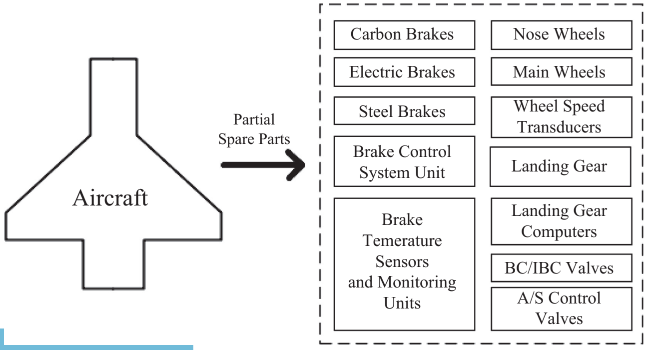

Figure 1.
MRO spare parts of aircraft

maintenance and overhaul so as to ensure the airworthiness and functionality. Typical rotable spare parts include the engine, landing gear, flying instrument and so on. The main reason for rotating the core spare parts is that the lead time for completing the overhaul on spare part is long. In this regard, to enhance the efficiency of aircraft MRO and minimize aircraft's on ground time, a rotation practice for core rotable spare parts with long overhaul lead time is adopted. Specifically, a group of aircraft shares the same type of core rotable spare parts in their MRO process, which means that the overhauled rotable spare parts from the earlier arrival aircraft can be installed on the later arrival aircraft. The prerequisites of spare parts rotation include: (1) the spare parts are reusable with standard airworthiness after overhaul process; (2) the spare parts are compatible between two aircrafts; (3) the overhaul process is completed on the rotable spare part upon newly arrival aircraft with associated spare part requirement. The conventional deterministic procurement and overhaul planning model is not capable to handle the uncertainties during the implementation of maintenance activities, as the optimal planning solution under deterministic stage can become impractical in real situations. In this connection, it is necessary to incorporate the uncertainty of maintenance demands into the procurement planning problem. Motivated by the incoordination and incapability of conventional approach in simultaneous rotation and procurement planning for aircraft MRO spare parts under uncertainties, we aim to develop a novel efficient optimization approach to support the aircraft spare part management system developments, which incorporates the capability in hedging against the risk of uncertain maintenance demands from airlines in practical situations.

The contributions of the paper include:

1. Aircraft overhaul spare parts management is addressed, which incorporates the procurement, overhaul and rotation planning for the core reusable spare parts as well as the procurement of one-time expendable spare parts;
2. Uncertain arrival aircraft and its associated maintenances and spare part demands are considered in aircraft spare part management;
3. A stochastic programming method is adopted to describe the spare parts planning under different scenarios, to accurately address uncertainties;
4. Given the structure of the mathematical model, a Benders decomposition (BD) approach is proposed to facilitate the optimization process, which provides high-quality solution within reasonable time;
5. Extensive computational experiment is conducted based on the maintenance demand data from industry. Managerial insights and suggestion are derived from the results, which enhances operation efficiency in practical situations.

The novel optimization model proposes a flexible decision support method in characterizing MRO spare part overhaul and procurement under uncertainty in maintenance service company, which utilizes the maintenance service demand data derived from enterprise management system. To better manage data and decision-making components scattering on different layers of enterprise information system, the proposed mathematical model can be a suitable tool in integrating the relational database layers, including inventory levels, warehouse management, production planning as well as risk forecast and control. Specifically, maintenance demand uncertainties with different specifications are characterized as discrete scenarios in the proposed mathematical model, and the randomness of different scenarios is prescribed with probabilities. The proposed algorithm is compared with the branch-and-bound algorithm provided by commercial solver CPLEX, and the experimental result demonstrates the suitability and effectiveness of the proposed BD algorithm in solving the two-stage stochastic programming model.

The rest of this paper is organized as follows: literature reviews investigating three aspects of aircraft MRO operations are presented in Section 2. The description of aircraft MRO spare parts planning problem under aircraft MRO outsourcing context is introduced in Section 3, then a stochastic programming mathematical model addressing the uncertain maintenance demands is presented afterward. In Section 4, the BD algorithm for the stochastic model is described. Computational experiments and respective managerial insights discussions are carried out and discussed in Section 5. Finally, the conclusions and future works of the problem are presented in Section 6.

2. Literature review

Aircraft Maintenance, Repair and Overhaul (MRO) operations involve substantial investments in maintaining the functionality of sophisticated aviation equipment and the associated spare parts (Li *et al.*, 2017). From the perspective of airlines, aircraft maintenance outsourcing is an attractive and feasible option to reduce their MRO costs, which helps to maintain airlines' competitive advantages in market and fulfill compulsory MRO requirements (Marcontell, 2013; Qin *et al.*, 2018).With an increasing trend of maintenance outsourcing adopted by airlines, efficiently fulfill maintenance requests associated with respective aircraft types becomes a great challenge to maintenance service company. For airline companies, reducing aircraft's on ground time is significant as they need to have sufficient transport capacity in serving passenger and cargo demands. As a result, airline attempts to have a robust schedule in managing flights maintenance and the associated MRO planning. Adopting MRO outsourcing practice facilitates airlines to construct a stable fleet schedule, which is essential in maintaining high level of transport service quality. Qin *et al.* (2019) developed a mathematical model to schedule the aircraft hangar maintenance planning problem under the MRO outsourcing mode from maintenance service company's perspective, based on the maintenance hangar capacity planning model (Qin *et al.*, 2018).

Though outsourcing facilitates airlines' MRO operations, challenges emerge and goes to aircraft MRO service provider who receives overwhelming maintenance demands nowadays. Specifically, MRO spare parts procurement and overhaul planning are vital to support maintenance services. All aircraft MRO activities associated with spare parts requirements should be properly arranged in advanced to ensure their availability. From other side, the inventory of MRO spare parts has to be maintained within a suitable safety level in view of uncertain maintenance demands in practical situations. Fulfilling uncertain spare parts demands is a common issue in various industry. Hong *et al.* (2018) carried out an overview on uncertainties occurred in procurements process under different stochastic scenarios. Zhen and Wang (2015) developed a two-phase stochastic programming model on the component replenishment decisions for an Assemble-To-Order (ATO) manufacturer. Afterward, optimization models for production and procurement planning under uncertain environments are studied in Zhen (2016). Regard to complex supply chain management, a multi-product, multi-component, procurement and assembly problem with both supply and demand uncertainties is addressed by Bollapragada *et al.* (2015), and the problem is formulated as a stochastic linear programming model by charactering uncertainties as finite scenarios. Furthermore, a multi-objective model for the preventive replacement of a spare part over a planning horizon is proposed by Nosoohi and Hejazi (2011). Meng *et al.* (2015) studied a carrying capacity procurement of rail and shipping service in automobile transportation problem with consideration of uncertain demands. Kaur *et al.* (2020) considered a stochastic production and procurement problem in the context of resilient supply chain managements. Tiwari *et al.* (2018) further studied a two-stage supply chain between supplier and retailers in view of stochastic demands. Bertazzi *et al.* (2015) considered stochastic demands in an inventory routing problem with transportation procurements.

Moreover, inventory routing problem was further extended to medical drug inventory routing context by Nikzad *et al.* (2019). Gu *et al.* (2015) developed a two non-linear programming models for prediction of impending demands based on installed spare parts' failure distributions. Hu *et al.* (2016) proposed a two-stage optimization framework and characterized the uncertain parameters with a scenario-based methodology. Gholizadeh *et al.* (2020) formulated a robust fuzzy scenario-based stochastic programming model for sustainable procurement and logistics planning with big data analysis. Aircraft MRO spare parts' procurement problem shares some similarities with Assemble-To-Order (ATO) manufacturers' product configuration problem. Product configuration problem aims to select components and constitute a personalized product with specified configurations (Li *et al.*, 2018), and aircraft MRO spare parts support different maintenance demands consuming heterogeneous MRO spare parts during maintenance operations. Ertogral and Öztürk (2019) proposed an integrated production and workforce planning model in the context of MRO operations in airline industry and took MRO spare parts' supply into consideration. Somarin *et al.* (2018) studied an emergency resupply policy that helps to improve MRO service providers' flexibility in the event of spare part's shortages.

MRO spare parts procurement planning is one of the significant components in aviation MRO supply chain, and spare parts inventory supply chain management has been addressed in different fields. It is common that the maintenance service providers are involved in global MRO supply chain and they have to purchase spare parts from different supplier globally, instead of producing all spare parts by their own (Bollapragada *et al.*, 2015). Zanjani and Nourelfath (2014) studied an integrated spare parts logistics and operation planning for general maintenance service provider. For aircraft MRO operations, aircraft configuration parameters, specific spare part demands and lead time of overhauling rotable spare parts have to be considered. These significant factors differentiate the spare part procurement and overhaul problem from the other context. Moreover, these uncertain maintenance demands associated with spare parts requirements can have the negative impact on aircraft MRO operations if the risk of uncertainty is not addressed properly (Zhang *et al.*, 2018). In literature, the uncertainties of maintenance demands are less considered in the context of aircraft MRO spare part procurement planning, together with the overhaul planning for multiple service life cycle spare parts. With the foundations of stochastic programming in describing demand uncertainties in literature (Bollapragada *et al.*, 2015; Li *et al.*, 2018; Tiwari *et al.*, 2018; Nikzad *et al.*, 2019; Kaur *et al.*, 2020), stochastic programming model should be further enhanced to address the research gaps between relevant works and aircraft MRO environment. Specifically, the impact of uncertain demands and associated maintenance requirement on spare parts procurement and overhaul planning should be investigated in an integrated manner. Furthermore, the framework of stochastic programming mathematical formulation envisions the directions of algorithmic development for resolving MRO spare parts planning problem within reasonable time for practical use.

3. Mathematical model for MRO spare parts procurement and rotation problem with uncertainty

3.1 Problem description

Aircraft maintenance check includes line maintenance and hangar maintenance. Different from daily regular line maintenance conducted at a gate or apron during a short turnover between two consecutive flights on aircraft, hangar maintenances are intensive MRO checks, which are carried out when the aircraft has completed a specific flying times or take-off/landing cycles. For hangar maintenance, aircraft needs to betaken out of service and sent to the maintenance hangar. MRO spare parts are indispensable, and different maintenance checks require respective MRO spare parts to support the maintenance operations on the aircraft. Moreover, for the same or some similar series of aircraft models, it is the case that the MRO spare parts are compatible among a group of aircraft and rotations among them are possible. Specifically, maintenance service provider has to obtain sufficient MRO spare parts to support maintenance demands from the clients. To control the inventory level and avoid holding excessive MRO spare parts, maintenance service provider adopts a mix of rotable overhaul and Procure-To-Order (PTO) practice, according to the maintenance demands specifications of arrival aircraft. In practical situations, unexpected maintenance demands may emerge as some urgent unscheduled maintenance demands arrive at maintenance company with a very short notice period, and maintenance service provider does not necessarily have sufficient components to satisfy the extra maintenance demands. In this connection, maintenance service company needs to determine rotable spare part's overhaul planning and expendable spare part's procurement quantity decisions and to take the uncertain additional maintenance demand into consideration.

The overall objective is to minimize the costs of overhaul, procurement and holding excessive inventory under uncertain environment. A pre-procurement practice is used at the deterministic planning stage and maintenance company may purchase more widely used spare part to reduce the cost of putting urgent procurement. For the spare parts with multiple service life cycles, the overhaul modes have to be determined, together with the spare parts rotation plan among aircraft under the deterministic stage. If the MRO spare parts procured in advance cannot meet the actual demands due to unexpected maintenance demands, maintenance company is able to put emergency order and procure additional spare parts to meet the remaining requirements of MRO parts under stochastic stage with higher costs. In this connection, aircraft MRO spare parts procurement and overhaul problem has to determine: (1) the overhaul modes for rotable spare parts, including regular and expedite modes with different lead time for completing the overhaul task; (2) rotation plan for the rotable spare parts; (3) number of pre-procure spare parts from suppliers; (4) the number of additional spare parts procurement if the unexpected maintenance demands cannot be fulfilled by the pre-procured spare parts.

3.2 Mathematical model

The MRO spare parts procurement and overhaul problem is formulated as a stochastic model. The pre-procurement process and overhaul arrangements are modeled under the deterministic stage, including overhaul mode selections for rotable spare parts and number of pre-procurement for both rotable and expendable spare parts. The concept of rotable spare part overhaul is shown in Figure 2. Specifically, aircraft's rotable spare parts demand can be fulfilled by the rotable spare part come from the other early arrival aircraft, after overhauling process. The rotation arrangement of these multiple service life cycles spare parts is also

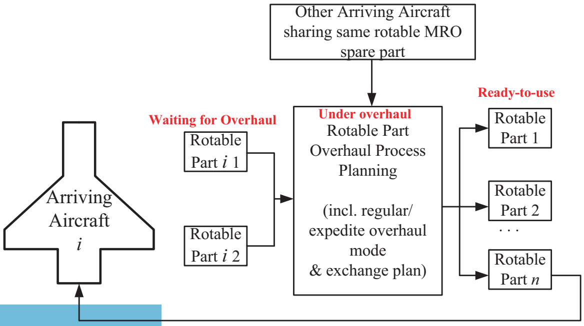

Figure 2.
Overhaul and exchange of rotable MRO spare parts

optimized under the deterministic stage. For overhaul process on rotable spare parts, there are two types of overhaul modes, namely regular and expedite types. The main differences between regular and expedite overhaul modes are the level of manpower input and the duration of lead time in finishing the overhaul tasks on the spare parts. Specifically, expedite overhaul mode requires more manpower input on the same overhaul task, aiming to shorten the lead time of respective overhaul operations and provide more available rotable spare parts to satisfy incoming aircraft's spare part requirements. Also, the expedite mode induces a higher manpower and relevant cost. To sum up, regular mode refers to the standard overhaul operations on rotable spare parts, while expedite mode refers to shortening the standard overhaul lead time by investing more manpower inputs.

Under the uncertainty (stochastic) stage, the additional/emergency procurement is determined under different scenarios to fulfill the unexpected arrivals maintenance demands. To characterize the uncertain maintenance demands, respective stochastic scenarios are generated together with respective probability of occurrence. Under each stochastic scenario, the unscheduled demands together with the specification of aircraft and requirements of spare parts are specified. Both rotable and expendable spare parts can be procured under stochastic scenarios, while the emergency procurement costs are higher than the pre-procurement practice.

The notations of the mathematical model are listed as follows:

i	Aircraft with maintenance demands, $i \in I$
EM	Set of expendable spare parts
RM	Set of rotable spare parts
xrm_{im}	Number of rotable spare parts m comes from aircraft i
RM_i	Set of rotable spare parts demands required by aircraft i
EM_i	Set of expandable spare parts required by aircraft i
K_{EM}	Set of expendable spare parts provider
K_{RM}	Set of rotable spare parts provider
s	Stochastic scenarios, $s \in S$
UD_s	Set of unscheduled maintenance demands under scenario s, $s \in S$
ETA_i	The expected arrival time of aircraft i
nrm_{im}	Number of rotable spare parts m required by aircraft i under deterministic stage
nem_{im}	Number of expendable spare parts m required by aircraft I under deterministic stage
nrm_{im}^{s}	Number of rotable spare parts m required by aircraft i in scenario s
nem_{im}^{s}	Number of expendable spare parts m required by aircraft i in scenario s
pe_{mk}	Unit cost of expendable rotable spare parts m from supplier k under deterministic stage
pr_{mk}	Unit cost of rotable spare parts m from supplier k under deterministic stage
Epr_m	Unit cost of emergency procurement for rotable spare part m from supplier k
Epe_m	Unit cost of emergency procurement for expendable spare parts m from supplier k
mp_m^{regular}	Manpower cost per day for rotable spare parts m under regular overhaul mode
mp_m^{expedite}	Manpower cost per day for rotable spare parts m under expedite overhaul mode
LT_m^{expedite}	Lead time in days to complete the overhaul on rotable spare part m under expedite mode
LT_m^{regular}	Lead time in days to complete the overhaul on rotable spare part m under expedite mode

pb^s	The probability that scenario *s* occurs
hc_m	Inventory holding cost of excessive spare part *m*
msc_m	Maximum storage capacity for spare part *m*

Decision variables

rt_{ijmkn}	Binary decision variable. 1 indicates that the *k*th required rotable spare part *m* of the incoming aircraft *i* is fulfilled by the *n*th rotable spare part *m* from aircraft *j*.
rgl_{im}	Binary decision variable. 1 indicates that the rotable spare part on aircraft *i* is overhauled with regular mode.
exp_{im}	Binary decision variable. 1 indicates that the rotable spare part on aircraft *i* is overhauled with expedite mode.
Qr_{mk}	Number of rotable spare part *m* procured from provider *k* under deterministic stage
Qe_{mk}	Number of expendable spare part *m* procured from provider *k* under deterministic stage
QEe^s_{mk}	Number of expendable spare part *m* emergency purchased from provider *k* under scenario *s*
QEr^s_{mk}	Number of rotable spare part *m* emergency purchase from provider *k* under scenario *s*
$Qexc^s_m$	Number of unused spare part *m* inducing inventory holding cost under scenario *s*

$$\text{Min}\sum_{i\in I}\sum_{m\in rm_i}\left(mp_{im}^{\text{regular}}\cdot rgl_{im}+mp_{im}^{\text{expedite}}\cdot \exp_{im}\right)+\sum_{m\in EM}\sum_{k\in K}pe_{mk}\cdot Qe_{mk}+\sum_{m\in RM}\sum_{k\in K}pr_{mk}\cdot Qr_{mk}$$
$$+\sum_{s\in S}pb^s\left\{\sum_{m\in EM}\sum_{k\in K}Epe_{mk}\cdot QEe^s_{mk}+\sum_{m\in EM}\sum_{k\in K}Epr_{mk}\cdot QEr^s_{mk}+\sum_{m\in RM\cap EM}hc_m\cdot Qexc^s_m\right\} \tag{1}$$

Subject to:

$$rgl_{im}+\exp_{im}=1,\ \forall i\in I,\ \forall m\in RM_i \tag{2}$$

$$rt_{ijmkn}\leq\frac{ETA_i-ETA_j}{LT_m^{\text{regular}}}\cdot rgl_{jm}+\frac{ETA_i-ETA_j}{LT_m^{\text{expedite}}}\cdot \exp_{jm},\ \forall i,j\in I,\ \forall m\in RM_i \tag{3}$$

$$\sum_{j\in I,i\neq j}\ \sum_{n=1}^{xrm_{jm}}rt_{ijmkn}\leq 1,\ \forall i\in I,\ k=1,\ \ldots,\ nrm_i,\ \forall m\in RM_i \tag{4}$$

$$\sum_{j\in I,i\neq j}\ \sum_{n=1}^{xrm_{jm}}rt_{ijmkn}\geq\sum_{j\in I,i\neq j}\ \sum_{n=1}^{xrm_{jm}}rt_{ijm(k+1)n},\ \forall i\in I,\ k=1,\ \ldots,\ nrm_i-1,\ \forall m\in RM_i \tag{5}$$

$$\sum_{i\in I,i\neq j}\ \sum_{k=1}^{nrm_{im}}rt_{ijmkn}\leq 1,\ \forall j\in I,\ n=1,\ \ldots,\ xrm_{jm},\ \forall m\in RM_i \tag{6}$$

$$\sum_{k\in K_{RM}} Qr_{mk} \geq \sum_{i\in I}\sum_{m\in RM_i} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}, \ \forall m\in RM \tag{7}$$

$$\sum_{k\in K_{EM}} Qe_{mk} \geq \sum_{i\in I}\sum_{m\in EM_i} nem_{im}; \forall m\in EM \tag{8}$$

$$\sum_{k\in K_{RM}} Qr_{mk} \leq msc_m; \forall m\in RM \tag{9}$$

$$\sum_{k\in EK_m} Qe_{mk} \leq msc_m; \forall m\in EM \tag{10}$$

$$\sum_{k\in K_{RM}} Qr_{mk} + \sum_{k\in K_{RM}} QEr^{s}_{mk} \geq \sum_{i\in I}\sum_{m\in RM_i} nrm_{im} + \sum_{i\in UD_s} nrm^{s}_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{n=1}^{xrm_{jm}} rt_{ijmn}, \quad \forall m\in RM, \ \forall s\in S \tag{11}$$

$$\sum_{k\in K_{EM}} Qe_{mk} + \sum_{k\in K_{EM}} QEe^{s}_{mk} \geq \sum_{i\in I}\sum_{m\in EM_i} nem_{im} + \sum_{i\in UD_s} nem^{s}_{im}, \ \forall m\in EM, \ \forall s\in S \tag{12}$$

$$\sum_{k\in K_{EM}} QEe^{s}_{mk} - \sum_{i\in UD_s} nem^{s}_{im} = Qexc^{s}_{m}; m\in EM; s\in S \tag{13}$$

$$\sum_{k\in K_{RM}} QEr^{s}_{mk} - \sum_{i\in UD_s} nrm^{s}_{im} = Qexc^{s}_{m}, \ m\in RM, \ s\in S \tag{14}$$

$$QEe^{s}_{mk}, \ QEr^{s}_{mk}, \ Qexc^{s}_{m} \geq 0, \ m\in RM\cap EM; s\in S \tag{15}$$

$$rgl_{im}\in\{0, 1\}, \ \forall i\in I; \forall m\in RM_i \tag{16}$$

$$\exp_{im}\in\{0, 1\}, \ \forall i\in I; \forall m\in RM_i \tag{17}$$

$$rt_{ijmkn}\in\{0, 1\}, \ \forall i\in I; \forall j\in I; i\neq j; \forall m\in RM_i; k=1,\ldots, nrm_{im}; n=1,\ldots xrm_{jm} \tag{18}$$

Objective (1) minimizes the overall MRO spare parts' overhaul and procurement costs, including rotable MRO spare parts' overhaul costs associated with regular mode and expedite mode, pre-purchase costs of expendable and rotable spare parts, expected costs of additional purchase under different stochastic scenarios and the expected penalty costs of holding excessive spare parts inventory. Constraint (2) regulates that either regular or expedite overhaul mode is selected for each rotable spare part come from incoming aircraft. Constraint (3) specifies that the rotable spare part from aircraft *j* can be supplied to aircraft *i* under the condition that the overhaul process of spare part from aircraft *j* can be completed before the arrival of aircraft *i*. Constraint (4) indicates that the demand of rotable spare part associated with aircraft *i* can be satisfied by the same type of spare part come from the other early arrival aircraft. Constraint (5) eliminates the redundant identical solution if the number of same types of rotable spare part required by aircraft *i* is larger than one. Constraint (6) indicates that each rotable spare part can be supplied to only one aircraft. Constraint (7) indicates that pre-purchase of rotable spare parts is activated if the supply from the incoming aircraft is not able to meet overall rotable spare parts demands under deterministic stage. Constraint (8) ensures that the total number of pre-purchase expendable spare parts is larger than the respective demand. Constraints (9) and (10) enforce the storage capacity restriction specifying that the number of pre-purchase spare parts should not exceed the maximum storage capacity. Constraints (11) and (12) ensure that the uncertain demands of rotable and expendable spare parts under different scenarios are met by additional emergency procurements. Constraints (13) and (14) compute the number of excessive spare parts. Constraints (15)–(18) impose the restrictions on respective decision variables.

4. Solution algorithm

Given the structure of the stochastic programming model formulated in Section 3, we adopt BD algorithm to solve aircraft MRO spare parts procurement and overhaul planning problem. BD is popular among solving the stochastic programming optimization model given its advantages in convergence efficiency, which has been enhanced and applied in different industrial optimization problems, such as logistics planning, locations arrangement, power system planning and product configuration optimizations (Calik and Fortz, 2019; Cheng *et al.*, 2019; Li and Grossmann, 2019; Bhuiyan *et al.*, 2020; Grass *et al.*, 2020; Pay and Song, 2020). The basic idea of BD algorithm is to divide and decompose the original stochastic programming model into a master problem and a subproblem. Optimization iteration among master problem and subproblem continues until the stopping criteria are met. The connections between master and subproblem are established by progressively generating and adding cuts to tighten the bounds of master problem (Costa, 2005; Fischetti *et al.*, 2010; Li and Li, 2016; Tarvin *et al.*, 2016). In this section, the decomposition scheme for the stochastic planning model is described. Specifically, the decision-makings of the proposed problem include (1) determination of maintenance modes and rotation plan for rotable spare parts, (2) procurement planning for deterministic demands and (3) procurement planning hedges uncertain demands. The uncertainties of demand are characterized by different scenarios associated with respective possibilities.

The above-mentioned three decisions are interdependent, as rotable spare parts' overhaul modes, rotation plan and amount of procurement under deterministic situation are able to strengthen the robustness in hedging against uncertain demands. For example, adopting expedite overhaul mode and procuring additional spare parts more than the deterministic demands with a lower price is able to alleviate the impact of uncertain demands. Meanwhile, procuring exceeding spare parts also result in inventory cost. Therefore, a tradeoff between risk averse and inventory cost control should be obtained under such dependent relationship.

The BD algorithm we adopted splits the original problem into "two-stage" optimization to accelerate the convergence process. The decomposition of the original problem is based on the model nature as the correlation between rotation and procurement of spare parts has impact on the additional procurement amount under uncertain scenarios. Given a large number of binary variables determining the maintenance modes/spare parts rotations for rotable spare part, the master problem optimizes the rotable spare part's maintenance operations and assignment of rotations to the other aircraft. The rest of the continuous variables determining the procurements under deterministic and uncertain situations forms subproblem of BD algorithm.

A detailed description of the algorithmic framework is provided as follows. Upon initialization of BD algorithm, the master problem solves the rotable spare parts' overhaul planning and rotation assignment problems under deterministic stage. Afterward, the solution (i.e. values of relevant decision variables) of the master problem is transferred to the subproblem as reference information. The values of the master problem solution are imposed as constraints in the primal and dual subproblems, and the subproblem is optimized under the solution space confined by the relevant constraints and the corresponding solution values. Given that the decision variables involved in the subproblem are all continuous, utilizing the duality properties of the subproblem facilitates the convergency progress. In this regard, we take the dual of the (primal) subproblem and generate corresponding optimality cut and feasibility cut after solving each dual subproblem. As the dual subproblem is optimized under the master problem solution information, the optimality cut/feasibility cut derived from each iteration of dual problem incorporates the latest solution from the master problem. Therefore, an effective connection between the master problem and the subproblem is established with the merits of duality properties, and the master problem's search space is tightened along iteration processes by adding optimality or feasibility cuts. Specifically, the binary variable $\{rgl_{imn}, \exp_{imn}, rt_{ijmn}\}$ and relevant constraints are included in the master problem, and the rest continuous variables and constraints form the primal subproblem.

4.1 Primal subproblem

The values of rgl^*_{imn}, $\exp^*_{imn}$, rt^*_{imn} indicate the overhaul modes for the rotable MRO spare part from aircraft *j* and the rotation arrangement associated with all incoming aircraft *i* under deterministic stage. Afterward, a linear primal subproblem is derived as follows:

Primal subproblem:

$$\begin{aligned}\text{Min} & \sum_{m\in EM}\sum_{k\in K} pe_{mk}\cdot Qe_{mk} + \sum_{m\in RM}\sum_{k\in K} pr_{mk}\cdot Qr_{mk} + \sum_{s\in S} pb^s \left\{ \sum_{m\in RM}\sum_{k\in K} Epr_{mk}\cdot QEr^s_{mk} \right. \\ & \left. + \sum_{m\in EM}\sum_{k\in K} Epe_{mk}\cdot QEe^s_{mk} + \sum_{m\in RM\cap EM} hc_m\cdot Qexc^s_m \right\}\end{aligned} \tag{19}$$

Subject to:

$$\sum_{k\in K_{RM}} Qr_{mk} \geq \sum_{i\in I}\sum_{m\in RM_i} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt^*_{ijmkn}, \ \forall m\in RM \tag{20}$$

$$\sum_{k\in K_{EM}} Qe_{mk} \geq \sum_{i\in I} nem_{im}, \ \forall m\in EM \tag{21}$$

$$\sum_{k\in K_{RM}} Qr_{mk} \leq msc_m, \ \forall m\in RM \tag{22}$$

$$\sum_{k\in K_{EM}} Qe_{mk} \leq msc_m, \ \forall m\in EM \tag{23}$$

$$\begin{gathered}\sum_{k\in K_{RM}} Qr_{mk} + \sum_{k\in K_{RM}} QEr^s_{mk} \geq \sum_{i\in I}\sum_{m\in RM_i} nrm_{im} + \sum_{i\in UD_s} nrm^s_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt^*_{ijmkn}, \\ \forall m\in RM, \forall s\in S\end{gathered} \tag{24}$$

$$\sum_{k\in K_{EM}} Qe_{mk} + \sum_{k\in K_{EM}} QEe^s_{mk} \geq \sum_{i\in I}\sum_{m\in EM_i} nem_{im} + \sum_{i\in UD_s} nem^s_{im}, \ \forall m\in EM, \ \forall s\in S \tag{25}$$

$$\sum_{k\in K_{EM}} QEe^s_{mk} - \sum_{i\in UD_s} nem^s_{im} = Qexc^s_m; m\in EM; s\in S \tag{26}$$

$$\sum_{k\in K_{RM}} QEr^s_{mk} - \sum_{i\in UD_s} nrm^s_{im} = Qexc^s_m, \ m\in RM, \ s\in S \tag{27}$$

$$Qr_{mk}\geq 0,\ \forall m\in RM,\ \forall k\in K_{RM} \tag{28}$$

$$Qe_{mk}\geq 0,\ \forall m\in EM,\forall k\in K_{EM} \tag{29}$$

$$QEr^{s}_{mk}\geq 0,\ \forall m\in RM,\ \forall k\in K_{RM},\ \forall s\in S \tag{30}$$

$$QEe^{s}_{mk}\geq 0,\ \forall m\in EM,\ \forall k\in K_{EM},\ \forall s\in S \tag{31}$$

$$\begin{gathered} Qrexc^{s}_{m}\geq 0,\ m\in RM,\ s\in S \\ Qeexc^{s}_{m}\geq 0,\ m\in EM,\ s\in S \end{gathered} \tag{32}$$

4.2 Dual subproblem

Let

$$\phi=\{\phi_m,\ m\in RM\},\ \varphi=\{\varphi_m,\ m\in EM\},$$
$$\gamma=\{\gamma_m,\ m\in RM\},\ \eta=\{\eta_m,\ m\in EM\},\ \chi=\{\chi_{ms},\ m\in RM,\ s\in S\},$$

$$\lambda=\{\lambda_{ms},\ m\in EM,\ s\in S\},\ \mu=\{\mu_{ms},\ m\in EM,\ s\in S\},\ \theta=\{\theta_{ms},\ m\in RM,\ s\in S\}$$

be the dual variables associated with constraints (19)–(32), respectively.

The dual form of the subproblem is formulated as follows:

$$\begin{aligned} \text{Max} & \sum_{m\in RM}\left(\sum_{i\in UD_s} nrm^{s}_{im}+\sum_{i\in I} nrm_{im}-\sum_{i\in I}\sum_{j\in I,j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}}\overline{rt_{ijmkn}}\right)\cdot\phi_m \\ & +\sum_{m\in EM}\sum_{i\in I} nem_{im}\cdot\varphi_m+\sum_{m\in RM} msc_m\cdot\gamma_m+\sum_{m\in EM} msc_m\cdot\eta_m \\ & +\sum_{s\in S}\sum_{m\in RM}\left(\sum_{i\in UD_s} nrm^{s}_{im}+\sum_{i\in I} nrm_{im}-\sum_{i\in I}\sum_{j\in I,j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}}\overline{rt_{ijmkn}}\right)\cdot\chi_{ms} \\ & +\sum_{s\in S}\sum_{m\in EM}\left(\sum_{i\in UD_s} nem^{s}_{im}+\sum_{i\in I} nem_{im}\right)\cdot\lambda_{ms}+\sum_{s\in S}\sum_{m\in EM}\sum_{i\in UD_s} nem^{s}_{im}\cdot\mu_{ms} \\ & +\sum_{s\in S}\sum_{m\in RM}\sum_{i\in UD_s} nrm^{s}_{im}\cdot\theta_{ms} \end{aligned} \tag{33}$$

Subject to:

$$\phi_m+\gamma_m+\sum_{s\in S}\chi_{ms}\leq pr_{mk},\ \forall m\in RM,\ \forall k\in K \tag{34}$$

$$\varphi_m+\eta_m+\sum_{s\in S}\lambda_{ms}\leq pe_{mk},\ \forall m\in EM,\ \forall k\in K \tag{35}$$

$$\theta_{ms}+\chi_{ms}\leq pb^{s}\cdot Epr_{mk},\ \forall m\in RM,\ \forall k\in K,\quad \forall s\in S \tag{36}$$

$$\mu_{ms}+\lambda_{ms}\leq pb^{s}\cdot Epe_{mk},\ \forall m\in EM,\ \forall k\in K,\quad \forall s\in S \tag{37}$$

$$-\theta_{ms}\leq pb^{s}\cdot hc_m,\ \forall m\in RM,\ \forall s\in S \tag{38}$$

$$-\mu_{ms}\leq pb^{s}\cdot hc_m,\ \forall m\in EM,\ \forall s\in S \tag{39}$$

$$\phi_m\geq 0,\ m\in RM \tag{40}$$

$$\varphi_m \geq 0,\ m \in EM \tag{41}$$

$$\gamma_m \leq 0,\ m \in RM \tag{42}$$

$$\eta_m \leq 0,\ m \in EM \tag{43}$$

$$\chi_{ms} \geq 0,\ m \in RM,\ s \in S \tag{44}$$

$$\lambda_{ms} \geq 0,\ m \in EM,\ s \in S \tag{45}$$

$$\mu_{ms} \in R,\ m \in EM,\ s \in S \tag{46}$$

$$\theta_{ms} \in R,\ m \in RM,\ s \in S \tag{47}$$

4.3 Benders cuts

The dual subproblem is utilized to generate two types of Benders cuts, which are added to the master problem iteratively until the stopping criteria are met. Two types of Benders cut are generated based on the dual subproblem objective function (33), and the optimal objective value and corresponding solutions in master problem and primal subproblem are equivalent to the original model. If the dual subproblem (33)–(47) is unbounded under current iteration, it implies an infeasible primal subproblem and leads to produce a feasibility cut, which is added to the master problem accordingly. The feasibility cut is expressed in (48), where $\overline{\phi_m}$, $\overline{\varphi_m}$, $\overline{\gamma_m}$, $\overline{\eta_m}$, $\overline{\chi_{ms}}$, $\overline{\lambda_{ms}}$, $\overline{\mu_{ms}}$, $\overline{\theta_{ms}}$ are the values of the extreme ray of the unbounded dual subproblem.

$$\begin{aligned}
&\sum_{m\in RM}\left(\sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\phi_m} + \sum_{m\in EM}\sum_{i\in I} nem_{im}\cdot\overline{\varphi_m} + \sum_{m\in RM} msc_m\cdot\overline{\gamma_m}\\
&+\sum_{m\in EM} msc_m\cdot\overline{\eta_m} + \sum_{s\in S}\sum_{m\in RM}\left(\sum_{i\in UD_s} nrm_{im}^{s} + \sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\chi_{ms}}\\
&+\sum_{s\in S}\sum_{m\in EM}\left(\sum_{i\in UD_s} nem_{im}^{s} + \sum_{i\in I} nem_{im}\right)\cdot\overline{\lambda_{ms}} + \sum_{s\in S}\sum_{m\in EM}\sum_{i\in UD_s} nem_{im}^{s}\cdot\overline{\mu_{ms}}\\
&+\sum_{s\in S}\sum_{m\in RM}\sum_{i\in UD_s} nrm_{im}^{s}\cdot\overline{\theta_{ms}} \leq 0
\end{aligned} \tag{48}$$

If the dual subproblem is bounded under current iteration, it implies a feasible primal subproblem and a optimality cut is generated and added to the master problem in the subsequent iterations.

The optimality cut is expressed in (49), where $\overline{\phi_m}$, $\overline{\varphi_m}$, $\overline{\gamma_m}$, $\overline{\eta_m}$, $\overline{\chi_{ms}}$, $\overline{\lambda_{ms}}$, $\overline{\mu_{ms}}$, $\overline{\theta_{ms}}$ are the value of the optimal dual variables of the dual subproblem. The variable Z is continuous one, which estimates the lower bound of the pre-purchase cost, additional purchase cost and excessive inventory cost of both rotable and expendable MRO spare parts based on the solution values of the master problem.

$$\begin{aligned} Z \geq & \sum_{m\in RM}\left(\sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\phi_m} + \sum_{m\in EM}\sum_{i\in I} nem_{im}\cdot\overline{\varphi_m} + \sum_{m\in RM} msc_m\cdot\overline{\gamma_m} \\ & + \sum_{m\in EM} msc_m\cdot\overline{\eta_m} + \sum_{s\in S}\sum_{m\in RM}\left(\sum_{i\in UD_s} nrm_{im}^{s} + \sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\chi_{ms}} \\ & + \sum_{s\in S}\sum_{m\in EM}\left(\sum_{i\in UD_s} nem_{im}^{s} + \sum_{i\in I} nem_{im}\right)\cdot\overline{\lambda_{ms}} + \sum_{s\in S}\sum_{m\in EM}\sum_{i\in UD_s} nem_{im}^{s}\cdot\overline{\mu_{ms}} \\ & + \sum_{s\in S}\sum_{m\in RM}\sum_{i\in UD_s} nrm_{im}^{s}\cdot\overline{\theta_{ms}} \end{aligned} \tag{49}$$

4.4 Master problem

Based on the dual subproblem solution outcome and two Benders cuts generated from the information and values of the dual decision variables $\overline{\phi_m}$, $\overline{\varphi_m}$, $\overline{\gamma_m}$, $\overline{\eta_m}$, $\overline{\chi_{ms}}$, $\overline{\lambda_{ms}}$, $\overline{\mu_{ms}}$, $\overline{\theta_{ms}}$, the master problem is formulated as follows:

$$\text{Min}\sum_{i\in I}\sum_{m\in rm_i}\left(mp_{im}^{\text{regular}}\cdot rgl_{im} + mp_{im}^{\text{expedite}}\cdot \exp_{im}\right) + Z \tag{50}$$

Subject to: (2)–(6) and (16)–(18)

$$Z \geq 0 \tag{51}$$

$$\begin{aligned} & \sum_{m\in RM}\left(\sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\phi_m} + \sum_{m\in EM}\sum_{i\in I} nem_{im}\cdot\overline{\varphi_m} + \sum_{m\in RM} msc_m\cdot\overline{\gamma_m} \\ & + \sum_{m\in EM} msc_m\cdot\overline{\eta_m} + \sum_{s\in S}\sum_{m\in RM}\left(\sum_{i\in UD_s} nrm_{im}^{s} + \sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\chi_{ms}} \\ & + \sum_{s\in S}\sum_{m\in EM}\left(\sum_{i\in UD_s} nem_{im}^{s} + \sum_{i\in I} nem_{im}\right)\cdot\overline{\lambda_{ms}} + \sum_{s\in S}\sum_{m\in EM}\sum_{i\in UD_s} nem_{im}^{s}\cdot\overline{\mu_{ms}} \\ & + \sum_{s\in S}\sum_{m\in RM}\sum_{i\in UD_s} nrm_{im}^{s}\cdot\overline{\theta_{ms}} \leq 0 \end{aligned}$$

$$\left(\overline{\varphi_m}, \overline{\phi_m}, \overline{\gamma_m}, \overline{\eta_m}, \overline{\chi_{ms}}, \overline{\lambda_{ms}}, \overline{\mu_{ms}}, \overline{\theta_{ms}}\right) \in R_D \tag{52}$$

$$
\begin{aligned}
Z \geq & \sum_{m\in RM}\left(\sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\phi_m} + \sum_{m\in EM}\sum_{i\in I} nem_{im}\cdot\overline{\varphi_m} + \sum_{m\in RM} msc_m\cdot\overline{\gamma_m} \\
& + \sum_{m\in EM} msc_m\cdot\overline{\eta_m} + \sum_{s\in S}\sum_{m\in RM}\left(\sum_{i\in UD_s} nrm^s_{im} + \sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}\right)\cdot\overline{\chi_{ms}} \\
& + \sum_{s\in S}\sum_{m\in EM}\left(\sum_{i\in UD_s} nem^s_{im} + \sum_{i\in I} nem_{im}\right)\cdot\overline{\lambda_{ms}} + \sum_{s\in S}\sum_{m\in EM}\sum_{i\in UD_s} nem^s_{im}\cdot\overline{\mu_{ms}} \\
& + \sum_{s\in S}\sum_{m\in RM}\sum_{i\in UD_s} nrm^s_{im}\cdot\overline{\theta_{ms}}\left(\overline{\varphi_m}, \overline{\phi_m}, \overline{\gamma_m}, \overline{\eta_m}, \overline{\chi_{ms}}, \overline{\lambda_{ms}}, \overline{\mu_{ms}}, \overline{\theta_{ms}}\right) \in P_D
\end{aligned}
\tag{53}
$$

where R_D, P_D refer to the sets of extreme rays and extreme points of the dual subproblem (33)–(47) associated with feasibility cuts and optimality cuts. As mentioned above, BD algorithm iteratively solves the master problem and dual problem. The feasibility cuts and optimality cuts are derived from the solution outcomes of the dual problem under each iteration, then the respective cuts are added into the master problem to further resolve the model. The values of the binary variable $\{rt^*_{ijmkn}, rgl^*_{im}, \exp^*_{im}\}$ are obtained from the master problem, and the solution provides a lower bound for the original problem (1)-(18) with the value of auxiliary variable Z. The dual subproblem is generated after inputting and fixing the values of binary variables $\{rt_{ijmkn}, rgl_{im}, \exp_{im}\}$. If the dual subproblem is unbounded, the respective extreme ray stores the infeasible information so as to generate a feasibility cut and add the cut back to the master problem. If the dual subproblem has a finite optimal value, the respective extreme point stores the optimality information to generate optimality cut and tighten the bounds of master problem, which identifies an updated upper bound for the original problem. The iteratively optimization process is terminated until the gap between the lower bound (LB) and the upper bound (UB) reaches the tolerate number ω, which indicates that the corresponding optimal solution for the original problem is found.

The pseudocode of BD algorithm for solving the aircraft MRO expendable and rotable spare parts planning problem under uncertainty is described in Algorithm 1. $\overline{Z}$ refers to the objective value of the subproblem, which corresponds to the optimal solution obtained in the last iteration by solving dual subproblem (33)–(47).

Algorithm 1. The Bender's decomposition algorithm for solve the stochastic spare parts planning problem

5. Numerical experiments

To evaluate the effectiveness of the proposed stochastic programming model and the respective BD algorithm for MRO spare parts planning problem, numerical experiments are designed and carried out in this section.

5.1 Instance generation and experiment configuration

In this section, we describe the ways to generate problem instances based on real data collected from an aircraft maintenance company, and then the analysis of the numerical experiment results is carried out. The approaches presented in the methodology section were programmed in C# language and implemented in Visual Studio 2010 in a personal computer with an Intel Core i7 processor, at 3.6 GHz with 32 Gb of RAM. The Mixed-Integer Linear Programming (MILP) model is solved by the optimizer CPLEX 12.7 serial model.

Algorithm 1

```
Initialization: $\{rt_{ijmkn}^{*},\ rgl_{im}^{*},\ exp_{im}^{*}\}$ = initial feasible solution. $LB$=0, $UBB = +\infty$
While $UB$-$LB > \omega$
    For all $s \in S$
        Solve dual subproblem
            If dual subproblem is unbounded then
                Get extreme ray $(\overline{\phi_m}, \overline{\varphi_m}, \overline{\gamma_m}, \overline{\eta_m}, \overline{\chi_{ms}}, \overline{\lambda_{ms}}\ \overline{\mu_{ms}}, \overline{\theta_{ms}}) \in R_D$
                Add the respective feasibility cut to the master problem
            Else if dual subproblem is feasible
                Get extreme point $(\overline{\phi_m}, \overline{\varphi_m}, \overline{\gamma_m}, \overline{\eta_m}, \overline{\chi_{ms}}, \overline{\lambda_{ms}}\ \overline{\mu_{ms}}, \overline{\theta_{ms}}) \in P_D$
                Add the respective optimality cut to the master problem
        $UB = \min\{UB, \sum_{i\in I}\sum_{m\in rm_i}(mp_{im}^{regular}\cdot rgl_{im}^{*} + mp_{im}^{expedite}\cdot exp_{im}^{*}) + \sum_{m\in RM}(\sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}^{*})\cdot\phi_m + \sum_{m\in EM}\sum_{i\in I} nem_{im}\cdot\varphi_m + \sum_{m\in RM} msc_m\cdot\gamma_m + \sum_{m\in EM} msc_m\cdot\eta_m + \sum_{m\in RM}(\sum_{s\in S}\sum_{i\in UD_s} nem_{im}^{s}\cdot\mu_{ms} + \sum_{i\in I} nrm_{im} - \sum_{i\in I}\sum_{j\in I, j\neq i}\sum_{k=1}^{nrm_{im}}\sum_{n=1}^{xrm_{jm}} rt_{ijmkn}^{*})\cdot\chi_{ms} + \sum_{m\in EM}(\sum_{s\in S}\sum_{i\in UD_s} nem_{im}^{s} + \mu_{ms}\sum_{m\in EM} msc_m)\cdot\lambda_m + \sum_{s\in S}\sum_{m\in RM}\sum_{i\in UD_s} nem_{im}^{s}\cdot\mu_{ms} + \sum_{s\in S}\sum_{m\in EM}\sum_{i\in UD_s} nrm_{im}^{s}\cdot\theta_{ms}\}$
    Solve Master problem
    $LB = \sum_{i\in I}\sum_{m\in rm_i}(mp_{im}^{regular}\cdot rgl_{im} + mp_{im}^{expedite}\cdot exp_{im}) + \bar{Z}$
End while
```

To create the problem instances, we collected aircraft MRO demands data from an independent aircraft maintenance company serving over 50 airline company clients. The data involves aircraft maintenance demands covering over 7 months. The maintenance demands information includes aircraft types specification, required maintenance service, corresponding overhaul spare parts used to support maintenance service, estimated arrival time as well as the lead time for finishing overhaul task on the rotable spare parts. We used two typical rotable spare parts (i.e. landing gear and engine) for different types of aircraft, together with normal expendable single service life cycle spare parts, to create MRO spare parts requirements in problem instances. As these 7 months cover along off season, standard season and peak season, we extracted partial maintenance demands information from each month to create representative problem instances. Based on each representative problem instances along 7 months, we further diverged maintenance uncertainties by incorporating different numbers of stochastic scenarios into the representative instance. Specifically, two instances with different ranges of unscheduled demands in stochastic scenarios are created based on the representative instance. Therefore, three problem instances are generated for each month, which results in 3 × 7 = 21 instances divided in seven groups. Meanwhile, we extended the planning period beyond 30 days to incorporate more maintenance demands to create challenge instances. For example, the D35, D40, D45 series' planning period is longer than one month. As a result, 21 random problems classified in seven groups are created, with different configurations of rotable and expendable spare parts, to carry out the computational experiment and analysis. A list of rotable and expendable MRO spare parts and respective descriptions are shown in Table 1. The number of rotable and expendable spare parts required by aircraft under deterministic and stochastic stages in different instances is presented in Tables 2 and 3, respectively. One-hour time limit is set while solving each problem instance. The cost of overhauling rotable MRO spare part is determined based on the intensity of labor inputs on overhauling the respective spare parts, and the cost expedite overhaul mode is higher than the regular overhaul mode, which is set as 1.8 times of the regular overhaul labor cost on. The standard regular overhaul lead times for the components of two types of rotable spare parts (landing gear and engine) are set as (3, 5),

Table 1. List of rotable and expendable MRO spare parts for aircraft overhaul in computational experiment

No	Spare part types/name	Corresponding functions
1	Rotable – Spare parts of Landing Gear (Regional Jet)	Enable aircraft for taxi, normal landing and take-off, support aircraft for normal ground operations
2	Rotable – Spare parts of Landing Gear (Business Jet)	
3	Rotable – Spare parts of Engine (Regional Jet)	A component of the propulsion system that helps to generate mechanical power
4	Rotable – Spare parts of Engine (Business Jet)	
5	Expendable – Group of Metal extrusions (Regional Jet)	Components of passenger seat and cargo track extrusion
6	Expendable – Group of Metal extrusions (Business Jet)	
7	Expendable - Group of Plastic extrusions (Regional Jet)	Components of passenger seat and hand carry luggage rack extrusion
8	Expendable – Group of Plastic extrusions (Business Jet)	

Table 2. Instance settings for rotable and expendable component (deterministic section)

			Deterministic section	
Instances	Planning horizon (Days)	Rotable Components from aircraft	Rotable Components demand	Expendable components demand
D10_S6	17	426	628	81
D10_S10				
D10_S15				
D20_S6	19	852	1,256	162
D20_S10				
D20_S15				
D25_S6	27	1,068	1,562	250
D25_S10				
D25_S15				
D30_S6	29	1,284	1868	338
D30_S10				
D30_S15				
D35_S6	33	1,500	2,174	371
D35_S10				
D35_S15				
D40_S6	38	1,716	2,480	459
D40_S10				
D40_S15				
D45_S6	45	1,932	2,786	547
D45_S10				
D45_S15				

and the expedite mode lead time is (2, 3). A variation of overhaul lead time exists among the rotable part from different types of aircraft. For example, the landing gear for large-sized aircraft requires more manpower resources inputs and longer overhaul lead time, compared with the medium-sized aircraft. The emergency additional purchase costs of rotable spare parts under the uncertain scenarios are set as five times or higher than the expedite overhaul mode under deterministic stage, due to the difficulties in seeking available spare parts from global market, industry as well as manufacturer within short time. The arrival of uncertain maintenance demands and the respective stochastic scenarios are created with high and moderate arrival numbers, so as to examine algorithms' flexibility in tackling different instances.

Section 5.2 compares the computational results and efficiency of the MILP model and the proposed BD algorithm.

5.2 Effectiveness of the Benders decomposition algorithm

The performances of the MILP formulation and BD are presented in this section. The performance comparison between the MILP model and the proposed BD algorithm is shown in Table 4. The first column in the table denotes the name of the instance. The second column records the number of binary variables determining the overhaul mode of rotable spares parts and rotation plan among aircraft, which is an indicator of the master problem's complexity in BD algorithm. It is shown that both methods can solve the problem instances optimally within the time limit of one hour. The computational results examine the performance of the BD algorithm proposed in Section 4. In the report of the computational results presented in Table 5, the advantages of BD algorithm are reflected in the view of computational times in tackling problem instances with large number of maintenance requests and stochastic scenarios.

On comparing with the MILP model, the increase of computational times while using BD algorithm is modest among the same problem instances group, e.g. D45_S6, D45_S10 and D45_S15. The computational outcome indicates that the number of scenarios involved in the instances is not a major determinant of problem complexity. In addition, it is noted that the BBD algorithm is able to solve the problem instance optimally around two iterations except one problem instances. With the increase of number of deterministic maintenance demands in different instance groups and the number of stochastic scenarios among the same group, the CPU time increases in both MILP model and proposed algorithm. A summary of the average performance of BD sorted in three stochastic scenario settings is presented in Table 5, which demonstrates the stabilities of the proposed algorithm in solving instances with more stochastic scenarios involved. As shown in the second column of Table 5, the average CPU times across problem instances with different number of stochastic scenarios involved are similar. The percentage of computational efficiency improvements demonstrates the capability of the optimality cut and feasibility cut in tightening the upper bound and lower bound of the original model, as the additional procurements of rotable and expendable spare parts under different scenarios directly affect the overhaul mode and rotation plan for rotable spare parts come from arrival aircraft under the determinist planning stage.

5.3 Managerial insights

The proposed stochastic programming model and optimization approach are able to bring direct benefits to aircraft maintenance service provider operating under aircraft hangar maintenance outsourcing mode, who needs to coordinate spare parts management to support

Table 3.
Instances settings for rotable and expendable component settings (stochastic section)

	Stochastic section setting 1 (for small scale)		Stochastic section setting 2 (for medium to large scale)	
Number of stochastic scenarios	Rotable components demand (all scenarios)	Expendable components demand (all scenarios)	Rotable components demand (all scenarios)	Expendable components demand (all scenarios)
6	992	518	496	518
10	1,012	1,067	1,012	1,067
15	1,518	1,598	1,518	1,598

Table 4. Comparison between MILP model and Benders decomposition algorithm

Instances	Binary variables	MILP models				Benders decomposition algorithm				
		UB	LB	Gap	CPU(s)	UB	LB	Gap	CPU(s)	Iteration
D10_S6	50,242	3925.00	3925.00	0	3.21	3925.00	3925.00	0	3.38	6
D10_S10		4232.05	4232.05	0	3.7	4232.05	4232.05	0	1.54	2
D10_S15		4281.20	4281.20	0	4.6	4281.20	4281.20	0	1.27	2
D20_S6	209,818	6458.00	6458.00	0	12.39	6458.00	6458.00	0	6.24	2
D20_S10		6765.05	6765.05	0	13.13	6765.05	6765.05	0	6.18	2
D20_S15		6814.20	6814.20	0	15.49	6814.20	6814.20	0	6.44	2
D25_S6	329,345	7476.00	7476.00	0	27.86	7476.00	7476.00	0	11.17	2
D25_S10		7783.05	7783.05	0	27.61	7783.05	7783.05	0	11.14	2
D25_S15		7832.20	7832.20	0	35.99	7832.20	7832.20	0	12.60	2
D30_S6	475,688	9154.00	9154.00	0	48.57	9154.00	9154.00	0	25.31	2
D30_S10		9461.05	9461.05	0	41.45	9461.05	9461.05	0	21.21	2
D30_S15		9510.20	9510.20	0	40.84	9510.20	9510.20	0	20.36	2
D35_S6	648,847	10144.00	10144.00	0	56.75	10144.00	10144.00	0	33.52	2
D35_S10		10451.05	10451.05	0	62.04	10451.05	10451.05	0	41.41	2
D35_S15		10500.20	10500.20	0	74.83	10500.20	10500.20	0	39.64	2
D40_S6	848,822	11287.00	11287.00	0	76.08	11287.00	11287.00	0	48.32	2
D40_S10		11594.05	11594.05	0	78.85	11594.05	11594.05	0	45.42	2
D40_S15		11643.20	11643.20	0	99.78	11643.20	11643.20	0	48.06	2
D45_S6	1,075,613	12466.00	12466.00		100.22	12466.00	12466.00	0	71.64	2
D45_S10		12773.05	12773.05	0	132.82	12773.05	12773.05	0	69.44	2
D45_S15		12822.20	12822.20	0	141.29	12822.20	12822.20	0	76.13	2

the MRO process of incoming aircraft. Also, indirect benefit also goes to the airline companies served by the maintenance service provider. Since the maintenance service company enhances its capability in handling unexpected arrival of maintenance service demands, the satisfactory levels of the airline companies, i.e. the clients of service company, can be strengthened. As a result, airline companies are able to focus more on their high-valued added businesses, such as passenger and air cargo transportation.

By adopting stochastic programming and BD algorithm, the uncertain maintenance demands are characterized in respective stochastic scenarios associated with respective probabilities. The practitioners are able to obtain planning solutions within reasonable time by the algorithm, and therefore they have capability in absorbing the impact of uncertainties under different scenarios. From academic perspective, this research extends the aircraft's overhaul spare part planning management from deterministic situation to stochastic environment, which enhances the adaptability of decision outcomes for practical use. In addition, the stochastic programming model provides possibility of incorporating other core decision-making components in aircraft overhaul planning in the context of maintenance service provider, which enriches the application of stochastic programming approach.

For the managerial insight to practical operations, depicting the uncertain demands under peak and off seasons of aircraft maintenance facilitates practitioner to understand the possible impact of uncertainty on their operating costs. For example, the variance of demand uncertainty is different under peak and off seasons. Specifically, more combinations of uncertain maintenance demands are expected in peak seasons. While reviewing the computational results, it is noted that fluctuations of objective values are recorded under different depictions of stochastic scenarios. In particular, a slight increase of objective is recorded under the peak seasons, as the practitioner inclines to involve more stochastic scenarios in describing the unexpected arrival of aircraft associated with maintenance and spare part demands. Additional MRO spare part should be procured under deterministic planning stage, and the inventory cost for excessive spare parts accounts for the increase of objective value, together with the stability of solution outcome in hedging against unexpected spare part demands. Therefore, it can be inferred that rotation of core spare parts is not necessarily able to meet all demands under uncertain environment during peak seasons. The pre-procurement of spare parts, including rotable and expendable ones, plays an important role in alleviating the negative impacts in overhaul spare part's managements.

6. Conclusion

Outsourcing aircraft MRO activities to an independent aircraft maintenance company is becoming a trend in aviation industry, and the MRO spare parts are essential to support respective MRO operations on incoming aircraft. In MRO spare parts' management, excessive procurement of the MRO parts leads to high inventory holding cost, but maintaining sufficient MRO spare parts with moderate inventory cost is critical for sustainable development of aircraft MRO service company. Moreover, proper overhaul and rotation plans for the MRO spare parts with long service life are another significant issue besides procurement planning. To better resolve aircraft MRO spare part procurement, overhaul and rotation planning problem, a stochastic programming model is developed in this paper at first, which assists the

Table 5.
Computational results for different stochastic scenarios solved by BD algorithm

Number of scenarios in instances	Average CPU times	Average improvements in times (%)	Average iterations
6	28.51	36.86	2.57
10	28.04	49.02	2
15	29.21	55.85	2

maintenance service company to better arrange MRO spare part planning so as to support maintenance schedule in fulfilling external maintenance demands from clients. Afterward, BD algorithm is proposed in order to solve the model efficiently. Computational experiment and relevant analysis are conducted, which demonstrate the effectiveness and capability of the proposed algorithm. The future avenue of this research includes: (1) consideration of integrating the other significant scheduling and planning components in aircraft maintenance service company, such as the hangar shop planning optimization decision. In practical situations, the shortage of some crucial MRO spare parts may create bottleneck in fulfilling maintenance demands; (2) extension of uncertainties into aircraft maintenance service planning in order to develop a robust maintenance schedule encompassing critical factors in serving MRO outsourcing demands; (3) consideration of maintenance demands rejection during the deterministic planning stage and stochastic scenarios, which closely depicts the practical situation in MRO service industry and further investigates the impact of demand rejections on maintenance service levels.

References

Bertazzi, L., Bosco, A. and Lagana, D. (2015), "Managing stochastic demand in an Inventory Routing Problem with transportation procurement", *Omega-International Journal of Management Science*, Vol. 56, pp. 112-121.

Bhuiyan, T.H., Medal, H.R. and Harun, S. (2020), "A stochastic programming model with endogenous and exogenous uncertainty for reliable network design under random disruption", *European Journal of Operational Research*, Vol. 285 No. 2, pp. 670-694.

Bollapragada, R., Kuppusamy, S. and Rao, U.S. (2015), "Component procurement and end product assembly in an uncertain supply and demand environment", *International Journal of Production Research*, Vol. 53 No. 3, pp. 969-982.

Calik, H. and Fortz, B. (2019), "A Benders decomposition method for locating stations in a one-way electric car sharing system under demand uncertainty", *Transportation Research Part B: Methodological*, Vol. 125, pp. 121-150.

Chan, H.K. and Chan, F.T.S. (2010), "A review of coordination studies in the context of supply chain dynamics", *International Journal of Production Research*, Vol. 48 No. 10, pp. 2793-2819.

Cheng, D., Zhang, W. and Wang, K. (2019), "Hierarchical reserve allocation with air conditioning loads considering lock time using Benders decomposition", *International Journal of Electrical Power and Energy Systems*, Vol. 110, pp. 293-308.

Choi, T.-M., Wen, X., Sun, X. and Chung, S.-H. (2019), "The mean-variance approach for global supply chain risk analysis with air logistics in the blockchain technology era", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 127, pp. 178-191.

Costa, A.M. (2005), "A survey on Benders decomposition applied to fixed-charge network design problems", *Computers and Operations Research*, Vol. 32 No. 6, pp. 1429-1450.

Dinis, D., Barbosa-Povoa, A. and Teixeira, A.P. (2019), "A supporting framework for maintenance capacity planning and scheduling: development and application in the aircraft MRO industry", *International Journal of Production Economics*, Vol. 218, pp. 1-15.

Eltoukhy, A.E.E., Chan, F.T.S., Chung, S.H., Niu, B. and Wang, X.P. (2017), "Heuristic approaches for operational aircraft maintenance routing problem with maximum flying hours and man-power availability considerations", *Industrial Management and Data Systems*, Vol. 117 No. 10, pp. 2142-2170.

Eltoukhy, A.E.E., Chan, F.T.S., Chung, S.H. and Niu, B. (2018), "A model with a solution algorithm for the operational aircraft maintenance routing problem", *Computers and Industrial Engineering*, Vol. 120, pp. 346-359.

Ertogral, K. and Öztürk, F.S. (2019), "An integrated production scheduling and workforce capacity planning model for the maintenance and repair operations in airline industry", *Computers and Industrial Engineering*, Vol. 127, pp. 832-840.

Fischetti, M., Salvagnin, D. and Zanette, A. (2010), "A note on the selection of Benders' cuts", *Mathematical Programming*, Vol. 124 Nos 1-2, pp. 175-182.

Gao, X. and Pishdad-Bozorgi, P. (2019), "BIM-enabled facilities operation and maintenance: a review", *Advanced Engineering Informatics*, Vol. 39, pp. 227-247.

Gholizadeh, H., Fazlollahtabar, H. and Khalilzadeh, M. (2020), "A robust fuzzy stochastic programming for sustainable procurement and logistics under hybrid uncertainty using big data", *Journal of Cleaner Production*, Vol. 258, p. 24.

Grass, E., Fischer, K. and Rams, A. (2020), "An accelerated L-shaped method for solving two-stage stochastic programs in disaster management", *Annals of Operations Research*, Vol. 284 No. 2, pp. 557-582.

Gu, J.Y., Zhang, G.Q. and Li, K.W. (2015), "Efficient aircraft spare parts inventory management under demand uncertainty", *Journal of Air Transport Management*, Vol. 42, pp. 101-109.

Hong, Z., Lee, C.K.M. and Zhang, L.D. (2018), "Procurement risk management under uncertainty: a review", *Industrial Management and Data Systems*, Vol. 118 No. 7, pp. 1547-1574.

Hu, H., Ng, K.K.H. and Qin, Y. (2016), "Robust parallel machine scheduling problem with uncertainties and sequence-dependent setup time", *Scientific Programming*, Vol. 2016, p. 13.

Kaur, H., Singh, S.P., Garza-Reyes, J.A. and Mishra, N. (2020), "Sustainable stochastic production and procurement problem for resilient supply chain", *Computers and Industrial Engineering*, Vol. 139, p. 14.

Li, C. and Grossmann, I.E. (2019), "A generalized Benders decomposition-based branch and cut algorithm for two-stage stochastic programs with nonconvex constraints and mixed-binary first and second stage variables", *Journal of Global Optimization*, Vol. 75 No. 2, pp. 247-272.

Li, D. and Li, X. (2016), "Domain reduction for Benders decomposition based global optimization", *Computers and Chemical Engineering*, Vol. 93, pp. 248-265.

Li, L., Liu, M., Shen, W.M. and Cheng, G.Q. (2017), "An improved stochastic programming model for supply chain planning of MRO spare parts", *Applied Mathematical Modelling*, Vol. 47, pp. 189-207.

Li, X.H., Yang, D. and Hu, M.Q. (2018), "A scenario-based stochastic programming approach for the product configuration problem under uncertainties and carbon emission regulations", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 115, pp. 126-146.

Li, X., Wang, Z.X., Chan, F.T.S. and Chung, S.H. (2019), "A genetic algorithm for optimizing space utilization in aircraft hangar shop", *International Transactions in Operational Research*, Vol. 26 No. 5, pp. 1655-1675.

Liu, B., Zhang, Y., Zhang, G. and Zheng, P. (2019), "Edge-cloud orchestration driven industrial smart product-service systems solution design based on CPS and IIoT", *Advanced Engineering Informatics*, Vol. 42, p. 100984.

Marcontell, D. (2013), "MRO's offshore edge shrinking", *Aviation Week and Space Technology*, Vol. 175 No. 22, p. 56.

Mcarthur, J.J., Shahbazi, N., Fok, R., Raghubar, C., Bortoluzzi, B. and An, A. (2018), "Machine learning and BIM visualization for maintenance issue classification and enhanced data collection", *Advanced Engineering Informatics*, Vol. 38, pp. 101-112.

Meng, Q., Hei, X.L., Wang, S.A. and Mao, H.J. (2015), "Carrying capacity procurement of rail and shipping services for automobile delivery with uncertain demand", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 82, pp. 38-54.

Nakandala, D., Lau, H. and Zhang, J. (2014), "Optimization model for transportation planning with demand uncertainties", *Industrial Management and Data Systems*, Vol. 114 No. 8, pp. 1229-1245.

Ng, K.K.H., Lee, C.K.M., Chan, F.T.S. and Qin, Y. (2017), "Robust aircraft sequencing and scheduling problem with arrival/departure delay using the min-max regret approach", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 106, pp. 115-136.

Nikzad, E., Bashiri, M. and Oliveira, F. (2019), "Two-stage stochastic programming approach for the medical drug inventory routing problem under uncertainty", *Computers and Industrial Engineering*, Vol. 128, pp. 358-370.

Nosoohi, I. and Hejazi, S.R. (2011), "A multi-objective approach to simultaneous determination of spare part numbers and preventive replacement times", *Applied Mathematical Modelling*, Vol. 35 No. 3, pp. 1157-1166.

Pay, B.S. and Song, Y. (2020), "Partition-based decomposition algorithms for two-stage Stochastic integer programs with continuous recourse", *Annals of Operations Research*, Vol. 284 No. 2, pp. 583-604.

Qin, Y., Chan, F.T.S., Chung, S.H., Qu, T. and Niu, B. (2018), "Aircraft parking stand allocation problem with safety consideration for independent hangar maintenance service providers", *Computers and Operations Research*, Vol. 91, pp. 225-236.

Qin, Y., Wang, Z.X., Chan, F.T.S., Chung, S.H. and Qu, T. (2019), "A mathematical model and algorithms for the aircraft hangar maintenance scheduling problem", *Applied Mathematical Modelling*, Vol. 67, pp. 491-509.

Somarin, A.R., Asian, S., Jolai, F. and Chen, S.L. (2018), "Flexibility in service parts supply chain: a study on emergency resupply in aviation MRO", *International Journal of Production Research*, Vol. 56 No. 10, pp. 3547-3562.

Tarvin, D.A., Wood, R.K. and Newman, A.M. (2016), "Benders decomposition: solving binary master problems by enumeration", *Operations Research Letters*, Vol. 44 No. 1, pp. 80-85.

Tiwari, S., Jaggi, C.K. and Sana, S.S. (2018), "Integrated supply chain of supplier and retailer for stochastic demand", *Mathematical Modelling and Analysis*, Vol. 23 No. 4, pp. 582-595.

Wen, X., Xu, X., Choi, T. and Chung, S. (2019), "Optimal pricing decisions of competing air-cargo-carrier systems–impacts of risk aversion, demand, and cost uncertainties", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, pp. 1-15, doi: 10.1109/TSMC.2019.2930725.

Zanjani, M.K. and Nourelfath, M. (2014), "Integrated spare parts logistics and operations planning for maintenance service providers", *International Journal of Production Economics*, Vol. 158, pp. 44-53.

Zhang, M., Lettice, F., Chan, H.K. and Hieu Thanh, N. (2018), "Supplier integration and firm performance: the moderating effects of internal integration and trust", *Production Planning and Control*, Vol. 29 No. 10, pp. 802-813.

Zhen, L. and Wang, K. (2015), "A stochastic programming model for multi-product oriented multi-channel component replenishment", *Computers and Operations Research*, Vol. 60, pp. 79-90.

Zhen, L. (2016), "Optimization odels for production and procurement decisions under uncertainty", *IEEE Transactions on Systems Man Cybernetics-Systems*, Vol. 46 No. 3, pp. 370-383.

Zheng, M. and Wu, K. (2017), "Smart spare parts management systems in semiconductor manufacturing", *Industrial Management and Data Systems*, Vol. 117 No. 4, pp. 754-763.

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