

Research Article

Multiobjective Optimization of Aircraft Maintenance in Thailand Using Goal Programming: A Decision-Support Model

Yuttapong Pleumpirom and Sataporn Amornsawadwatana

School of Engineering, University of the Thai Chamber of Commerce, 126/1 Vibhavadee-Rangsit Rd, Dindaeng, Bangkok 10400, Thailand

Correspondence should be addressed to Sataporn Amornsawadwatana, sataporn.amo@utcc.ac.th

Received 3 April 2012; Revised 6 June 2012; Accepted 15 July 2012

Academic Editor: Richard H. Weston

Copyright © 2012 Y. Pleumpirom and S. Amornsawadwatana. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The purpose of this paper is to develop the multiobjective optimization model in order to evaluate suppliers for aircraft maintenance tasks, using goal programming. The authors have developed a two-step process. The model will firstly be used as a decision-support tool for managing demand, by using aircraft and flight schedules to evaluate and generate aircraft-maintenance requirements, including spare-part lists. Secondly, they develop a multiobjective optimization model by minimizing cost, minimizing lead time, and maximizing the quality under various constraints in the model. Finally, the model is implemented in the actual airline's case.

1. Introduction

With severe competition and under the current global uncertainty, airlines have to generate new strategies in order to enhance their competitive advantages in the current marketplace [1–4]. Currently, an individual airline mainly focuses on its existing business function, while impacts from supply chain efficiency have been neglected. Consequently, the aviation supply chain management is not well understood and effectively implemented like other industries for example, automobiles, electronics, and so forth [5]. Thus, the effective management of the aviation supply chain must be considered [6]. Major findings show that there is information about new trends in the aviation supply chain that correlate with existing problems [7]. The supply chain in aircraft maintenance includes the flow of materials or services from many suppliers through airline maintenance [8]. The airline must fulfill air travelling demand as committed to in their flight schedule.

The supply chain in Thai Aviation starts from the aircraft owner requesting services to commercial maintenance centers or internal maintenance department. The maintenance manager buys the materials or outsources services from overseas suppliers. There are more

than 1,000 aircraft in Thailand, which are operated by commercial airlines, government, commercial flying training schools, and private owners [9].

Government agencies fly their aircraft under a self-quality assurance system with support from manufacturers. The Royal Thai Air Force, Royal Thai Navy, Royal Thai Army, Ministry of Agriculture, and the Ministry of Natural Resources are operating aircraft fleets under different maintenance systems. They usually buy spare parts overseas. Most of them believe that aircraft parts which are manufactured or repaired by the OEM (original equipment manufacturer) are top-quality products, Federal Aviation Administration (FAA) or European Aviation Safety Agency (EASA) is the second-class quality aircraft parts. These government agencies prefer the OEM's parts. However, prices and lead times are other trade-off issues in decision-making. They frequently find long lead time problems in purchasing and repairing. Sometimes, the repair in the US has an 18-month lead time. The operator must cannibalize aircraft parts from other unserviceable aircraft. This uses double manpower and is risky for unexpected malfunctions during removing. Moreover, some aircraft must stop flying and wait for the spare parts. This problem results in cancelling some government missions.

On the other hand, commercial airlines and commercial flying training schools are operating in Thailand under the Department of Civil Aviation (DCA) regulations [10]. They prefer the lowest costs with minimum quality required by DCA regulation. The lead time is also an important factor for the airline, especially the highly utilized airline such as Thai Air Asia. They lose a lot of income for each day of unserviceable aircraft. Moreover, they have other extra expenses for example, parking fees, recovering costs, and so forth.

The privately owned aircraft in Thailand are operated under DCA regulations. They mostly fly for leisure and seek the cheapest aircraft maintenance cost. Since they are not in a hurry to fly, they can wait for a long lead time purchase in return of lower material price.

The supply chain of aircraft operators in Thailand is different than airlines in the USA. In the USA, several suppliers and repair shops are located near airlines. Buying and repairing lead time is shorter and also costs are lower. The procurement lead time in Thailand is longer. Also, manpower costs in Thailand are lower.

This paper reviews important factors which impact aircraft maintenance performance. Later, this research formulates the multi-optimization model to minimize cost and lead time, and maximize quality of aircraft maintenance, which benefits aircraft maintenance managers in making decisions for material procurement. Moreover, this research presents the actual airline case in Thailand and outlines the empirical results of the method.

2. Literature Review

There are several studies in performance measurement methods in the aviation supply chain [8, 11]. Most of them used a single factor to measure their systems. However, in a practical environment, the system composes several important factors, which relate to an enterprise's success. The authors specify key factors in aircraft maintenance to be cost, time, quality, reliability, maintainability, availability, and flexibility or replace ability.

2.1. Cost

The cost is the primary factor of firms, especially in a highly competitive industry. Researchers mention unsatisfactory global sourcing costs [12]. Airline operations directly affect the costs of the products or services and their purchase price. These costs are generated directly or

indirectly from the supply chain. Consequently, higher costs and prices decrease airline competitiveness [13]. Choy et al. studied the costs of aircraft parts and developed a performance measurement system to monitor the effectiveness of the logistics flow in handling various components for rework, maintenance or replacement, and benchmark with the best-in-class practice [8].

However, the process analysis or cost-reduction strategy provides insights into the inefficiencies which exist within current processes and place more emphasis on demand pull-type processes which require forecasting operational schedules [14].

Nevertheless, aircraft fuel is the most important issue to airlines cash flow. It is the highest operating cost portion (26.5%) of the total cost [3]. Airlines separately manage fuel cost and maintenance. Aircraft climb technique results in a 5 per cent fuel saving [15]. Thai Airways International tries to manage high fuel price risk by hedging, but they are not successful [16]. Other airlines in Thailand face a fuel crisis and share the risk with passengers under a fuel surcharge.

2.2. Times

Time refers to maintenance time and material procurement lead time. Maintenance time is the job-processing time since the service was requested by a customer up to completely fulfilling that requirement [11, 17]. Procurement lead time begins from an order issued until the part's arrival at the promised location [18]. Lead times include transport time, custom clearance time, and other unexpected delays. Moreover, the supplier relationship possibly affects procurement lead time [19].

Chen studied the minimization of completion time, subject to maintenance and the proposed integer linear programming model [20]. This model only applies to jobs performed in a serial fashion, but in aircraft maintenance, practical operations are continuously performed in both parallel and serial fashions.

2.3. Quality

Aircraft parts must be manufactured by factories, which are officially approved by the civil aviation organization of the state. Also, inspection, repair, altering, or overhauls of aircraft parts must performed by an approved factory [21]. The worldwide-accredited auditors are the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA). The Department of Civil Aviation (DCA) of Thailand is also an approved auditor for repairing factories, which are located in Thailand [22]. On the other hand, the quality of aircraft maintenance is related to approval organization. Airlines trust FAA/EASA-certified repair stations as top quality and DCA-certified repair station as lower quality. However, both FAA/EASA and DCA are acceptable as explained in ICAO annex 6 [23].

2.4. Reliability

Langford explained the meaning of reliability as *"the probability that a system will perform its intended function for a specified interval under stated conditions"* [11] and expressed as an equation as follows:

$$R_t = e^{-\lambda t}, \quad (i)$$

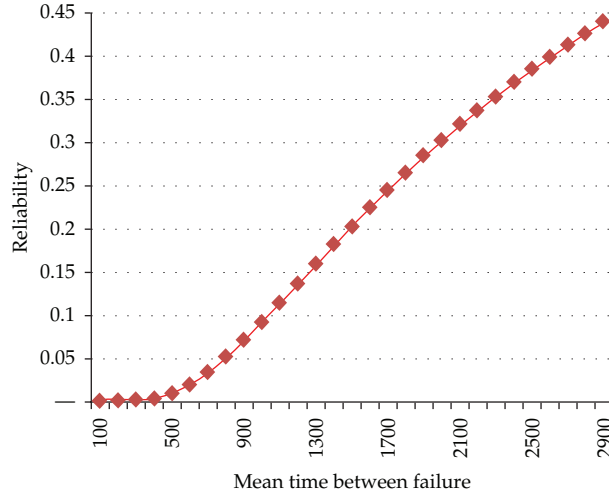


Figure 1: The relationship between MTBF and reliability [11].

where R_t = probability that the system will successfully perform as required over the interval of time t . λ (failure rate) = $1/\text{mean time between failures (MTBF)}$, t = specified operation interval. $e = 2.7182818$.

Figure 1, the longer mean time between failures (MTBF) results in higher reliability. In order to increase aircraft reliability, maintenance managers must reduce aircraft downtime due to maintenance, which is related to aircraft-part-procurement lead time and repairing time [11].

The failure rate dictates the frequency of unscheduled corrective maintenance (or repair) of a system affected by random malfunction. Low reliability indicates frequent failures, which trigger more frequent corrective maintenance. Consequently, the reliability can be improved by enhancing maintenance support in forms of facilities, skilled technicians, tools, and supporting stocks of spare components, and repair parts [24]. Increased system reliability based on high-quality components can greatly extend the intervals of operation between failures and eliminate or minimize corrective maintenance support requirements [25].

2.5. Maintainability

The maintainability measures ability of a system to be restored to a specified level of operational readiness within defined intervals with the use of the aforementioned facility, and equipment resources [11, 26]. The maintainability, (ii), is related to scheduled and unscheduled maintenance. The minimization of related factors (time, procurement lead time, corrective/preventive time) results in maximization of maintainability.

$$\overline{M} = \frac{\lambda \cdot \overline{M}_{ct} + f_{pt} \cdot \overline{M}_{pt}}{\lambda + f_{pt}}, \quad (\text{ii})$$

where \overline{M} = mean active maintenance time, λ = corrective maintenance frequency, \overline{M}_{ct} = mean time between corrective maintenance, f_{pt} = schedule maintenance frequency, and \overline{M}_{pt} = mean preventive maintenance time.

Maintainability refers to ease and speed at which any maintenance activity can be carried out on any equipment. Maintenance can be measured by mean time to repair (MTTR) [27]. It is a function of equipment design, and maintenance task design including use of appropriate tools, jigs, work platforms, and so forth [28]. Once a piece of equipment has failed, it must be possible to get it back into an operating condition as soon as possible [11].

2.6. Availability

Availability measures the readiness of a system to fulfill its assigned function [29]. Airlines try to obtain high utilization to maximize their income. The aircraft must be available before next scheduled flight; otherwise, the flight delay may be costly [30]. Maintenance managers must predict unforeseen troubles and preplan materials, skilled technicians, and facilities [31]. They seek possible solutions for minimizing aircraft-maintenance times which results in maximized availability [32]. Thus, aircraft availability relates to flight hours per period. Higher flight hours (lower ground time) results in higher availability.

2.7. Flexibility/Replace Ability

Operation managers frequently experience problems of material shortage or malfunction of equipment. Flexibility is an ability of production plant or service provider by which he switches the planned operation to another process or solution to meet the customer expectation [33].

Supply chain flexibility is an ability to reconfigure the supply chain and alter the supply of product in line with customer demand [34]. It is composed of two dimensions: (1) resource flexibility refers to a resource that can be applied to a range of alternative uses with low costs and low difficulties are associated with the switching from one resource to another as well as a short time is required for the switch [35], (2) coordination flexibility is a flexibility of process that redefines product strategies in reconfiguring the chain of resources to produce the product, and re-deploy those resources needed to produce the product [36, 37].

In this research, the three factors of aircraft maintenance cost, aircraft downtime, and quality are considered, since the reliability, maintainability, and availability relate to aircraft downtimes in an adverse direction. On the other hand, flexibility, and replace ability relate to the choice of alteration, material sources, or outsource maintenance centers. In the next section, the authors formulate an optimization aircraft maintenance model by using these three factors.

3. Multiobjective Optimization Model

In order to formulate the model, an aircraft supply chain is first explained. The supply chain of an aircraft can be illustrated as Figure 2. The suppliers deliver materials or maintenance services to an airline. Later, the airline delivers services to passengers, tour agencies, and

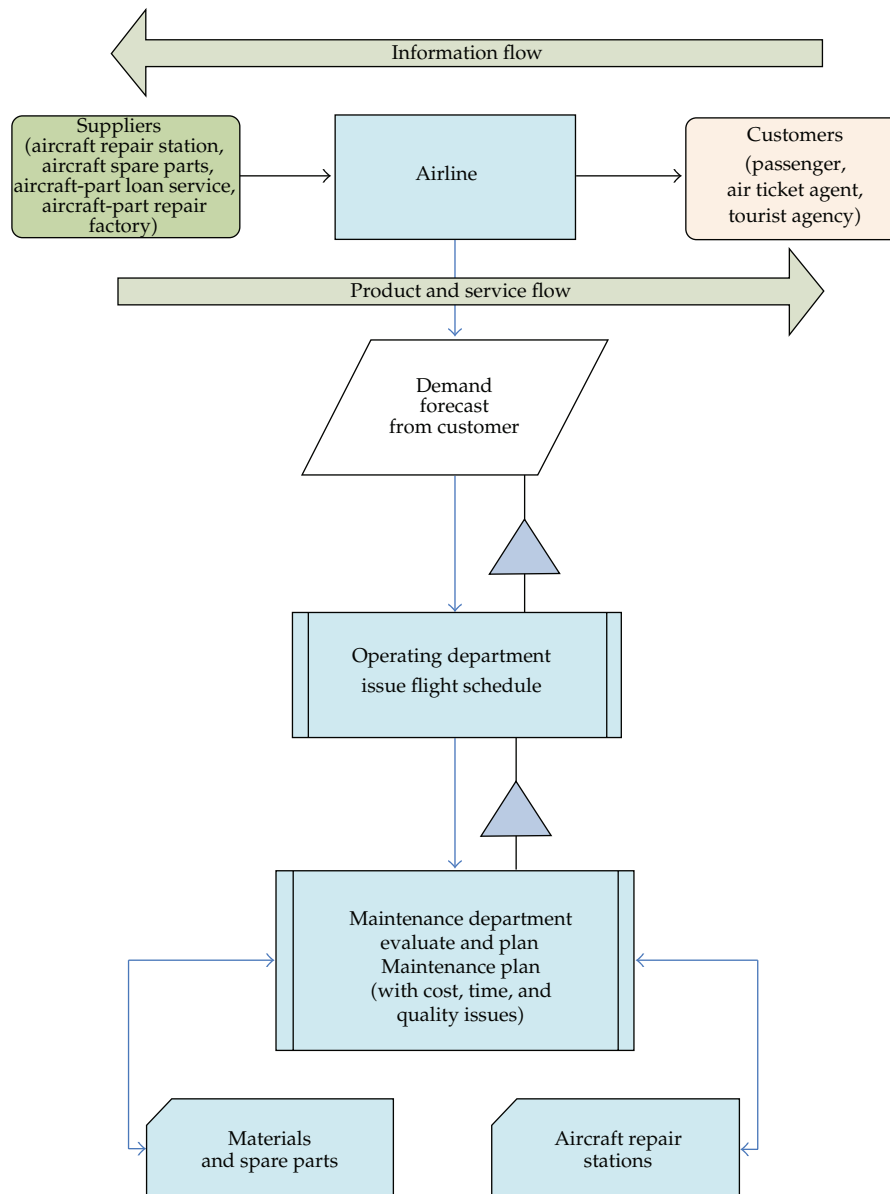


Figure 2: Supply chain of airline with maintenance support.

air cargo agencies with a promised quantity and specified time. The airline must prepare its aircraft with effective and efficient maintenance [38]. Back office has to plan future maintenances, which conform to a flight plan. The manager must make a decision whether to insource or outsource maintenance services as well as material suppliers in advance.

These activities need powerful and impacting decision tools for aircraft maintenance and relevant supply chain. The planner has to survey aircraft flying requirements and

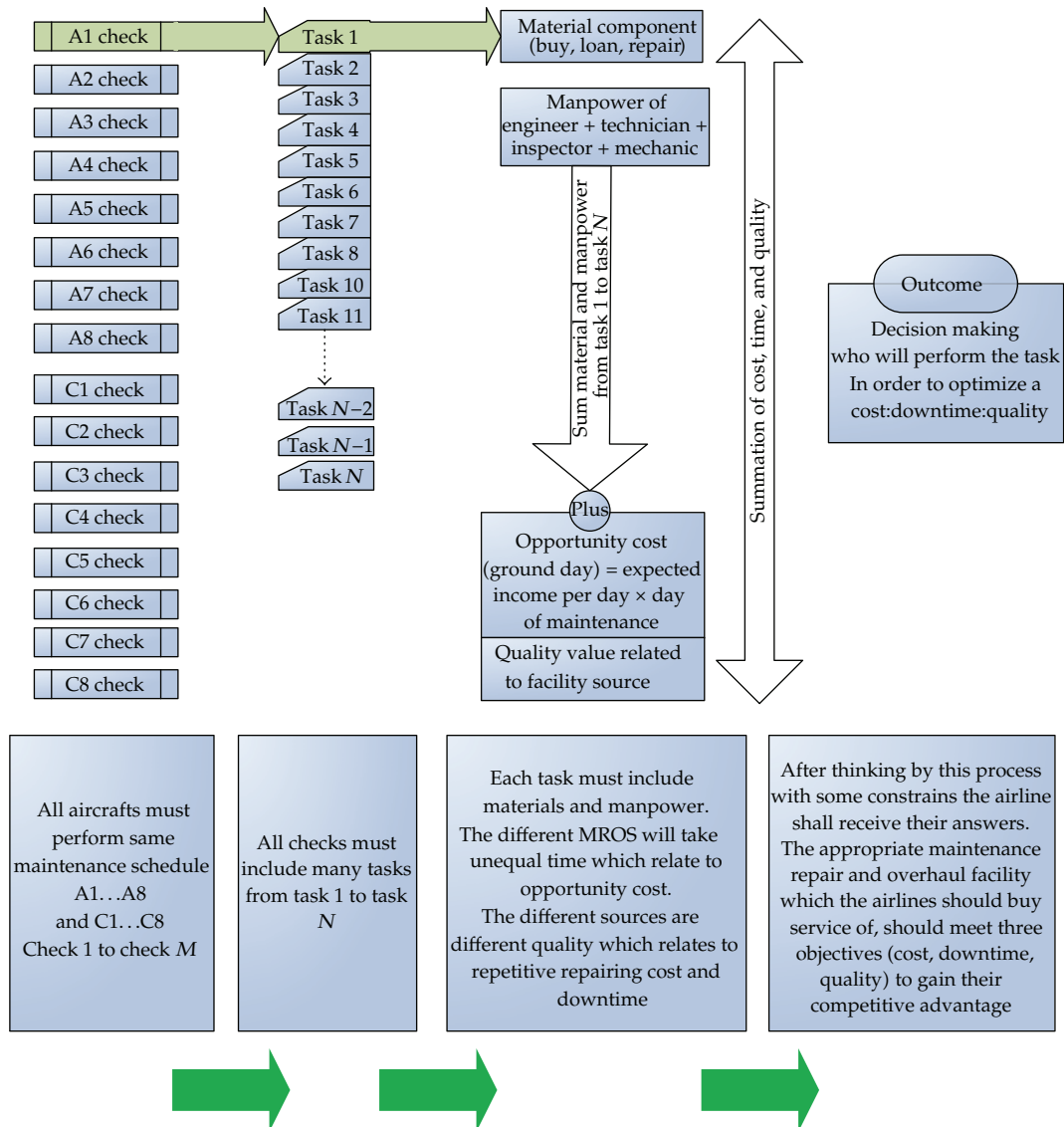


Figure 3: Aircraft maintenance planning process.

transform them to a flight plan, which indicates exactly the aircraft registration number and flight schedule. Then, the planner reviews the aircraft maintenance planning data along with the aircraft use. The results provide the maintenance scope of works and an individual maintenance schedule.

The next process is the resource preparation for future inspection. There are different types of inspection for example, A-check (aircraft inspection 600 flight hours interval) and C-Check (aircraft inspection 6000 flight hours interval). The aircraft maintenance plan can be depicted in Figure 3.

The quality of aircraft parts must be high realized, which conform to an aviation organization's certificate. In this research, quality is classified as follows:

- (i) the value of OEM (original equipment manufacturer) equals 4;
- (ii) FAA (Federal Aviation Administration) or EASA (European Aviation Safety Agency) equals 3;
- (iii) Thai DCA (Department of Civil Aviation) equals 2;
- (iv) other state aviation organizations approval equal 1;
- (v) the Bogus part (no accepted document) or cannibalized part equal 0.

The Airlines should accept at least Thai DCA approval quality.

The mathematical model is formulated for maintenance planning decision support in preparation of the material sources. Figure 3 illustrates an Aircraft Maintenance Planning Document (APMD) issued by an aircraft manufacturer. The manual declares inspection, service, and repair procedures in several intervals related to flight hours. The airline must perform A-check every 600 flight hours and C-Check in every 6,000 flight hours (the different aircraft models may have different intervals). Each check includes several task cards, which indicate manpower, tools, materials, and procedures. The maintenance manager must prepare internal capability economically. The airline hires external services for any checks that are cheaper than investing their own capability. The aircraft material procurement process is separated from man powers and tools. The manager surveys material suppliers and approves them. The aircraft part procurement criteria are prices, lead time, and quality. The mathematical model of multiobjective optimization can be formulated as follows:

Indices

$$i \in \{1, \dots, I\},$$

I = Number of jobs (A-check, C-Check),

$$j \in \{1, \dots, J\},$$

J = Number of tasks (inspection task card or service task card).

The index i represents the i th job. There are I jobs such as A1-check, A2-check, and so forth. On each job, there are J tasks. The index j represents the j th task.

Decision Variables

$$X_{ij} = \begin{cases} 1 & \text{if a manager chooses to buy the material for check } i, \text{ job task } j \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{ij} = \begin{cases} 1 & \text{if a manager chooses to loan the material for check } i, \text{ job task } j \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{ij} = \begin{cases} 1 & \text{if a manager chooses to repair the material for check } i, \text{ job task } j \\ 0 & \text{otherwise.} \end{cases}$$

(3.1)

There are three binary decision variables which are valued 0 and 1. The X_{ij} represent a decision of buying the material. It equals "1" when the manager chooses buy and "0" otherwise. The Y_{ij} represents a decision of loaning the material. It equals "1" when the manager chooses loan and "0" otherwise. The Z_{ij} represents a decision of repairing the material. It equals "1" when the manager chooses repair and "0" otherwise.

Parameters

- a_{ij} = material selling price (United State dollars),
- b_{ij} = material loan price (United State dollars),
- c_{ij} = material repair price (United State dollars),
- d_{ij} = lead time of buying material (days),
- e_{ij} = lead time of loaning material (days),
- f_{ij} = lead time of repairing material (days),
- p_{ij} = quality value of buying material (0, 1, 2, 3, and 4),
- q_{ij} = quality value of loaning material (0, 1, 2, 3, and 4),
- r_{ij} = quality value of repairing material (0, 1, 2, 3, and 4).

The a_{ij} , b_{ij} , and c_{ij} represent a sell price, loan price, and repair price of material respectively. The d_{ij} , e_{ij} , and f_{ij} represent a lead time of buying material, a lead time of loan material, and a lead time of repairing material consecutively. The p_{ij} , q_{ij} , and r_{ij} represent a quality value of buying material, a quality value of loan material, and quality value of repairing material. The values of material's qualities are scored by referring to the certificate of approval of the factory issued by an aviation organization as follows: (1) the Bogus part (no certificate) = 0; (2) the other state aviation organization approval = 1; (3) the Thai DCA = 2, FAA or EASA = 3; the OEM = 4).

Objective Function

$$\text{Minimize } z_1 = \sum_{i=1}^m \sum_{j=1}^n a_{ij}X_{ij} + b_{ij}Y_{ij} + c_{ij}Z_{ij}. \quad (3.2)$$

Equation (3.2) is objective function 1: minimize total cost

$$\text{Minimize } z_2 = \sum_{i=1}^m \sum_{j=1}^n d_{ij}X_{ij} + e_{ij}Y_{ij} + f_{ij}Z_{ij}. \quad (3.3)$$

Equation (3.3) is objective function 2: minimize total lead time

$$\text{Maximize } z_3 = \sum_{i=1}^m \sum_{j=1}^n p_{ij}X_{ij} + q_{ij}Y_{ij} + r_{ij}Z_{ij}. \quad (3.4)$$

Equation (3.4) is objective function 3: maximize total quality.

Constraints

$$X_{ij} + Y_{ij} + Z_{ij} \geq 1 \quad (3.5)$$

$$Y_{ij} - Z_{ij} \leq 0 \quad \forall(i, j), \quad (3.6)$$

$$c_{ij} \cdot Z_{ij} \leq 0.85X_{ij} \quad \forall(i, j), \quad (3.7)$$

$$\sum_{i=1}^m \sum_{j=1}^n p_{ij} X_{ij} \geq \sum_{i=1}^m \sum_{j=1}^n q_{ij} Y_{ij}, \quad (3.8)$$

$$d_{ij}X_{ij} - 30 \leq e_{ij}Y_{ij} + f_{ij}Z_{ij} \quad \forall(i, j), \quad (3.9)$$

$$X_{ij} \in \{0, 1\} \quad \forall(i, j), \quad (3.10)$$

$$Y_{ij} \in \{0, 1\} \quad \forall(i, j), \quad (3.11)$$

$$Z_{ij} \in \{0, 1\} \quad \forall(i, j), \quad (3.12)$$

$$a_{ij}, b_{ij}, c_{ij}, d_{ij}, e_{ij}, f_{ij}, p_{ij}, q_{ij}, r_{ij} \geq 0 \quad \forall(i, j). \quad (3.13)$$

Constraint (3.5) ensures that each task card chooses at least one choice. If the system chooses loan, it must choose a repair (constraint (3.6)). In normal repair, repair price of the item should not higher 85% of current buying price. If it is higher than 85%, maintenance manager mostly chooses buying (constraint (3.7)). Technically, the quality of purchasing items should be higher than repairing in overall (constraint (3.8)). Flexible and replaceable channels of material sources are loan and repair but it should receive spare parts at least thirty days faster (constraint (3.9)). Decision variables are binary (Constraints (3.10)–(3.12)). Constraint (3.13) ensures that parameters are not negative.

4. Solution Algorithm

In this research, goal programming is used to solve multiobjective optimization. The problem will be solved by generating decision variables as follows:

Decision Variables

d_1^- = underachievement deviation from the minimum total cost,

d_1^+ = overachievement deviation from the minimum total cost,

d_2^- = underachievement deviation from the minimum total lead time,

d_1^+ = overachievement deviation from the minimum total lead time,

d_3^- = underachievement deviation from the minimum total quality,

d_3^+ = overachievement deviation from the minimum total quality.

There are six decision variables which are: (1) an underachievement deviation from the minimum total cost; (2) an overachievement deviation from the minimum total cost; (3) an underachievement deviation from the minimum total lead time; (4) an overachievement

deviation from the minimum total lead time; (5) an underachievement deviation from the minimum total quality; (6) an overachievement deviation from the minimum total quality.

Variables

TC = total cost of a single minimized object 1

TLT = total lead time of a single minimized object 2

TQ = total quality of a single maximized object 3

$$\text{Minimize } z_1 = \sum_{i=1}^m \sum_{j=1}^n a_{ij}X_{ij} + b_{ij}Y_{ij} + c_{ij}Z_{ij}. \quad (4.1)$$

The equation (4.1) is a single-objective optimization from a previous problem. After solving (4.1) using the X-press program of cost optimization, total cost is 58,418,000 US dollars.

$$\text{Minimize } z_2 = \sum_{i=1}^m \sum_{j=1}^n d_{ij}X_{ij} + e_{ij}Y_{ij} + f_{ij}Z_{ij}. \quad (4.2)$$

The equation (4.2) is a single-objective optimization from a previous problem. Solving (4.2) using the X-press program of time optimization, total lead time is 151,000 days.

$$\text{Maximize } z_3 = \sum_{i=1}^m \sum_{j=1}^n p_{ij}X_{ij} + q_{ij}Y_{ij} + r_{ij}Z_{ij}. \quad (4.3)$$

The equation (4.3) is a single-objective optimization from a previous problem. Solving (4.3) using the X-press program of quality optimization, the total quality is 57,670 points.

This problem can be formulated as a linear goal programming model. The new objective function minimizes the sum of undesirable deviations. In goal programming, a specific numeric goal is established for each goal function (constraint), and then a solution is derived that minimizes the weighted sum of deviations of these goal functions from their respective goals.

Objective Function

$$\text{Minimize } Q = d_1^+ + d_2^+ + d_3^-, \quad (4.4)$$

where, d_1^+ , d_2^+ , and d_3^- are the overachievement and underachievement deviations from the goals.

Constraints

$$\begin{aligned}
\sum_{i=1}^m \sum_{j=1}^n a_{ij} X_{ij} + b_{ij} Y_{ij} + c_{ij} Z_{ij} + d_1^- - d_1^+ &\leq \text{TC}, \\
\sum_{i=1}^m \sum_{j=1}^n d_{ij} X_{ij} + e_{ij} Y_{ij} + f_{ij} Z_{ij} + d_2^- - d_2^+ &\leq \text{TLT}, \\
\sum_{i=1}^m \sum_{j=1}^n p_{ij} X_{ij} + q_{ij} Y_{ij} + r_{ij} Z_{ij} + d_3^- - d_3^+ &= \text{TQ}, \\
Y_{ij} - Z_{ij} &\leq 0 \quad \forall (i, j), \\
c_{ij} \times Z_{ij} &\leq 0.85 \times X_{ij} \quad \forall (i, j), \\
\sum_{i=1}^m \sum_{j=1}^n p_{ij} X_{ij} &\geq \sum_{i=1}^m \sum_{j=1}^n q_{ij} Y_{ij}, \\
d_{ij} X_{ij} - 30 &\leq e_{ij} Y_{ij} + f_{ij} Z_{ij} \quad \forall (i, j), \\
X_{ij} &\in \{0, 1\} \quad \forall (i, j), \\
Y_{ij} &\in \{0, 1\} \quad \forall (i, j), \\
Z_{ij} &\in \{0, 1\} \quad \forall (i, j), \\
a_{ij}, b_{ij}, c_{ij}, d_{ij}, e_{ij}, f_{ij}, p_{ij}, q_{ij}, r_{ij} &\geq 0 \quad \forall (i, j), \\
d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+ &\geq 0.
\end{aligned} \tag{4.5}$$

5. Case Study

The AAA airline in Thailand flies from Bangkok to Chiang Mai, Phuket, Udon Thani, and other airports, which are two-hour flights. The AAA airline maintenance manager plans five years' maintenance of 15 aircraft with 10,000 spare-part requirements. He must indicate the upcoming aircraft scheduled maintenance with service centers and suppliers. The mathematical algorithms are used in AAA airline's case. The different lead time deviations and different quality deviations are used on each solving. The results are cost deviations. Each solution is shown in each row of Tables 1, 2, and 3.

The minimum-cost solutions do not meet the minimum lead time and the maximum quality. Then, the authors apply +154,500 deviations to the total time and -25,000 deviations to quality. Therefore, the solution is 107,810 higher costs as shown in Table 1 Row 1. The first solutions are 58,525,810 total material costs, 154,500 total waiting days, and 32,671 total quality points. For the second row, the total lead time is changed to +3,400 deviate days and -25,000 deviate qualities. The result is a higher total cost than row 1's solution. The testing changes several lead time deviations. This table illustrates fifteen different parameter sets which result in different cost deviations. Then, it is concluded that the shorter lead time produces higher cost at the same quality level.

Table 1: Quality average = 2.83 ($d_3^- \leq 25000$).

d_1^-	d_1^+	d_2^-	d_2^+	d_3^-	d_3^+	TT cost	TT LT	TT Q	Qavg
0	107,810.00	0	3500	24999	0	58,525,810	154,500	32,671	2.83
0	120,810.00	0	3400	24999	0	58,538,810	154,400	32,671	2.83
0	134,950.00	0	3300	24999	0	58,552,950	154,300	32,671	2.83
0	149,950.00	0	3200	24999	0	58,567,950	154,200	32,671	2.83
0	164,950.00	0	3100	24999	0	58,582,950	154,100	32,671	2.83
0	179,950.00	0	3000	24999	0	58,597,950	154,000	32,671	2.83
0	200,005.00	0	2900	24999	0	58,618,005	153,900	32,671	2.83
0	246,505.00	0	2800	24999	0	58,664,505	153,800	32,671	2.83
0	293,860.00	0	2700	24999	0	58,711,860	153,700	32,671	2.83
0	341,860.00	0	2600	24999	0	58,759,860	153,600	32,671	2.83
0	389,860.00	0	2500	24999	0	58,807,860	153,500	32,671	2.83
0	437,860.00	0	2400	24999	0	58,855,860	153,400	32,671	2.83
0	626,520.00	0	2300	24999	0	59,044,520	153,300	32,670	2.82
0	950,520.00	0	2200	25000	0	59,341,320	153,200	32,670	2.82
0	1,220,120.00	0	2100	25000	0	59,638,120	153,100	32,670	2.81

Note: TT cost: total material cost, TT LT: total lead time (in procurement), TT Q: total quality, and Qavg: average quality.

Table 2: Quality average = 2.84 ($d_3^- \leq 22000$).

d_1^-	d_1^+	d_2^-	d_2^+	d_3^-	d_3^+	TT cost	TT LT	TT Q	Qavg
0	235,250.00	0	5300	21999	0	58,653,250	156,300	35,671	2.84
0	240,250.00	0	5200	21999	0	58,658,250	156,200	35,671	2.84
0	245,250.00	0	5100	21999	0	58,663,250	156,100	35,671	2.84
0	250,250.00	0	5000	21999	0	58,668,250	156,000	35,671	2.84
0	263,440.00	0	4900	21999	0	58,681,440	155,900	35,671	2.84
0	305,440.00	0	4800	21999	0	58,723,440	155,800	35,671	2.84
0	347,440.00	0	4700	21999	0	58,765,440	155,700	35,671	2.84
0	389,440.00	0	4600	21999	0	58,807,440	155,600	35,671	2.84
0	432,010.00	0	4500	21999	0	58,850,010	155,500	35,671	2.84
0	475,010.00	0	4400	21999	0	58,893,010	155,400	35,671	2.84
0	519,150.00	0	4300	21999	0	58,937,150	155,300	35,671	2.84
0	564,150.00	0	4200	21999	0	58,982,150	155,200	35,671	2.84
0	776,700.00	0	4100	21999	0	59,194,700	155,100	35,670	2.84

Table 3: Quality average = 2.85 with $d_3^- \leq 20000$.

d_1^-	d_1^+	d_2^-	d_2^+	d_3^-	d_3^+	TT cost	TT LT	TT Q	Qavg
0	380,200.00	0	6200	19998	0	58,798,200	157,200	37,672	2.85
0	410,200.00	0	6100	19998	0	58,828,200	157,100	37,672	2.85
0	441,400.00	0	6000	19998	0	58,859,400	157,000	37,672	2.85
0	476,400.00	0	5900	19998	0	58,894,400	156,900	37,672	2.85
0	511,400.00	0	5800	19998	0	58,929,400	156,800	37,672	2.85
0	546,400.00	0	5700	19998	0	58,964,400	156,700	37,672	2.85
0	583,080.00	0	5600	19998	0	59,001,080	156,600	37,672	2.85
0	625,080.00	0	5500	19998	0	59,043,080	156,500	37,672	2.85
0	1,261,700.00	0	5400	19998	0	59,679,700	156,400	37,670	2.84

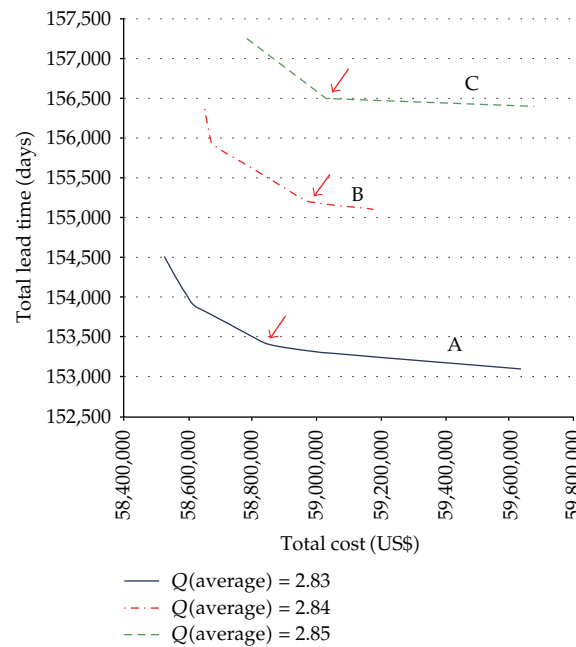


Figure 4: Total cost and total lead time of three different qualities.

The maintenance manager may tradeoff between reducing the waiting time and higher material expenses. In practical exercise, the AAA airline generates average income at US\$33,000 per day. Thus, the maintenance manager can make technical decisions to overpay aircraft recovery up to US\$16,500 (50% from income) to reduce a single AOG (Aircraft on ground) day.

Table 2 shows the results as an average 2.84 quality points and different lead time periods. This table illustrates thirteen different parameter sets which result in different cost deviations. However, the trend of data is similar to Table 1. It is only different in longer lead time at equal prices. Thus, the maintenance manager can use the data from two tables for making decisions among expected quality, lead time, and increasing/decreasing prices. In Table 2, if the maintenance manager aims to increase material's average quality, he must pay higher material costs. Furthermore, if he wants shorter procurement lead time, it will result in higher material expenses, which indicate in Table 2.

Table 3 shows the results under a higher average quality and different lead time periods (compare with Table 2). This table illustrates nine different parameter sets which result in different cost deviations. The AAA airline maintenance manager confirms that these results are valid by reviewing empirical results with their operational records. Therefore, the data from Tables 1, 2, and 3 are created in a single chart, which is used for comparisons between total cost, total lead time, and average quality.

Figure 4 shows a graphical comparison of Tables 1, 2, and 3. The high total cost at an early stage produces shorter lead time with a high negative slope. Each point on the three curves explains three objective dimensions: cost, lead time, and quality. Line B represents when airlines increase average quality, they pay a higher cost for the same lead time in order to buy, repair, or loan higher-quality aircraft parts. The arrow position points are the limit

points to increase costs for a shorter time. It is not worth to pay a higher price for a small reduction of time beyond the arrows.

The solutions of the multiobjective optimization are not only three factors beneficial but also reliability, availability, and maintainability. Meanwhile, the material lead time is shorter, it reduces the aircraft downtime, which results in a shorter mean time to repair (higher maintainability), the longer MTBF (higher reliability), and the higher availability of the aircraft. The solutions are beneficial to the airlines that aim to fulfill travelling demand. The cost minimization results in lower airfare. Hence, the airlines gain a higher competitive advantage. The time minimization results in a higher flight time. Then, there are higher available flight hours of the airlines in responding to the market demand. Thus, this model is beneficial to the airlines on competitive advantage.

6. Conclusions

A multiobjective optimization using goal programming is particularly useful to aircraft maintenance organizations in simultaneous reduction of cost and aircraft downtime, as well as for increasing quality. Also, it is valuable to the improvement of supplier flexibility/replace ability, aircraft availability, and aircraft reliability. For airlines in Thailand, the results of the model with AAA airline's data are used as a decision-support strategy of multi-factors in aircraft maintenance, which generates the best solution among 7.8×10^5 possible solutions.

There are six contributions in this paper. First, the mathematic model supports the commercial aviation industry or the military aircraft fleet in survival under limited cost or certain budgets in Thailand by developing the supply chain. Second, this research illustrates the critical factors to aviation performance measurement. Third, the model assists the aircraft maintenance manager in decision support of resources selection. Fourth, the airline maintenance manager could develop the mathematical algorithm in their maintenance to optimize relative benchmarking and continue their best operation to enhance their competitive advantage. Fifth, the outcome of this research can be applied in aircraft operational risk management. Finally, it is beneficial to future research in performance analysis of other industries for example, ship, train, truck, and so forth.

However, aircraft fuel price is a vital factor that is related to operating costs and this needs to be carefully watched, thus future research may review and add the fuel cost factor into the optimization model.

References

- [1] B. Pearce, "The state of air transport markets and the airline industry after the great recession," *Journal of Air Transport Management*, vol. 21, pp. 3–9, 2012.
- [2] I. Dostaler and T. Flouris, "Business strategy and competition for the future in the airline industry," <http://www.aerlines.nl/issue.28/28.Dostaler.Flouris.pdf>.
- [3] P. Belobaba, A. Odoni, and C. Barnhart, *The Global Airline Industry*, John Wiley and Sons, New York, NY, USA.
- [4] C. Hofer, M. E. Dresner, and R. J. Windle, "The impact of airline financial distress on US air fares: a contingency approach," *Transportation Research E*, vol. 45, no. 1, pp. 238–249, 2009.
- [5] E. Pels, "Airline network competition: full-service airlines, low-cost airlines and long-haul markets," *Research in Transportation Economics*, vol. 24, no. 1, pp. 68–74, 2009.
- [6] M. Christopher, *Logistics and Supply Chain Management: Creating Value-Adding Networks*, FT Prentice Hall, New York, NY, USA, 2005.
- [7] F. T. S. Chan and H. J. Qi, "An innovative performance measurement method for supply chain management," *Supply Chain Management*, vol. 8, no. 3, pp. 209–223, 2003.

- [8] K. L. Choy, H. K. H. Chow, W. B. Lee, and F. T. S. Chan, "Development of performance measurement system in managing supplier relationship for maintenance logistics providers," *Benchmarking*, vol. 14, no. 3, pp. 352–368, 2007.
- [9] Department of Civil Aviation, "Aviation statistics," http://portal.aviation.go.th/dca/stat_index.jsp.
- [10] M. Milde and S. Kumpeera, "International air laws," <http://www.aviation.go.th/airtrans/airlaw/content.html>.
- [11] J. W. Langford, *Logistics Principles and Applications*, McGraw-Hill, New York, NY, USA, 2nd edition, 2006.
- [12] K. W. Platts and N. Song, "Overseas sourcing decisions—the total cost of sourcing from China," *Supply Chain Management*, vol. 15, no. 4, pp. 320–331, 2010.
- [13] S. L. Beckman and D. B. Rosenfield, *Operations Strategy Competing in the 21st Century*, McGraw-Hill, New York, NY, USA, 2008.
- [14] S. Kumar, K. L. Johnson, and S. T. Lai, "Reflective practice performance improvement possibilities within the US airline industry," *International Journal of Productivity and Performance Management*, vol. 58, no. 7, pp. 694–717, 2009.
- [15] P. Miroslavljevic, S. Gvozdenovic, and O. Cokorilo, "The turbofan aircraft minimum cost climb technique," *Aircraft Engineering and Aerospace Technology*, vol. 81, no. 4, pp. 334–342, 2009.
- [16] Bangkokpost, "Fuel-hedging dooms THAI's performance costs so far could approach B4-6bn," 2009, <http://www.skyscrapercity.com/showthread.php?t=169502&page=49>.
- [17] S. L. Yang, Y. Ma, D. L. Xu, and J. B. Yang, "Minimizing total completion time on a single machine with a flexible maintenance activity," *Computers and Operations Research*, vol. 38, no. 4, pp. 755–770, 2011.
- [18] C. Chandra and J. Grabis, "Inventory management with variable lead-time dependent procurement cost," *Omega*, vol. 36, no. 5, pp. 877–887, 2008.
- [19] A. Brandon-Jones, J. Ramsay, and B. Wagner, "Trading interactions: supplier empathy, consensus and bias," *International Journal of Operations and Production Management*, vol. 30, no. 5, pp. 453–487, 2010.
- [20] W. J. Chen, "Methodology and theory: minimizing completion time with maintenance schedule in a manufacturing system," *Journal of Quality in Maintenance Engineering*, vol. 16, no. 4, pp. 382–394, 2010.
- [21] H. A. Kinnison, *Aviation Maintenance Management*, McGraw-Hill, New York, NY, USA, 2004.
- [22] D. K. Yadav, "Licensing and recognition of the aircraft maintenance engineers—a comparative study," *Journal of Air Transport Management*, vol. 16, no. 5, pp. 272–278, 2010.
- [23] International Civil Aviation Organization, *ANNEX 6—Operation of Aircraft (Amdt 33-B)*, Aeroplane Maintenance, 2012.
- [24] H. Wang and H. Pham, *Reliability and Optimal Maintenance*, Springer, New Jersey, NJ, USA, 2010.
- [25] Department of The ARMY, *Reliability/Availability of Electrical & Mechanical Systems for Command, Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance Facilities?* Department of The ARMY, Washington DC, 2007.
- [26] B. S. Dhillon, *Maintainability Maintenance and Reliability for Engineers*, Taylor and Francis, Boca Raton, Fla, USA, 2006.
- [27] R. Smith and R. K. Mobley, *Rules of Thumb for Maintenance and Reliability Engineers*, Butterworth-Heinemann, Oxford, UK, 2007.
- [28] R. Gulati and R. Smith, *Maintenance and Reliability Best Practices*, Industrial Press, New York, NY, USA, 2008.
- [29] S. Samet, A. Chelbi, and F. Ben Hmida, "Methodology and theory: optimal availability of failure-prone systems under imperfect maintenance actions," *Journal of Quality in Maintenance Engineering*, vol. 16, no. 4, pp. 395–412, 2010.
- [30] J. Ferguson, A. Q. Kara, K. Hoffman, and L. Sherry, "Estimating domestic US airline cost of delay based on European model?" *Transportation Research C*. In press.
- [31] L. H. Su and H. L. Tsai, "Methodology and theory: flexible preventive maintenance planning for two parallel machines problem to minimize makespan," *Journal of Quality in Maintenance Engineering*, vol. 16, no. 3, pp. 288–302, 2010.
- [32] S. Hennequin, G. Arango, and N. Rezg, "Optimization of imperfect maintenance based on fuzzy logic for a single-stage single-product production system," *Journal of Quality in Maintenance Engineering*, vol. 15, no. 4, pp. 412–429, 2009.
- [33] A. Oke, "A framework for analysing manufacturing flexibility," *International Journal of Operations and Production Management*, vol. 25, no. 10, pp. 973–996, 2005.

- [34] Q. H. Soon and Z. M. Udin, "Supply chain management from the perspective of value chain flexibility: an exploratory study," *Journal of Manufacturing Technology Management*, vol. 22, no. 4, pp. 506–526, 2011.
- [35] M. Stevenson and M. Spring, "Supply chain flexibility: an inter-firm empirical study," *International Journal of Operations and Production Management*, vol. 29, no. 9, pp. 946–971, 2009.
- [36] P. Kumar, R. Shankar, and S. S. Yadav, "Flexibility in global supply chain: modeling the enablers," *Journal of Modelling in Management*, vol. 3, no. 3, pp. 277–297, 2008.
- [37] L. K. Duclos, R. J. Vokurka, and R. R. Lummus, "A conceptual model of supply chain flexibility," *Industrial Management and Data Systems*, vol. 103, no. 5-6, pp. 446–456, 2003.
- [38] Y. Pleumpirom and S. Amornsawadwatana, "Performance development method for the aviation supply chain," in *Proceedings of the International Conference on Logistics and Transport*, pp. 1107–1113, Queens Town, New Zealand, 2010.

