# MULTI-AGENT BASED APPROACH FOR INTEGRATED AIRCRAFT MAINTENANCE MANAGEMENT PROBLEMS

(APPROCHE MULTI-AGENT POUR LA GESTION DES PROBLEMES D'ENTRETIEN D'AERONEFS ENTEGRE)

by

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## LIST OF SYMBOLS

**RPK** : Revenue Passenger Kilometers
**ICAO** : International Civil Aviation Organization
**GMF** : Global Market Forecast
**GDP** : Gross Domestic Product
**DSS** : Decision Support System
**STRIPS** : Stanford Research Institute Problem Solver
**SA** : Single Aisle
**HL** : Hand Luggage
**GDP** : Ground Delay Program
**IATA** : International Air Transport Association
**FAA** : Federal Aviation Administration
**MA** : Maintenance Agent
**OA** : Operation Management Agent
**MR** : Maintenance Requirements
**PAR** : Prescheduled Aircraft Routing
**HUM** : Handling Uncheduled Maintenance
**IMA** : Inventory Management Agent
**AS** : Allocating Staff
**MI** : Managing Inventory
**SMA** : Staffing Management Agent
**ARO** : Aircraft Routing Operation

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# ABSTRACT

With the highly competitive nature of airline business, optimizing the aircraft maintenance problems have gained increasing importance. In the aircraft routing, a flight sequence or route is built for each individual aircraft so as to cover each flight exactly once at a minimum cost while satisfying maintenance requirements. Aircraft maintenance management has been troubled by many problems, such as scheduling determined maintenance, handling unscheduled maintenance, inventory management, and operation crew assignment. Most of the study solves separately these problems by following a sequence of tasks, and there exist novel studies that solve by integrating some of these problems.

In this study, we consider the aircraft maintenance management problems with a new agent based approach which aims to support the airlines' operation managers for scheduling maintenance mandated by authorities, handling unscheduled maintenance, predicting unscheduled maintenance, managing aircraft component inventory, and managing staff allocation. We described four different agents for solving integratetly maintenance management problems by using STRIPS language and planned these agents by using partial order planning algorithm.

The method, which we developed, differentiate from the classical integrated aircraft routing models (which integrate all optimization problems in one model and add new constraints to this model) because it does not use only one model when it integrated different problems in aircraft maintenance management. Also, our approach is more flexible because it is enough to change only the relevant agent when a regulation is changed on some constraints. The other difference is to be enough to only solve the problem which has an error instead of solving all models as classical integrated models.

## RÉSUMÉ

Avec la nature hautement compétitive de l'activité aérienne, l'optimisation de la gestion de la maintenance des aéronefs a gagné en importance. Dans le routage de l'avion, une séquence ou un itinéraire de vol est construit pour chaque avion individuel afin de couvrir chaque vol exactement une fois à un coût minimum tout en satisfaisant les exigences de maintenance. Le routage des aéronefs a été perturbé par de nombreux problèmes, tels que la planification de la maintenance déterminée, la maintenance imprévue, la disponibilité de l'aéroport et l'embarquement. La plupart des études résolvent séparément ces problèmes en suivant une séquence de tâches, et il existe des études nouvelles qui résolvent en intégrant certains de ces problèmes.

Dans cette étude, nous considérons les problèmes de gestion de l'entretien de l'avion avec une nouvelle approche basée sur l'agent qui vise à soutenir les gestionnaires d'opérations des compagnies aériennes pour la planification de l'entretien prescrit par les autorités, la gestion de la maintenance imprévue, la prédiction de la maintenance imprévue, et la gestion de l'inventaire des composants de l'avion. Nous avons décrit quatre agents différents pour résoudre intégralement les problèmes de gestion de la maintenance en utilisant le langage STRIPS et pour planifier ces agents en utilisant un algorithme de planification de classement partielle.

La méthode, que nous avons développée, se distingue des modèles classiques de routage d'aéronef intégrés (qui intègrent tous les problèmes d'optimisation dans un modèle et ajoutent de nouvelles contraintes à ce modèle), car il n'utilise pas un seul modèle lorsqu'il intègre différents problèmes dans la gestion de la maintenance des aéronefs. En outre, notre approche est plus souple car, il suffit de changer uniquement l'agent concerné lorsqu'un règlement est modifié sur certaines contraintes. L'autre différence est d'être suffisante pour résoudre le problème qui a une erreur au lieu de résoudre tous les modèles comme modèles intégrés classiques.

# 1. INTRODUCTION

## 1.1. Background

The aviation industry has been steadily challenging with growing in response to an increase in both passenger and freight traffic demands, and play an essential role in both local and global economic development by contributing to the global economy with \$2400 million that translates to about 3.4% of the global GDP. According to Airbus Global Market Forecast, the airline traffic (RPK) is doubling every fifteen years (see figure 1.1.) and Airbus forecasts the air traffic to grow 4.4 % per annual between 2017 and 2035. Also, Airbus forecasts that the Aviation Mega Cities number will increase from 58 in 2016 to 95 in 2035 (See Figure 1.1 Air Traffic Growth). However, despite this significant increase; there exist some mega cities such as London which are currently used with full capacity and which not able to improve airports capacities because of lack of available area, environmental policy or geographic reasons.

In order to response the increase in demand, to maximize the profit in the highly competitive business, and to improve airport capacity, airline companies are working to solve problems such as airline scheduling, network design, fleet design, aircraft routing, crew pairing, and pricing. In previous studies, the demand is the most common data which use the maximization function of the profit, and typically, demand contributes to the characteristics of flight schedules and route networks of an airline, and governs the composition of nonstop flights or multi-leg itineraries, origins and destinations of markets, and the departure and arrival times of related flight legs and their days of operation as well as seasonal variations. The maintenance management has an important place in these problems because it can reduce the use of airport capacity and increase profit by avoiding the flight delay, flight cancellation, and decrease demand.  Even though airlines use sophisticated management tools for managing the maintenance processes, the aircraft maintenance management problems can cause loss to an airline company such as canceling a flight because of delay, staying in the airport more than planned, changing the gate because of retard etc.

Aircraft maintenance management aims to determine the sequence of flight legs to be flown by each individual aircraft to cover each leg exactly once while ensuring appropriate aircraft maintenance by satisfying appropriated maintenance crews and components of aircraft.

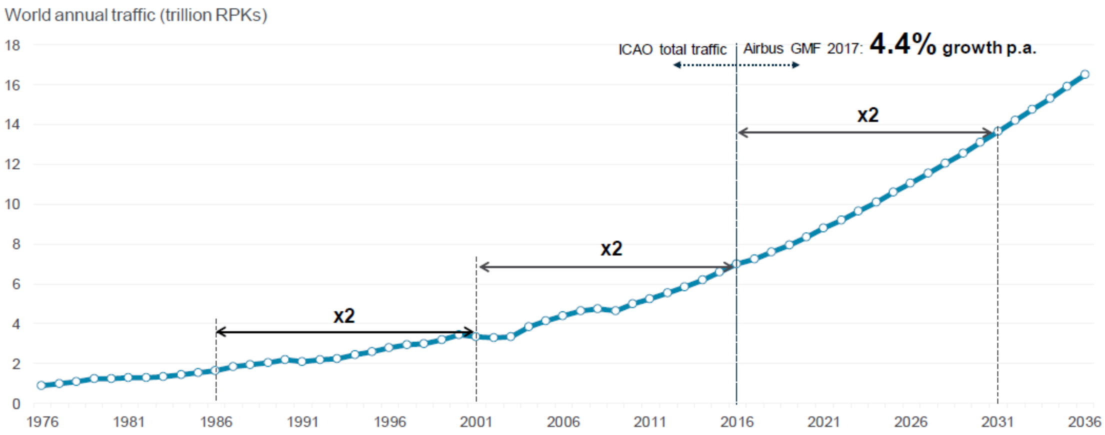

Figure 1.1 Air Traffic Growth

| Years | 2016 | 2021 | 2026 | 2031 | 2036 |
|---|---|---|---|---|---|
| Africa | 1 | 2 | 5 | 6 | 8 |
| Asia-Pacific | 19 | 22 | 24 | 25 | 25 |
| CIS | 1 | 1 | 1 | 1 | 1 |
| Europe | 12 | 15 | 19 | 20 | 22 |
| Latin America | 6 | 8 | 8 | 9 | 9 |
| Middle East | 5 | 6 | 7 | 9 | 11 |
| North America | 14 | 16 | 18 | 18 | 19 |
| Grand Total | 58 | 70 | 82 | 88 | 95 |

Figure 1.2 Aviation Mega Cities Number Forecast

## 1.2. Motivation

After creating a schedule that defines origin and destination cities as well as departure and arrival times for each flight leg to be flown during a given period, most of the airlines use a sequential procedure to plan their operations. The first step of this procedure is the fleet assignment problem which consists in assigning an aircraft type to each flight leg to maximize anticipated profits. For each aircraft type, an aircraft routing problem is then solved to determine the sequence of flight legs to be flown by each individual aircraft to cover each leg exactly once while ensuring appropriate aircraft maintenance. The problems such as maintenance scheduling, fueling, boarding are solved independently by using a sequential procedure for decreasing the complexity of the procedure, but it is clear that there is a considerable interaction between them, because outputs of some problems are used as input for others. Also, these problems are solving at least 2 weeks in advance. Because of that, airlines may not the response the change in airline or aircraft environment in 2 weeks.

Consequently, airline companies are actively seeking additional novel approaches to model and solve these problems simultaneously so as to obtain improved solutions that would lead to substantial savings over the sequential approach. In this study, we try to solve aircraft maintenance management problems by applying the agent based approach to satisfy a real-time integrated solution.

## 1.3. Organization of Report

This report is organized as follows. In the first section, we review the literature on models for the aircraft maintenance management problems. In the second section, we study on the problems which exist in the aircraft maintenance managements such as maintenance, logistics, boarding etc. In the third section, we discuss our model for solving these problems in real-time by integrating agents that have different kinds of capabilities. Also, in this section, we will explain the agent integration, planning, and description. The final section provides conclusion and future studies.

## 2. LITERATURE REVIEW

After the Airline Deregulation Act of 1978, the airline business has witnessed dramatic changes in their operating environment. Low-cost carriers have led to continuing to do discounts and promotions which totally change customer expectations. The major carriers focused on their operations for avoiding loss / maximizing their profits, and this lead to the studies on the aircraft routing problems.

Feo and Bard (1989) present a mathematical model that can be used by planners to both locate maintenance stations and to develop flight schedules that meet the cyclical demand for maintenance. The problem is constructed as a minimum cost formulation, multi-commodity flow network with integral constraints, and solved by using two phase heuristics. Data was supplied by American Airlines for their Boeing 727 fleet.

Dijkstra et al. (1991) describe a decision support system for the aircraft maintenance department of Dutch national airline company at the main airport in Netherlands. The DSS that has been developed can be used to support the management of the maintenance department in solving several capacity planning problems related to the size and the composition of the workforces. Dijkstra et al. (1994) also developed a DSS for the aircraft maintenance department of KLM Royal Dutch Airlines at Schiphol Airport. This department inspects and maintains aircraft during their ground time at the airport. Its main resource is its workforce.

Cobb (1995) focused on the development and use of a generalized simulation model of an airline component maintenance shop that could be modified to study the performance characteristics of any specific maintenance shop design. The simulation results could then be assessed to determine whether inferences could be made concerning the value of simulation modeling as an aid to vendors of maintenance services in today’s dynamic airline industry.

Mathaisel (1996) proposes decision support system applications with GUIs which provide the supports to crew management, aircraft maintenance, airport operations, aircraft routers, flight dispatch, irregular operations, and system operations managers by using different clusters which may share data via the internet. Gatland et al. (1997) propose an aircraft engine maintenance system for defining the capacity planning problem by designing a simulation model and they tested its applicability.

Clarke et al. (1997) presented a mathematical model which maximizes the benefit derived from making specific connections in the aircraft rotation problem and discussed its similarity with the asymmetric traveling salesman problem.

Dietz and Rosenshine (1997) propose an analytical model for determining an optimal specialization strategy for a maintenance workforce. Markov decision analysis is employed to determine an optimal assignment of maintenance personnel to pending tasks as the network status varies over time and a linear programming algorithm is derived to enable simultaneous optimization of specific assignment decisions and the overall workforce structure.

Hopp and Kuo (1998a) consider the maintenance of engine components that are subject to stress. They incorporate stress information collected via sensors into the scheduling decision process by means of a partially observable Markov decision process model.

Hopp and Kuo (1998b) formulate three easy-to-implement heuristics and test their performance against a lower bound for various numerical examples.

Talluri (1998) consider the routing problem when the requirement is to overnight at a maintenance station after at most four days of flying and to undergo the balance check every n days, where n is the number of planes in the fleet of the equipment type under consideration.

Gopalan and Talluri (1998) propose fast and simple polynomial time algorithms for finding a routing of aircraft in a graph whose routing during the day is fixed, that satisfies both the three days maintenance as well as the balance check visit requirements under two different models: a static infinite horizon model and a dynamic finite horizon model. They represent an implementation of static horizon model for finding a maintenance routing of aircraft.

Barnhart et al. (1998) propose a string based model for aircraft routing and fleeting. The objective is to minimize the total cost of the selected strings. Five sets of constraint exist in this model for satisfying balance constraint, ensuring arriving and departing fleet size in a maintenance center, ensuring to be on only one string of a flight, ensuring the counting constraint, and ensuring the fleet size. They propose two different methods for solving this model.

Duffuaa and Andijani (1999) propose an integrated simulation model for the maintenance routing problem by devising several sub-modules such as planning and scheduling, quality control, supply, and inventory etc. The Saudi Arabia Airline is taken as an example in this study, and they use simulation languages and statistics tools for creating their model.

Crocker and Kumar (2000) propose a model for age related maintenance problem using the concept hard life and soft life to optimize maintenance costs. The proposed model is applied to find optimal maintenance policies in case of military aero-engines using Monte Carlo Simulation.

Latorella and Prabhu (2000) review current approaches to identifying, reporting, and managing human error in aviation maintenance and inspection.

Stojkovic et al. (2002) propose an optimization model for re-routing and re-planning a flight when a perturbation occurred. Their dual model is shown to be a capacitated network model which is solvable in real-time.

Gupta et al. (2003) develop a computerized simulation model for aircraft maintenance routing department in Continental Airlines. Day to day maintenance activities are planned to lead to the development of enhanced staffing models and a better understanding of resource requirements on a daily basis.

Sriram and Haghani (2003) propose a heuristic approach and a complete maintenance routing formulation of maintenance scheduling for A and B checks for one-week period. Their heuristics solve the aircraft maintenance routing problem at most 5% of the difference to the optimal solution obtained by the complete maintenance routing formulation and it uses less CPU time than the complete maintenance routing formulation.

Rosenberger et al. (2003) propose an optimization model that reschedules the flight and reroutes aircraft by minimizing an objective function involving rerouting and cancellation costs. They develop a heuristic for selecting which aircraft are rerouted, and they provide proof of their concept.

Ghobbar and Friend (2003) compare 13 different demand forecasting analysis for aircraft maintenance repair parts. They use a statistical method for clarifying the demand forecasting analysis methods.

Wu et al. (2004) discuss a concept reliability and maintenance design for reducing direct maintenance costs.

Yan et al. (2004) propose a mathematical programming model by considering technicians with multiple types of aircraft maintenance certificates incorporated with three flexible management strategies and the related operating constraints. The proposed model is formulated as mixed integer programs.

Lan et al. (2006) propose two models for minimizing passenger disruptions and achieve robust airline schedule plans. The first approach involves the aircraft routing, and the second involves retiming flight departure times.

Chang and Wang (2010) studied human risk factors in aircraft maintenance technicians in the airline industry. They developed an expert questionnaire for determining the risk factor in the aircraft maintenance processes.

Papakostas et al. (2010) propose a decision support methodology for deferring maintenance actions that affect the dispatching of the aircraft, aiming at high fleet operability and low maintenance cost. They used multi criteria decision-making model for decision alternative maintenance process by using different criteria.

Eggenberg et al. (2010) propose a modeling framework for the recovery of an airline schedule after a disruption.

Liang et al., (2010) propose a compact network representation of the aircraft maintenance routing problem and a mixed integer programming formulation to solve the problem.

Beliën et al. (2011) propose an application of visualization tool and optimization model based on mixed-integer linear programming to solve a workforce staffing and scheduling problem.

Chen et al. (2012) propose a PHM technology for upgrading aircraft condition monitoring system, and real-time data link for transmitting aircraft condition monitoring information to the terminal on the ground to complete the automatic maintenance diagnosis.

Karadžić et al. (2012) propose a conditional-based maintenance model for old aircraft in the limits and conditions of small countries and in accordance with global technological achievements.

Haouari et al. (2012) propose a linearized mixed integer programming model with a polynomial-sized representation for the aircraft routing problem.

Liang and Chaovalitwongse (2012) propose a network-based model for weekly aircraft maintenance routing and fleet assignment problem by using mixed integer linear programming model, linear programming relaxation, and heuristics.

Marais and Robiachaud (2012) investigate and quantify the contribution of maintenance in terms of frequency and severity, to passenger airline risk by analyzing three different sources of data from 1999 to 2008.

Gavranis and Kozanidis (2013) propose an exact solution algorithm for the Flight and Maintenance Planning, which is capable of identifying the global optimal solution of realistic size problems in reasonable computation times. The algorithm obtains a valid upper bound on the optimal objective function value by solving a simplified relaxation of the original problem, then, this value gradually reduced, until a feasible solution that attains it is identified.

Beliën et al. (2013) propose an enumerative algorithm with a bounding which each node of enumeration three represents a mixed integer linear programming. The MILP is reformulated for becoming tractable by commercial MILP Solver.

Bajestani and Beck (2013) propose a complete approach based on the logic-based Benders decomposition to solve static sub-problem of mixed integer programming for dynamic repair shop scheduling in the context of military aircraft fleet management.

Quinlan et al. (2013) review the effect of outsourcing and offshoring aircraft maintenance in the US.

Başdere and Bilge (2014) propose an integer linear programming model for maximizing utilization of the total remaining flying time of fleet by providing a feasible route for each aircraft.

Maher et al. (2014) propose a mixed integer programming model for single day aircraft maintenance routing problem. For reducing solving time of model, they apply bender decomposition to the model and solve it with two stages cutting.

Erkoc and Ertogral (2016) propose an exact solution algorithm practical or the model based on a full-delay scheduling approach with backward allocation. The proposed procedure is demonstrated through both a numerical study and a case study from the airline MRO service industry.

Schmidt (2017) provides a review of an introduction to aircraft ground operations focusing on the aircraft turn around and passenger process.

Wijk et al. (2017) propose an approach for cost-effective optimization of stop-maintenance strategies for a set of repairable items. The optimization method has two steps. First, the novel concept of matrix simulations is introduced to locate the solution space of the optimization problem in question. Second, a genetic algorithm is applied to find the minimum cost solution. The combination of matrix simulations and genetic algorithm is shown to constitute a powerful method for solving the optimization problem in a fast manner.

# 3. PROBLEM STATEMENT

The goal of aircraft maintenance routing problem is to determine a sequence of flight legs, called aircraft routings, to be flown by individual aircraft such that each flight leg is included in exactly one aircraft routing, and all aircraft are properly maintained. In most optimization models for the aircraft maintenance routing problem, the objective is to maximize revenue, the potential revenue obtained by offering passengers the opportunity to stay on the same aircraft when making a connection at an airport. In practice, this additional revenue is very difficult to determine accurately and the financial impact is relatively small. The aircraft maintenance routing problem can thus be cast as a feasibility problem, providing an opportunity to achieve robustness with minimal cost implications.

## 3.1. Operation Management

Airports are the fundamental core of all commercial passenger flights. They allow aircraft to take-off and land and provide necessary facilities to service the aircraft. Airport operations are divided into “landside processes”, where passenger arrive, drop off their luggage and go through security, and “airside processes”, where passengers board and disembark planes. Airside processes cover also the take-off and landing of the aircraft, as well as taxiing procedures. Turnaround can take place directly at the gate or at a remote apron position (See Figure 3.1.1. Airport Description).

The aircraft operations management contains four main goals for minimizing lost in the aircraft maintenance routing problem. These goals are the minimization of flight cancellation, minimization of delay, minimization of repair turn time, and effective utilization of maintenance resources. Bad weather condition, headwinds on the route, technical difficulties on aircraft, crew and passenger delay, peak hour congestion at the airport, poorly calculated block and catering time, strikes can cause changes on operations. The operators must decide which operations changes must change by considering aircraft operation main goals. Our purpose is to create a decision support system to the operators that consider not only aircraft operations main goals but also airline preferences on operations.

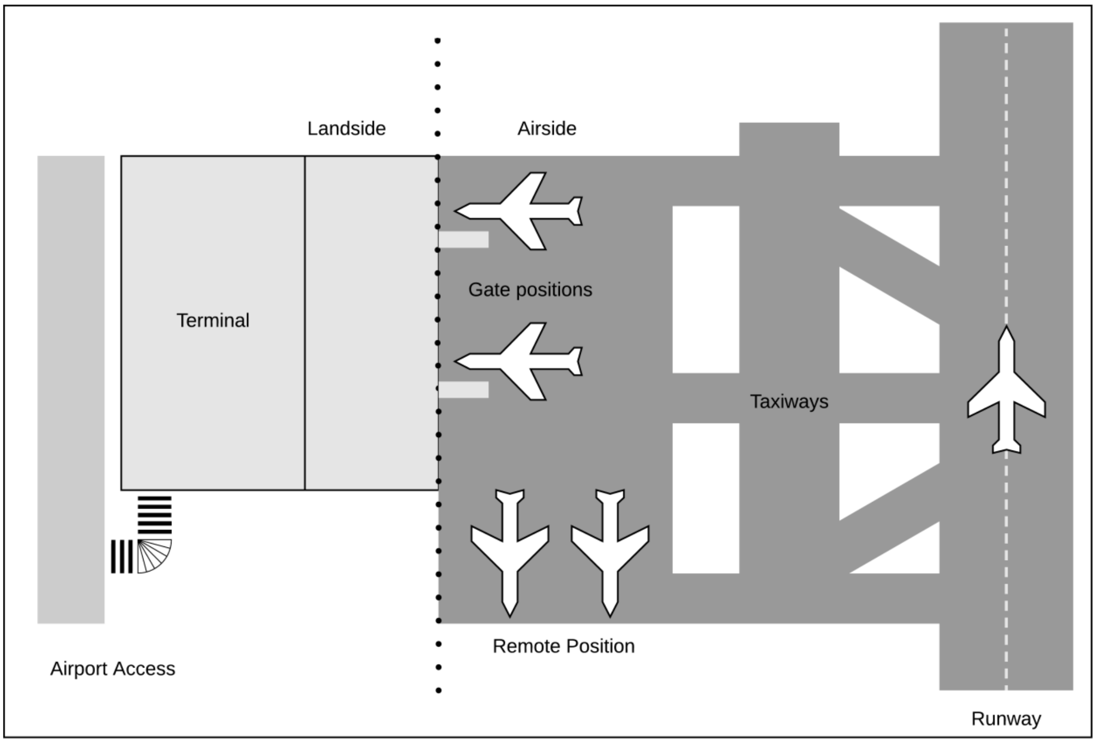

Figure 3.1.1. Airport Description

### *Aircraft characteristics related to ground operation*

Aircraft are equipped with multiple interfaces, such as doors and hatches, to exchanges goods, passengers or liquids during the ground services. The position of these interfaces varies depending on if the aircraft features wing-mounted or aft-fuselage-mounted engines, or if it is a low-wing or high-wing aircraft. A cluster analysis of regional an single aisle(SA) aircraft in and out of production revealed a trend shifting towards commonality, such as for the potable and waste water connector at the aft fuselage. Also, the electrical power interfaces were in general located on the outer side from the engine. In general, passenger doors were located at each end of the passenger cabin, enabling an uninterrupted passenger cabin where passenger emergency pass ways do not obstruct the seat rows. Ground operations can change according to aircraft characteristics.

### *Aircraft turnaround process*

Aircraft ground handling, or also referred to as turnaround, is a fundamental part of commercial aircraft operations and describes all operations for preparing an aircraft for flight. The turnaround process starts when the aircraft reaches the parking position after landing and the chocks are set (‘on-block time’). The parking position can be located at the terminal, referred to as gate position, or on the apron, known as remote position. The process ends when the aircraft is ready to leave and the chocks are removed (‘off-block time’). Commercial aircraft depend on vehicles and systems known as GSE (Ground support equipment) to perform the required processes. In general, the turnaround time depends on the aircraft type, the number of passengers, amount of loaded and unloaded cargo, as well as, the business model of the aircraft operator. The aircraft turn around consists of various processes which are, in general, provided by more than one service provider. The course of activities follows a strict chronological order, however, some processes can be executed concurrently, while others only sequentially.

### *Passenger egress and ingress*

The passenger aircraft boarding process has been an issue since the late 1970’s. Over the past decades, the average boarding velocity dropped from around 20 passengers per minute to nearly nine passengers per minute. This decline is a result from increased hand luggage (HL), diverse airline service strategies on passenger boarding schemes, passenger anthropometrics and airport environment one contributing aspect that cannot be influenced by the aviation stakeholders are the passengers themselves. The passenger ratio of male and female air traveler changes, as well as their anthropometrics in terms of average weight and body size.

To better understand the scope of disruption problems, we need to take a closer look at their external and internal determinants.

### *Regulations and guidelines in place*

The regulatory framework for turnaround operations examines the procedures from an aircraft design point of view in the Certification Specification (CS) for large airplanes CS-24 and Federal Aviation Regulations (FAR) part 25 – airworthiness standards: transports category airplanes. From an operational perspective, guidelines can be found in the International Ari Transport Association (IATA) AHM, IATA Ground Operation Manual (IGOM), as well as the European Commission Regulations.

An aircraft should be staffed with one cabin crew member for every 50 passenger seats installed to ensure safe operation. The crew must be on board if passengers board or disembark, the aircraft should not be refueled. Otherwise necessary precautions must be taken to initiate a required evacuation of the aircraft. Before the departure, all hand luggage which is taken into the passenger cabin should be adequately and securely stowed.

The IATA AHM covers process specifications for passenger, baggage and cargo handling, and moreover serves as a guideline for aircraft loading and airside safety management. All aircraft operators should determine a ground time which is designed to meet operational requirements but should not compromise safety (AHM 021). In general, the potable water servicing should comply with the world health organization standards and the connectors shall be kept a certain distance away from the waste storage or treatment and toilet servicing equipment ( AHM 440, AHM 441). The IGOM delivers step-by-step procedures for each necessary handling task. Cabin baggage cannot be accepted if it is unsuitable due to its weight exceeds 32 kg (70 IB). Also, the incident reporting duty is highlighted, since aircraft damage can endanger passengers and employees, and the resulting disruptions could negatively impact sage airline operations. (Schmidt, 2017)

### *External Constraints:*

Apart from traditionally independent service providers like ATC and airports, the list of external suppliers is extending towards key operational activities – passenger handling, aircraft maintenance, IT and catering services shaping the quality and costs of airline output. Some of the most damaging disruption events in the past few years were linked with problems related to external service providers like ATC, airports and outsourced ground and IT services. They typically cause massive, days' long disruptions, affecting tens or even hundreds of thousands of passengers each time they occur.

### *Internal obstacles:*

Despite technological advances, accumulated industry knowledge, and simplification of business models, airlines generally do not have an organized system to track disruptions, their causes, costs, and the effects they have on revenue. Unforeseen changes cause many executives to accept a great deal of waste in operating cost – they may be hiring more staff than they need to support the unnecessary changes, overpay for faulty subcontracted services, operate a route network that is not synchronized with available resources or overprice their products, without being aware of their full financial consequences.

### *Self-induced and uncalculated disruption risks:*

A great number of airline operational irregularities are created internally during the process of strategic planning. Whenever an airline decides to expand its services to highly congested airports, operate a diversified fleet, introduce multiple maintenance and crew bases, overused capacities, increase airline dependency on outsourced services or decide to lay off its workforce, and is not aware of its operational capabilities, it increases the level of uncalculated business risks.

## 3.2. Maintenance

### 3.2.1. Maintenance Requirements

A station is an airport that an airline serves, and a leg has an origin station, a destination station, a departure time, and an arrival time. A route is a sequence of legs, and prior to each disruption, the aircraft is scheduled to fly a set of initial routes. Upon the realization of a disruption during which the initial aircraft routes become infeasible, ARO provides a new route for each aircraft. The new routes must comply with the airline's and the FAA's rules that require each aircraft to receive periodic maintenance service. A route that satisfies these rules is maintenance feasible.

Aircraft disruptions arise when a plane is not available to fly at least one of its assigned flight legs. Unscheduled maintenance problems and prolonged in-flight delays induce aircraft disruptions. Severe weather and airport congestion provoke station disruptions that reduce the number of landings and takeoffs allowed. In fact, weather accounts dor approximately 75% of airline disruptions (Dobbyn 2000).

Ground delay programs (GDPs) allocates arrival time periods, or slots, for each flight leg landing at a specific airport. Subsequently, the airlines could propose reassigning legs to the arrival slots. The primary advantage of a GDP is that those legs arriving at a disrupted airport are delayed prior to takeoff. Consequently, air traffic control (ATC) does not force the aircraft to circle the airspace of the disrupted airport, which endangers passengers and increases the cost of fuel and pilots. Since the introduction of GDPs, the FAA has removed most of the reassignment restrictions, and airlines will likely assign legs to slots freely within a few years.

Aircraft maintenance takes place in a series of checks of increasing diligence except for unscheduled fixes. The frequency of these checks depends on the combination of flight hours and number of take-off and landing cycles and may be performed at any site appropriately equipped. Because each aircraft type has different inventory requirement, little savings can be achieved by combining facilities for different fleets.

To be compliant with the Federal Aviation Administration constraints, some companies have adopted maintenance policies that call for routine inspections at least every four days. There are four major types of check mandated by the FAA that each aircraft must undergo. These vary in scope, duration, and frequency.(Clarke et al., 1997)

#### 3.2.1.1.Type A check

Type A checks involve inspection of all major systems such as landing gear, engines and control surfaces. The first major check (donated as Type A) mandated by the FAA occurs at every 65 flight-hours or about one a week. Check A periodical time can be retarded by the company if some predefined conditions have been recognized.  It is realized in a maintenance station on its route or main base of the airline, because it needs specific tools and equipment. In general, the processes of Check A are performed in a hangar, but rarely its can be performed on gate position or remote position. It takes between 3 and 6 hours depending on the aircraft scheduling planning.

#### 3.2.1.2.Type B check

The second major check (designated as Type B) is performed every 300-600 flight-hours and entails a thorough visual inspection plus lubrication of all moving parts such as horizontal stabilizers and ailerons. It is a control of the system and the components of aircraft more detailed than Check A. Now, the Check B interval is not used exactly in the maintenance program and its processes have been distributed to the Check A and Check C.

#### 3.2.1.3.Type C check

The Check C is the part that is named the “heavy checks”. This kind of checks is generally performed in low season to avoid the lack of tools that impact negatively the aircraft routing. The Check C is a high-level maintenance that puts the aircraft out of service. The maintenance can take between 3 days and one week according to aircraft types and maintenance hubs features.

#### 3.2.1.4.Type D check

The Check D is the heaviest check for an aircraft. It is approximately performed for all 4 or 5 years of service of aircraft, environ 16000-18000 flight hours, but it depends on the aircraft type and constructor instructions. It should be noted that this visit tends to disappear because it is much too heavy for the operators in the sense that the latter immobilizes the plane on the ground for at least four weeks. In this case, the different tasks are generally divided into other types of check.

## 3.3. Inventory Management

### 3.3.1. Fuel Management

Given is an aircraft route described in terms of the sequence of flight segments covering a certain horizon of interest. Each flight is defined by unique flight number, mileage, dynamic load, and expected fuel price at the origin airport. Given also is the net weight of the aircraft and the maximum capacity of its fuel tank. In addition, the aircraft fuel burn rate per mile as a function of the total aircraft weight at departure is assumed to be known. This fuel burn rate could vary with the flight plan designed for each flight. The objective is to determine the optimal amount of fuel to be loaded at each airport such that it minimizes the total fuel cost along the given aircraft route. Furthermore, the additional aircraft maintenance cost associated with flying with heavier fuel weight is minimized. In determining the optimal fuel ferrying pattern, several operational constraints are considered. First, the amount of fuel available in the aircraft fuel tank before the flight departure should be equal to or greater than the amount of fuel required for this flight. Second, the extra amount of fuel loaded at an airport must be within a certain threshold. This limits the amount of extra fuel loaded at each airport and ensures that the aircraft total weight is not dramatically increased because of the extra fuel. Third, a considerable portion of the amount of fuel used by a flight should be loaded at its origin airport. This ensures that the fuel demand is uniform along the different airports in the aircraft route. Fourth, the aircraft weight before taking off and before landing should be within the allowed limits specified by the aircraft manufacturer. Finally, the amount of fuel to be loaded into the aircraft should be less than the capacity of its fuel tank. It is assumed that there are no constraints on the amount of fuel that can be purchased from a single vendor or from a single airport. (Abdelghany et al., 2005)

### 3.3.2. Components Inventory Management

To maximize aircraft utilization, the most critical functions in aircraft are designed to be quickly repairable so that there is a collection of compact functional components that can easily be replaced between flights if necessary. Every time a failed component is removed from an aircraft, a similar functional component should cause the demand for a spare unit in the spares supply.

After being removed from an aircraft the failed component is sent to a workshop. Depending on the reason for its removal, many MRO operations are performed on it. When it is fully functional, it is certified and sent back to spares supply. With the certification, the component becomes airworthy, i.e. it can be installed in an aircraft. Spare units are identical in function to units installed in the aircraft but have an insurancelike role compared to the revenue generating role of the installed units. In time, installed units fail and the roles change and, if the rotation is working well, all the units take turns in being in revenue generating role and being a spare.

## 3.4. Staffing Management

The line maintenance scheduling problem consists of a staffing decision and a rostering decision. As mentioned earlier, shifts are assigned to teams in cycles instead of individuals in our problem. The staffing decision entails the determination of the team sizes, while the rostering decision concerns the definition and timing of the shifts. A workforce schedule is, in fact, the result of the combination of multiple sub schedules, called cycles. Each cycle is defined by its team size, a number of week, shift definitions and shift sequence. Teams may vary in size; depending on the cycle have equal team sizes. A cycle can be seen as a number of consecutive weeks. The number of weeks in a cycle is equal to the number of teams to whom the cycle applies. The number of week in a cycle is also equal to the number of shift sequences that can be fulfilled by the teams working in the cycle. In one particular week, each team of the cycle will execute on specific shift sequence.

In examining human error that may occur within the maintenance arena, several key issues can be identified.

- The first involves shortcomings in the detection of critical cues regarding the state of the aircraft or subsystem. Several accidents have been traced to metal fatigue or loose and missing bolts that should have been visible to maintenance crews. Incidents exist of aircraft being complete repairs. Frequent errors include loose objects left in aircraft, fuel and oil caps missing or loose, panel and other parts not secured, and pins not removed.
- Often, even when important information is perceived, there may be difficulties in properly interpreting the meaning or significance of that information. While the symptoms may be observed correctly, a significant task remains in properly diagnosing the true cause of the failure. While not much data exists regarding the impact of misdiagnoses of this type, there is a significant increase in the probability of an accident occurring when the aircraft undertakes the next flight with the faulty system still aboard.
- Problems in properly detecting the state of the system and diagnosing or interpreting cues that are perceived are compounded by the fact that many different individuals may be involved in working on the same aircraft. In this situation, it is very easy for information and tasks to fall through the cracks. The

presence of multiple individuals heightens the need a clear understanding of responsibilities and good communications between individuals to support the performance of shared tasks.

- In addition to the need for intra-team coordination, a significant task for maintenance crews is the coordination of activities and provision of information across teams to those on different shifts or in different geographical locations.

### 3.5. Fault Diagnosis

During the phase of problem detection in maintenance, cognitive errors became an issue. An existing problem can be misclassified as "System OK" (Type 1 Error) – or a part that meets specifications can be wrongly classified as dysfunctional (Type 2 Error). The occurrence of Type 1 error can decrease the safety of an aircraft because the undetected or misclassified problem can cause an incident in flight. A type 2 error can increase the likelihood of delay because the maintenance crew will have to address a non-existent problem. Other types of errors can occur during maintenance operations, e.g. the use of a wrong part or damaging other parts of the LE system. These errors are not considered specifically in our illustration, which is limited to failures to identify and address existing problems.

Faults may occur in any component of the system, or in the connections or interfaces between system components. As already stated these faults fall into two main categories: random hardware failures, assumed to occur with a constant random failure rate, common mode failures (including specification and design errors).

It is important to recognize the existence of these two types of failure. A single random hardware failure will affect only one component or element of the system whereas a common mode failure may affect only one component or element of the system whereas a common mode failure may affect more than one component or element. This is of great significance when considering the use of redundancy.

Current standard practice for airplane maintenance is a three-step process. First, a problem is identified and reported by the flight crew by means of a pilot report ("pilot's write-up"). Second, once the plane arrives at an airport, troubleshooting ("verification") is performed on the reported problem. Third, problems that have been confirmed are repaired.

All pilot reports are communicated to the flight's destination airport and a local maintenance crew is informed. If a maintenance crew is available when the plane lands, they inspect the plane and confirm or not the pilot's write-up. Any confirmed problem is the classified into "deferrable" or "not deferrable".

A key issue in the management of unplanned maintenance operations is to ensure the safety of airplane while keeping delays to an acceptable level. It is thus useful to assess the effect of maintenance decisions on flight delays and on the risk of an in-flight incident. Whereas it is generally assumed that an airplane satisfies regulatory or company requirements have a zero probability of an accident, the fact is that combinations of rare events, errors and undetected departures from rules do rarely, but occasionally, cause a plane crash. Reliability data are usefuls to check that proper working requirements are satisfied. (Sachon and Paté-Cornell, 2000)

# 4. AGENT BASED MODEL

## 4.1. Introduction

Performing an agent based system that solves the aircraft maintenance routing problem by combining the solutions of the subproblems of the problem can improve the profit in airlines' decision processes without creating complex optimization programming which has at least polynomial algorithmic complexity to solve. Airline operation managers are working for handling problems both of airside and landside of airports and taking decision in real time is too important for avoiding flight delay, flight cancellation, decrease on demand etc. In this project, we aimed to design an agent based model that partially solve aircraft maintenance management problems and integrate them to support to decision makers for making more profitable decision for airlines.

Aircraft maintenance management compromises 4 major problems for operations that are solved by airline/airport operation management units. We have created an agent for separately solving each problem (maintenance, staffing, inventory, fault diagnosis), and an agent for integrating these agents and for supporting to decision makers (See Figure 4.1 Agent Based Design ) Each agent will be described in the following sections one by one.

### 4.1.1. Operation Management Agent

The operation management agent manages the other entire agents for supporting the deciders about aircraft maintenance management problems such as predicting unscheduled maintenance, performing unscheduled maintenance, and scheduling maintenance by satisfying maintenance requirement, managing stock, allocating staff to maintenance etc. In the first step, the agent does not learn user habits, but in the near future, the agent will learn the user habit and decide without user help. Because the aim of this study is to automatize the aircraft routing problem for avoiding aircraft crash caused by human error.

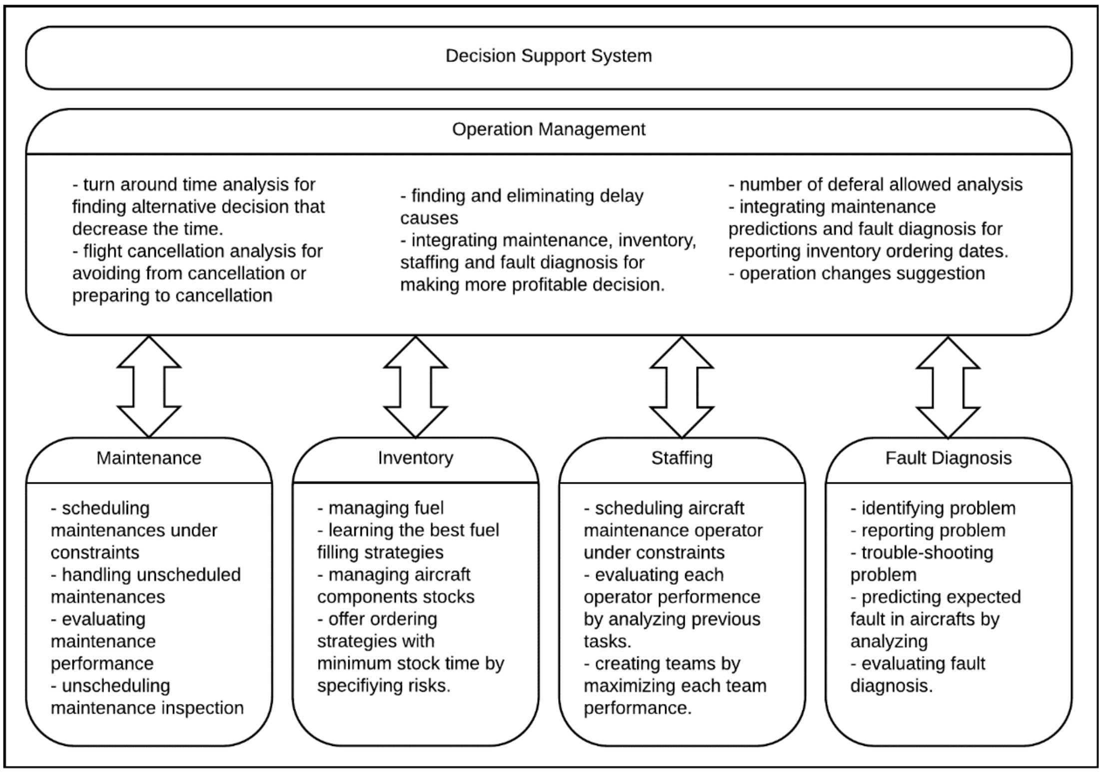

Figure 4.1 Agent Based Design

### 4.1.2. Maintenance Agent

There is two types of maintenance in the aircraft maintenance management. First, the scheduled maintenance that is programmed at least two weeks in advance for satisfying air traffic authorities' constraints such as IATA and FAA. Second, the unscheduled maintenance, which is not programmed, happens in an unpredictable way.

In general, the airline cannot perform their scheduled maintenance program due to changes in operations. The aim of the maintenance agent is to handle the changes in operations by minimizing the lost according to changes. We assumed that the all flights have been scheduled according to different fleet type in advance. The maintenance agent has three different functions to perform, and in the following part, we will explain the processes which are performed by the maintenance agent.

***Scheduled Maintenance:***

One of the main tasks of the maintenance agent is to schedule maintenance mandated by FAA or IATA (or local aviation admiration) by considering airline marketing department flight scheduling in terms of passenger demands. The maintenance agent should schedule maintenance by considering hub and spoke distribution paradigm. Each aircraft should return to first takeoff airport (or another hub station) to satisfy maintenance requirement. This model can be represented by a Eulerian graph which is a directed graph having connected nodes which have in-degree equal to out-degree. A Euler tour of a Eulerian digraph is cycle that includes all the arcs (in our case, flight, and ground arcs) exactly once. Our aim is to find an Euler tour that maximizes value and satisfies maintenance constraints when scheduling maintenance. We are using (Clarke et al., 1997) maintenance rotation model as an example due to confidential issues on CIMPA's own model.

*Parameters:*

$N$ : An Eulerian digraph

$A$ : Sequence of arcs which represent $N$

$i_n$ : An arc of the sequence A as $\epsilon \{1, 2, \ldots, |A|\}$ :

Such that: - $i_k$ and $i_{k+1}$ are adjacent for $k \epsilon \{1, 2, \ldots, |A|\}$

- $i_{|A|+1} = i_1$

$j_n$ : An arc of the sequence A as $n \epsilon \{1, 2, \ldots, |A|\}$

If $i$ and $j$ are adjacent, we assume that there is a connection from $i$ to $j$ donated $i \rightarrow j$.

$h(i)$ : Head node of arc $i \in A$

$t(i)$ : Tail node of arc $i \in A$

$K$ : Set of maintenance type

$P^k$ : Set of minimal violation paths for maintenance type $k \in K$

$P'$ : Set of arcs of $P \in P^k$ excluding the last arc

$f(i)$ : Follower of $i \in P'$

*Decision Variables:*

$x_{ij}$ : Decision variable of connection $i \in A$ to $j \in A$

$$x_{ij} = \begin{cases} 1 & if\ i \rightarrow j \\ 0 & otherwise. \end{cases}$$

Such that: - $h(i) = h(j)$ and $j \neq i$

*The aircraft rotation problem model:*

Objective function:

$$Maximize\ \sum_{(i,j)\in C} v_{ij} x_{ij} \tag{1}$$

Subject to:

$$\sum_{j:h(i)=t(j),j\neq i} x_{ij} = 1 \text{ for all } i \in A. \tag{2}$$

$$\sum_{i:h(i)=t(j),j\neq i} x_{ij} = 1 \text{ for all } j \in A. \tag{3}$$

$$\sum_{i\in S,j\in A\setminus S\ s.t.\ h(i)=t(j)} x_{ij} \geq 1 \text{ for all } S \subset A. with\ 2 \leq |S| \leq |A| - 2 \tag{4}$$

$$\sum_{i\in P',j\in A\setminus f(i)\ s.t. h(i)=t(j)} x_{ij} \geq 1\ \ \forall P \in P^k, k \in K \tag{5}$$

### *Unscheduled Maintenance*

The aim of unscheduled maintenance process of the maintenance agent is to manage the airport operation when non-deferral faults have been reported in aircraft (Figure 4.2 Unscheduled Maintenance Operations). This management process contains tasks such as available operation crew management, passenger ingress – egress, components management, aircraft maintenance. Also, the agent should find all possible solution for minimizing flight delay such as canceling flight, accepting the delay, and swapping aircraft.

### *Unscheduled Maintenance Prediction*

The unscheduled maintenance prediction examines aircraft troubles that occur periodically. Aircraft, which generally fly in the same line of flight between arrivals to the destination point, can get out of order according to aircraft information such as similar weather conditions, total flight hours of aircraft, the total number of takeoff and landing etc.

The first task of the agent on unscheduled maintenance prediction is to classify fleets according to similar / not similar flight information for better understanding the periodicity of aircraft troubles due to flight conditions. After this task, the agent should study on the periodicity of aircraft fault one by one by considering the aircraft classification. If there is a periodicity on a fault, the agent will add a fault diagnosis check one of the hangar maintenance processes which is before the nearest date to the period of the fault of each aircraft. Also, the agent will inform to organization agent for requesting an update of the inventory due to the period of the fault.

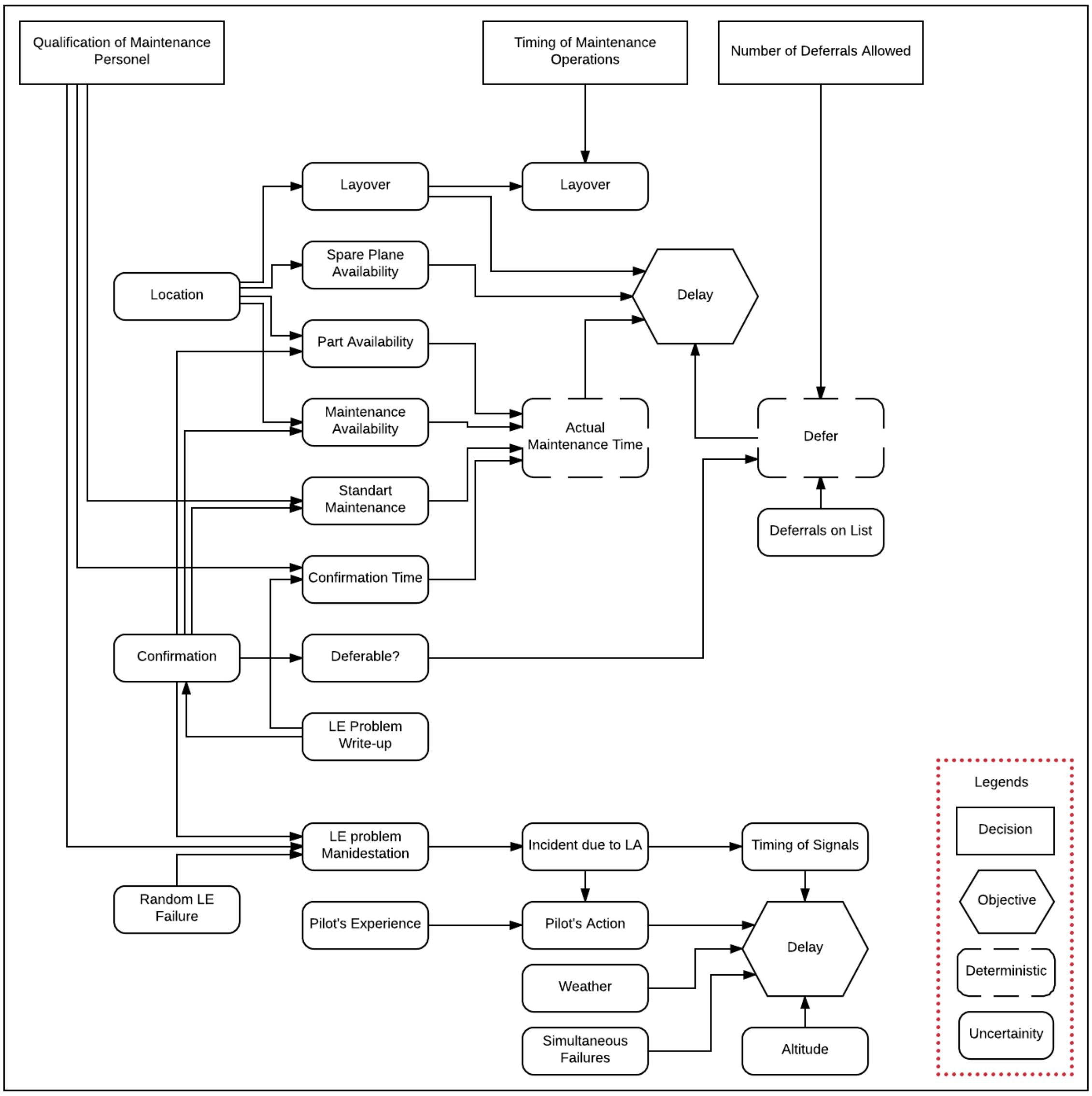

Figure 4.2 Unscheduled Maintenance Operations

### 4.1.3. Inventory Management Agent

Two different type of service exists in inventory management of turnaround process named fuel management and aircraft component inventory management. In this study, we will focus on the aircraft component inventory management because our problem is related to aircraft routing, and the fuel management has no relation to the aircraft maintenance process except its effect on turnaround time.

The aim of inventory management agent is to order necessary aircraft components by minimizing the time of staying in stock. This agent uses two sources for deciding ordering time. One of them is coming from the unscheduled maintenance prediction task of the maintenance agent. The inventory agent will use this information by merging with the second source that has been created by itself by analyzing previous orders' information. The agent will use the supervised learning method for determining the order timing by minimizing it.

### 4.1.4. Staffing Management Agent

Staffing management is important for performing necessary maintenance tasks just in time. The staffing management agent aims to create teams by satisfying certified worker constraints and by homogeneously assigning workers to teams according to their experience level. The staffing management is responsible to decide that the airline company needs how many maintenance operations considering its fleet and flight density of the company. The agent uses classical research operation model for creating team and supervised learning method for classifying workers according to their experience levels.

## 4.2. Agent Planning

### 4.2.1. Operation Management Agent

The operation management agent aims to help decision to operation manager about the aircraft maintenance management problems. The agent will manage all different agents according to the situation on the flights and in the airports due to maintenance. This agent does not aim to decide all alone, its goal to find all relevant information for deciding better for now.

The agent is described in the following figure in STRIPS languages (See Figure 4.3 Decision Support System Description). The operation management agent (OA) has not the information about airline's aircraft, fleets, staffs, aircraft component stocks, pre scheduled aircraft routing (PAR), maintenance requirement (MR) and order history. The aim of the agent is to send necessary information to the responsible employee for deciding better in real time. The final state of the agent is to send information about maintenance cost, aircraft swapping cost, canceling flight cost, accepting delay cost, maintenance history, maintenance and their periods, fleet classification, staff allocation to maintenance, free teams for performing unscheduled and un predicted maintenance to operation management department. Also, the agent should send component to order for stocking with their order periods and their risks on the periods.

The agent has 5 order actions for ordering to the other agents about their tasks. When an aircraft had the no go status, the agent order to maintenance agent (MA) about handling unscheduled maintenance (HUM). When necessary maintenance and fleet information is created by the other action, the agent may order to the maintenance agent (MA) about the predicting unscheduled maintenance (PUM). One of the other order actions is about to order from the operation management agent (OA) to maintenance agent (MA). The inventory management agent (IMA) has the order from the operation agent about managing inventory (MI) with the order action, and the last order action is about to order from the operation management agent to the staffing management agent (SMA) about allocation staffs (AS) to maintenance. Send, get, send data, and get data actions are for creating a relation between agents, and also between operation management agent and users.

We mentioned that the aircraft may continue to the following flight if the occurred fault is in GO status, and if the fault is NO GO status the aircraft cannot continue the following flight without being maintained. The operation management agent controls the aircraft fault for understanding the fault status (GO/NO GO) with check action. With report action, aircraft is reported about its fault by pilots, aircraft diagnosis system and aircraft operation.

```
$Init(Connect(User, OA) \wedge \neg Have(Aircrafts) \wedge \neg Have(Fleets)$
        $\wedge \neg Have(Stocks) \wedge \neg Have(Crews) \wedge \neg Have(PAR) \wedge \neg Have(MR)$
        $\wedge \neg Have(Order\ History))$
$Goal\ (Send(Operation, Maintenance\ Cost) \wedge Send(Operation, Accepting\ Cost)$
        $\wedge Send(Operation, Cancelling\ Cost)$
        $\wedge Send(Operation, Swapping\ Cost)$
        $\wedge Send(Operation, Maintenance\ History)$
        $\wedge Send(Operation, Periods, Maintenance)$
        $\wedge Send(Operation, Fleet\ Classification)$
        $\wedge Send(Operation, Team, Maintenance)$
        $\wedge Send(Operation, Free\ Team)$
        $\wedge Send\ (Purchasing\ Department, Component, Period, Risks))$

Action (Get Data (User, Fleets, Aircrafts, Stocks, Crews)),
  PRECOND: $Connect\ (User, OA) \wedge \neg Have(Fleets)$
        $\wedge \neg Have(Aircrafts) \wedge \neg Have(Stocks) \wedge \neg Have(Crews)$
  EFFECT: $Have(Fleet) \wedge Have(Aircrafts)$
        $\wedge Have(Stocks) \wedge Have(Crews)$

Action (Report (Pilot, Aircraft)),
  PRECOND: $Have(Aircraft, Fault)$
  EFFECT: $Reported(Aircraft)$

Action (Report (Aircraft Diagnosis System, Aircraft)),
  PRECOND: $Have(Aircraft, Fault)$
  EFFECT: $Reported(Aircraft)$

Action (Report (Airport Operation, Aircraft)),
  PRECOND: $Have(Aircraft, Fault)$
  EFFECT: $Reported(Aircraft)$

Action (Check (Deferrals, Aircraft)),
  PRECOND: $Have(Aircraft, Fault) \wedge Reported(Aircraft)$
  EFFECT: $Continue(Flight) \uparrow Order(OA, MA, HUM)$

Action (Check (Deferrals, Fault)),
  PRECOND: $Have(Aircraft, Fault) \wedge Reported(Aircraft)$
  EFFECT: $Set(Aircraft, GO) \uparrow Set(Aircraft, NO\ GO)$

Action (Send Data (MA, Aircraft, Stock, Operation Crew, Flight)),
  PRECOND: $Ordered\ (OA, MA, HUM) \wedge Have(Aircraft) \wedge Have(Stock)$
        $\wedge Have(Flight) \wedge Have(Crew)$
  EFFECT: $Send(MA, Aircraft) \wedge Send(MA, Stock) \wedge Send(MA, Flight)$
        $\wedge Send(MA, Operation\ Crew)$

Action (Send (User, Swapping Cost, Accepting Cost, Cancelling Cost)),
  PRECOND: $Have(Accepting\ Cost)$
        $\wedge Have(Cancelling\ Cost) \wedge Have(Swapping\ Cost)$
  EFFECT: $Send(User, Accepting\ Cost)$
        $\wedge Send(User, Cancelling\ Cost) \wedge Send(User, Swapping\ Cost)$
```

*Action (Order (OA, MA, HUM)),*
PRECOND: *Set (Aircraft, NO GO)*
EFFECT: $Ordered(OA, MA, HUM)$

*Action (Fault (Aircraft)),*
PRECOND: *Have (Aircraft)*
EFFECT:$Have(Aircraft, Fault)$

*Action (Send (Operation, Maintenance History)),*
PRECOND: *Have (Maintenance History)*
EFFECT: $Send(Operation, Maintenance\ History)$

*Action (Send (Operation, Maintenance Cost)),*
PRECOND: *Have (Maintenance Cost)*
EFFECT: $Send(Operation, Maintenance\ Cost)$

*Action (Get Data (Marketing Department, PAR, MR)),*
PRECOND: $\neg Have\ (PAR) \land \neg Have\ (MR)$
EFFECT: $Have\ (PAR) \land Have\ (MR)$

*Action (Order (OA, MA, SM)),*
PRECOND: $Have\ (Fleet) \land Have\ (PAR) \land Have\ (MR)$
EFFECT: $Send\ (MA, Fleet) \land Send\ (MA, PAR) \land Send(MA, MR)$

*Action (Get Data (MA, Scheduled Maintenance, Cost)),*
PRECOND: $Send\ (MA, Fleet) \land Send\ (MA, PAR) \land Send(MA, MR)$
EFFECT: $Have(Scheduled\ Maintenance) \land Have(Maintenance\ Cost)$

*Action (Filter (Scheduled Maintenance)),*
PRECOND: $Have(Scheduled\ Maintenance)$
EFFECT: $Have(Maintenance\ Schedule) \land Have(Flight\ Information)$

*Action (Order (OA, MA, PUM)),*
PRECOND: $Have\ (Flight\ Information) \land Have\ (Maintenance\ Information)$
$\land Have\ (Fleets)$
EFFECT: $Send(OA, Flight\ Information) \land Send(OA, Maintenance\ Information)$
$\land Send(OA, Fleets)$

*Action (Get (Periods Unscheduled Maintenance, Fleet Classification)),*
PRECOND: $Send(OA, Flight\ Information) \land Send(OA, Maintenance\ Information)$
$\land Send(OA, Fleets)$
EFFECT: $Have(Unscheduled\ Maintenance\ Predictions)$
$\land\ Have(Periods, Maintenance) \land Have(Fleet\ Classification)$

*Action (Send (Operator, Periods, Maintenances, Fleet Classification)),*
PRECOND: $Have(Periods, Maintenance) \land Have(Fleet\ Classification)$
EFFECT: $Send(Operation, Periods, Maintenances)$
$\land Send(Operation, Fleet\ Classification)$

```
Action (Get Data (Purchasing Department, Orders)),
   PRECOND: ¬ Have (Order History)
   EFFECT: Have(Order History)

Action (Order (OA, IMA, MI)),
   PRECOND: Have(Order History) ∧ Have(Unshceduled Maintenance Prediction)
   EFFECT: Send(IMA, Order History)
                ∧ Send(IMA, Unshceduled Maintenance Prediction)

Action (Get Data (IMA, Component Periods, Risks)),
   PRECOND Send(IMA, Order History)
                ∧ Send(IMA, Unshceduled Maintenance Prediction)
   EFFECT: Have (Component, Period, Risks)

Action (Send (Purchasing Department, Component, Period, Risks)),
   PRECOND: Have (Component, Period, Risks)
   EFFECT: Send (Purchasing Department, Component, Period, Risks)

Action (Order (OA, SMA, AS)),
   PRECOND: Have(Unscheduled Maintenance Predictions)
                ∧ Have(Maintenance Shedule) ∧ Have(Staff Information)
   EFFECT: Ordered (OA, SMA, AS)

Action (Get Data (SMA, Staff Allocation, Free Team)),
   PRECOND: Ordered (OA, SMA, AS)
   EFFECT: Have(Team, Maintenance) ∧ Have(Free Team)

Action (Send Data (Operation, Staff Allocation, Free Team)),
   PRECOND: Have(Team, Maintenance) ∧ Have(Free Team)
   EFFECT: Send(Operation, Team, Maintenance) ∧ Send(Operation, Free Team)

Action (add (Maintenance Info, Maintenance History)),
   PRECOND: Have(Maintenance Info)
   EFFECT: Have (Maintenance History)


Action (Get Data (MA, Maintenance Info, Cancelling Cost, Swapping Cost, Accepting Cost),
   PRECOND:  Ordered (OA, MA, HUM)
   EFFECT: Have(Maintenance Info) ∧ Have(Accepting Cost)
                ∧ Have(Cancelling Cost) ∧ Have(Swapping Cost)
```

Figure 4.3 Decision Support System Description

The operation management agent planning (See Figure 4.4 Decision Support System Planning) starts with the initial state previously described. Firstly, the agent gets necessary information from the user, purchasing department and marketing department. After, if an aircraft has a fault and it has a NO GO status, the agent orders to maintenance agent about handling unscheduled maintenance task. The results of this order are canceling flight cost, accepting delay cost, swapping aircraft cost, and maintenance information. The agent sends them to the operation management department in order that the operation manager can decide which option accords to the company policies. After the maintenance was performed, the agent adds the maintenance information to the maintenance history and sends it to operation management department. In the same time, the agent schedules maintenance mandated by the aviation authorization by getting pre-scheduled aircraft routing and maintenance information from the marketing department and fleet information from the user. In the following action, the agent finds necessary maintenance information such flight and maintenance scheduling by filtering the scheduled maintenance information. Until this moment, the agent produces necessary maintenance information for predicting unscheduled maintenance in previous actions, so that the agent orders to the maintenance agent about the prediction of unscheduled maintenance. After these actions, the agent order to the inventory management agent for calculating components' order periods and their risks, and send them to the purchasing department for helping them to decide ordering time by considering company policies.

When maintenance is scheduled or an unscheduled maintenance is predicted, the agent order to the staffing management agent about allocating staffs to the teams and allocating teams to the maintenance. Finally, the agent sends all created information to the necessary users such as operators and purchasing department.

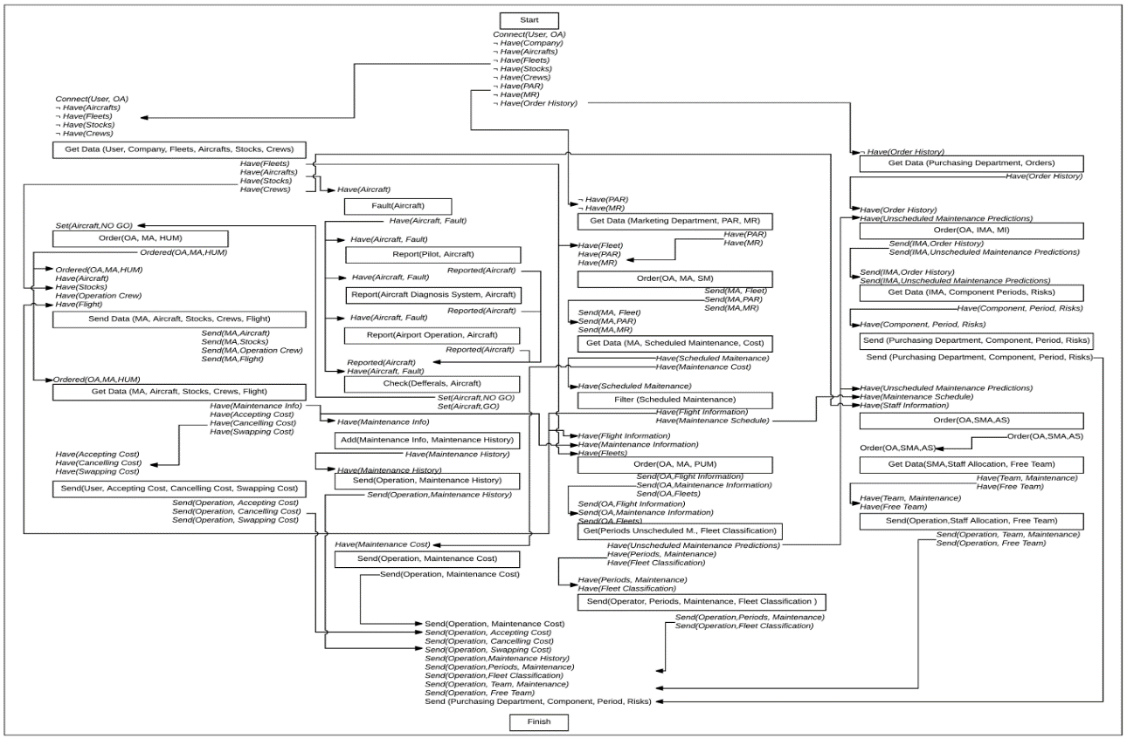

Figure 4.4 Decision Support System Planning

### 4.2.2. Maintenance Agent

Maintenance agent has three tasks to perform that have been described in previous part. The aim of the maintenance agent is to realize the organization agent order based on maintenance processes. These tasks are:

Schedule Maintenance (SM),

Handle Unscheduled Maintenance (HUM).

Predict Unscheduled Maintenance (PUM)

***"Schedule Maintenance" Planning***

The scheduled maintenance problem is aiming to schedule maintenance by using pre-scheduled flight data and necessary maintenance requirement as mentioned previous section.

For beginning to schedule maintenance, it is necessary to provide an order about maintenance scheduling(SM) from operation agent (OP) to maintenance agent (MA), and the maintenance agent must not have the data about the fleet, the pre-scheduled aircraft routing and maintenance requirement (See Figure 4.5 Maintenance Scheduling Problem Description).

*Init*$(Order\ (OA, MA, SM) \wedge\ \neg Have(Fleet) \wedge \neg Have(PAR) \wedge \neg Have(MR))$
*Goal* $(Have(OP, Scheduled\ Maintenance) \wedge Have(OA, Cost, Fleet))$

*Action (Get Data (OA, Fleet, PAR, MR)),*
PRECOND: $Order\ (OA, MA, SM) \wedge\ \neg Have(Fleet) \wedge \neg Have(PAR) \wedge \neg Have(MR)$
EFFECT: $Have(Fleet) \wedge Have(PAR) \wedge Have(MR)$

*Action (Solve Scheduling Problem (Fleet, PAR, MR)),*
PRECOND: $Have(Fleet) \wedge Have(PAR) \wedge Have(MR)$
EFFECT: $Have(Scheduled\ Maintenance) \wedge Have(Cost, Fleet)$

*Action (Send Data (OA, Fleet, Scheduled Maintenance, Cost)),*
PRECOND: $Order\ (OA, MA, SM) \wedge\ Have(Scheduled\ Maintenance) \wedge Have(Cost, Fleet)$
EFFECT: $Have(OP, Scheduled\ Maintenance) \wedge Have(OA, Cost, Fleet)$

Figure 4.5 Maintenance Scheduling Problem Description

The get data action aims to get the fleet, the pre-scheduled aircraft routing, and the maintenance requirement information from operation agent (OA). There is a condition for this action such as getting an order from OA to MA about SM, do not have fleet, PAR, and MR information. Scheduling problem-solving action aims to solve the problem by using cost maximization model. The last action named Send Data aims to send the result to an operational agent.

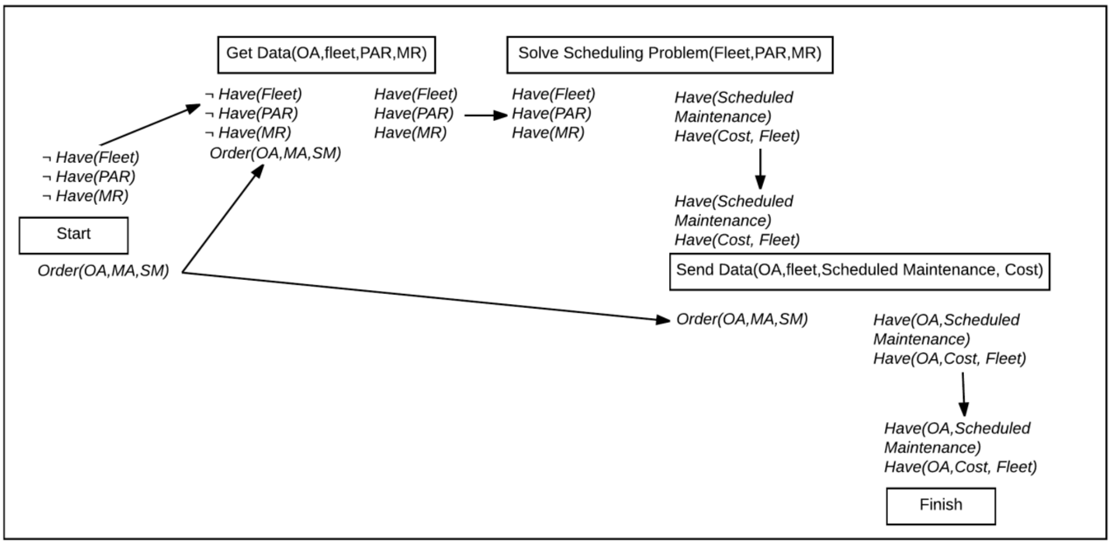

Figure 4.6 Solution of the Maintenance Scheduling Problem

The planning of the scheduled maintenance task is being solved by using POP algorithm (See Figure 4.6 Solution of the Maintenance Scheduling Problem). The maintenance agent follows the actions in the following order for scheduling maintenance with operation agent order:

$$Start\ >\ Get\ Data\ >\ Solve\ Scheduling\ Problem\ >\ Send\ Data\ >\ Finish$$

### *“Handle Unscheduled Maintenance” Planning*

The most important aim of maintenance agent for handling unscheduled maintenance is to maintain the aircraft without any flight delay. If there is a possible flight delay the maintenance agent should list the available solutions such as swapping aircraft, canceling the flight and accepting delay for avoiding lost due to a flight delay. The decision on the flight due to unscheduled maintenance can change according to airline company policies. So that, the maintenance agent calculates costs of changing aircraft, canceling flight and accepting delay with maintenance information to the operation agent which aims to support to decisions of operation managers.

The agent does not have aircraft, stock and flight information about reported aircraft in the initial state. The agent’s goal is to send information to the operation agent about swapping aircraft cost, canceling flight cost, accepting delay cost, and aircraft maintenance information. The action such as inspection of aircraft for finding the problem, investigating the problem for finding broken components, controls stock for broken components, allocation available maintenance operators or waiting for available maintenance operators, maintaining aircraft and sending information to the operation agent. The description of the unscheduled maintenance process done by the maintenance agent can be seen in the following figure in STRIPS language (See Figure 4.7 Unscheduled Maintenance Problem Description).

```
$Init(\ Order\ (OA, MA, HAM) \land \neg Have(Aircraft) \land \neg Have(Stock) \land \neg Have(Flight)\ )$
$Goal\ (\ Send(OA, Maintenance\ Infos) \land Send(OA, Accepting\ Cost)$
                    $\land Send(OA, Cancelling\ Cost) \land Send(OA, Swapping\ Cost))$

Action (Get Data (OA, Aircraft, Stock, Operation Crew, Flight)),
   PRECOND: $Order\ (OA, MA, HAM) \land \neg Have(Aircraft) \land \neg Have(Stock)$
                    $\land \neg Have(Flight)$
   EFFECT: $Have(Aircraft) \land Have(Stock) \land Have(Flight)$

Action (Inspect (Aircraft)),
   PRECOND: $Have(Aircraft) \land \neg Find(Problem)$
   EFFECT: $Find(Problem)$

Action (Investigate (Problem)),
   PRECOND: $Find(Problem)$
   EFFECT: $Find(Broken\ Aicraft\ Components) \land Have(Maintenance\ Procedure)$

Action (Allocate Crew (Operation Crew, Aircraft))
   PRECOND: $Have(Operation\ Crew) \land Have(Maintenance\ Procedure)$
                    $\land InStock(Broken\ Aicraft\ Components) \land Have(Aircraft)$

   EFFECT: $Allocated(Operation\ Crew, Aircraft)$
                 $\uparrow (\neg Allocated(Operation\ Crew, Aircraft) \land Wait(time))$

Action (Control Stock (Broken Aircraft Components)),
   PRECOND: $Find(Broken\ Aircraft\ Component)$
   EFFECT: $InStock(Broken\ Aicraft\ Components)$
                $\uparrow (\neg InStock(Broken\ Aicraft\ Components)$
                    $\land StockingTime(Broken\ Aircraft\ Components))$
Action (Calculate Canceling Cost (flight))
   PRECOND: $Have(Flight) \land Allocated(Operation\ Crew, Aircraft)$
                    $\land Delay(time) \land Have(Maintenance\ Procedures)$
   EFFECT: $Cancellation\ Cost(Flight)$

Action (Calculate Swapping Cost (flight))
   PRECOND $Have(Flight) \land Allocated(Operation\ Crew, Aircraft)$
                    $\land Delay(time) \land Have(Maintenance\ Procedures)$
   EFFECT: $Swapping\ Cost(Flight)$

Action (Calculate Accepting Cost (flight))
   PRECOND: $Have(Flight) \land Allocated(Operation\ Crew, Aircraft)$
                    $\land Delay(time) \land Have(Maintenance\ Procedures)$
   EFFECT: $Accepting\ Cost(Flight)$
```

*Action (Realize (Maintenance Procedure)),*
PRECOND: $InStock(Broken\ Aicraft\ Components) \wedge Have(Maintenance\ Procedure)$
$\wedge\ Allocated(Operation\ Crew, Aircraft)$
EFFECT: $Maintained(Aircraft)$

*Action (Reallocate Crew (Operation Crew, Aircraft))*
PRECOND: $\neg Allocated(Operation\ Crew, Aircraft) \wedge Wait(time)$
EFFECT: $Allocated(Operation\ Crew, Aircraft)$

*Action (Stocking (Broken* $Aircraft\ Component$*)),*
PRECOND: $\neg InStock(Broken\ Aicraft\ Components) \wedge Stocking(Time)$
EFFECT: $InStock(Broken\ Aicraft\ Components)$

*Action (Send Data (OA, Aircraft, Flight)),*
PRECOND: $Maintained(Aircraft) \wedge Cancelling\ Cost(Flight)$
$\wedge\ Accepting\ Cost(Flight) \wedge Swapping\ Cost(Flight)$
EFFECT: $Send(OA, Maintenance\ Infos) \wedge Send(OA, Accepting\ Cost)$
$\wedge\ Send(OA, Cancelling\ Cost) \wedge Send(OA, Swapping\ Cost)$

*Action (Calculate Delay (Maintenance)),*
PRECOND: $Allocated(Operation\ Crew, Aircraft) \wedge Have(Maintenance\ Procedure)$
$\wedge\ Wait(Time) \wedge StockingTime(Aircraft\ Broken\ Components)$
EFFECT: $Delay(time)$

**Figure 4.7 Unscheduled Maintenance Problem Description**

Unscheduled maintenance planning solution begins with the getting aircraft, flight and operation crew data from the operation agent. After getting these data, the agent inspects aircraft for finding the problem. The inspection of aircraft can be done by pilots, aircraft problem inspection system or visual checks. Then, the agent will investigate the problem for determining the broken component in aircraft which is the cause of the problem. Controlling the stock due to broken components is important after investigating problem because the stock affects the maintenance time. Also, the maintenance time can change due to allocated maintenance personnel so that the agent allocates the maintenance crew to the aircraft for realizing the maintenance procedure after investigating the problem. If there is not any available maintenance crew the maintenance procedure should wait until a crew is available. After this step, the agent will calculate delay time by considering the operation crew performance and availability, the flight information, maintenance procedure, and stocking time of not in stock aircraft component.  After calculating this delay, in any case, the aircraft should be maintained so that the agent will consider in that manner. At the final step, the agent will calculate the canceling flight cost, swapping aircraft cost, accepting delay cost, and maintenance information and send them to operation agent (See Figure 4.8 Unscheduled Maintenance Problem Solution).

For calculating the canceling cost, the agent should consider following the flight of the aircraft, airport fares, and effect on demand of the cancellation. When swapping aircraft the agent will consider swapped flight delay and profit. Also, the agent calculates the accepting delay cost according to following flight, airport fares and effect on the demand.

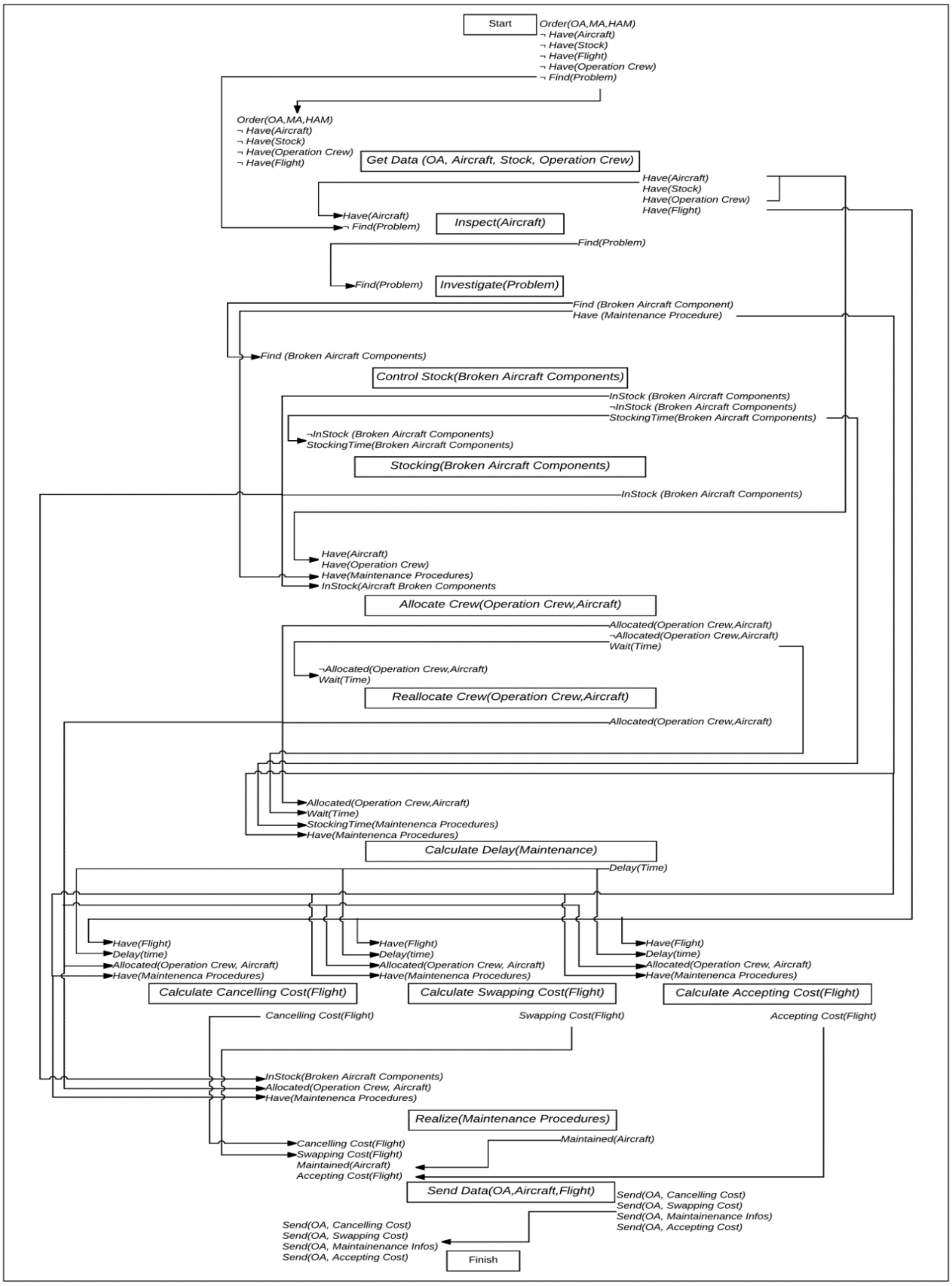

Figure 4.8 Unscheduled Maintenance Problem Solution

### "*Predict Unscheduled Maintenance" Planning*

There exist some periodical unscheduled faults in aircraft according to similar flight conditions. The maintenance agent aims to predict this unscheduled maintenance by analyzing previous unscheduled maintenance processes. In the initial state, the agent does not have fleet, flight, and maintenance information of all aircraft of the company. The goal state of agent for predicting unscheduled maintenance planning is to send the founded a period of maintenance in a classified fleet. The agent has actions such as getting data, classifying fleets, getting maintenance according to the fleet, analyzing periodicity and sending periodicity information to operation agent for performing this planning. In the following figure, the predicting unscheduled maintenance description can be seen (See Figure 4.9 Predict Unscheduled Maintenance Description).

$Init(Order\ (OA, MA, PUM) \land\ \neg Have(Fleet) \land \neg Have(Flight\ Information)$
$\land \neg Have(Maintenace\ Information))$
$Goal\ (Send(OA, Periods) \land Send(OA, Periodic\ Unscheduled\ Maintenance$
$\land Send(OA, Classified\ Fleet)))$

*Action (Get Data (OA, Fleet, Maintenance Information, Flight Information)),*
PRECOND: $Order\ (OA, MA, PUM) \land\ \neg Have(Fleet)$
$\land \neg Have(Flight\ Information)$
$\land \neg Have(Maintenace\ Information)$
EFFECT: $Have(Fleet) \land Have(Maintenance\ Information)$
$\land Have(Flight\ Information)$

*Action (Classify (Fleet, Flight Information)),*
PRECOND: $Have(Fleet) \land Have(Flight\ Information)$
EFFECT: $Have(Classified\ Fleet)$

*Action (Get Maintenance (Classified Fleet))*
PRECOND: $Have(Classified\ Fleet) \land Have(Maintenance\ Information)$
EFFECT: $Have(Maintenances, Classified\ Fleet)$

*Action (Analyze Periodicity (Maintenance, Classified Fleet))*
PRECOND: $Have(Maintenances, Classified\ Fleet)$
EFFECT: $Have(Periodic\ Unscheduled\ Maintenance, Classified\ Fleet)$
$\land Have(Periods, Unscheduled\ Maintenances)$

*Action (Send Data (OA, Unscheduled Maintenance Periods per Classified Fleet)),*
PRECOND: $Have(Periodic\ Unscheduled\ Maintenance, Classified\ Fleet)$
$\land Have(Periods, Unscheduled\ Maintenances)$
EFFECT: $Send(OA, Periods) \land Send(OA, Periodic\ Unscheduled\ Maintenance$
$\land Send(OA, Classified\ Fleet)$

Figure 4.9 Predict Unscheduled Maintenance Description

Predicting unscheduled maintenance planning begins with the order of the operation agent to maintenance agent about predicting unscheduled maintenance. After the order the agent gets necessary information for prediction. Firstly, it classifies the fleet in the term of the flight information for finding similar fleet in term of similar flight conditions. After classifying the fleet, the agent will split the maintenance information according to the classified fleet. Then it will analyze periodicity of unscheduled maintenance according to the classified fleet, and finally, the agent will send periodical unscheduled maintenance with its periods and classified fleet to the operation agent.

For classifying the fleet, the agent will use unsupervised classification method because there is not a classification of fleet according to flight condition in the current prediction system. The agent can use Fourier Formulas for finding periodicity.

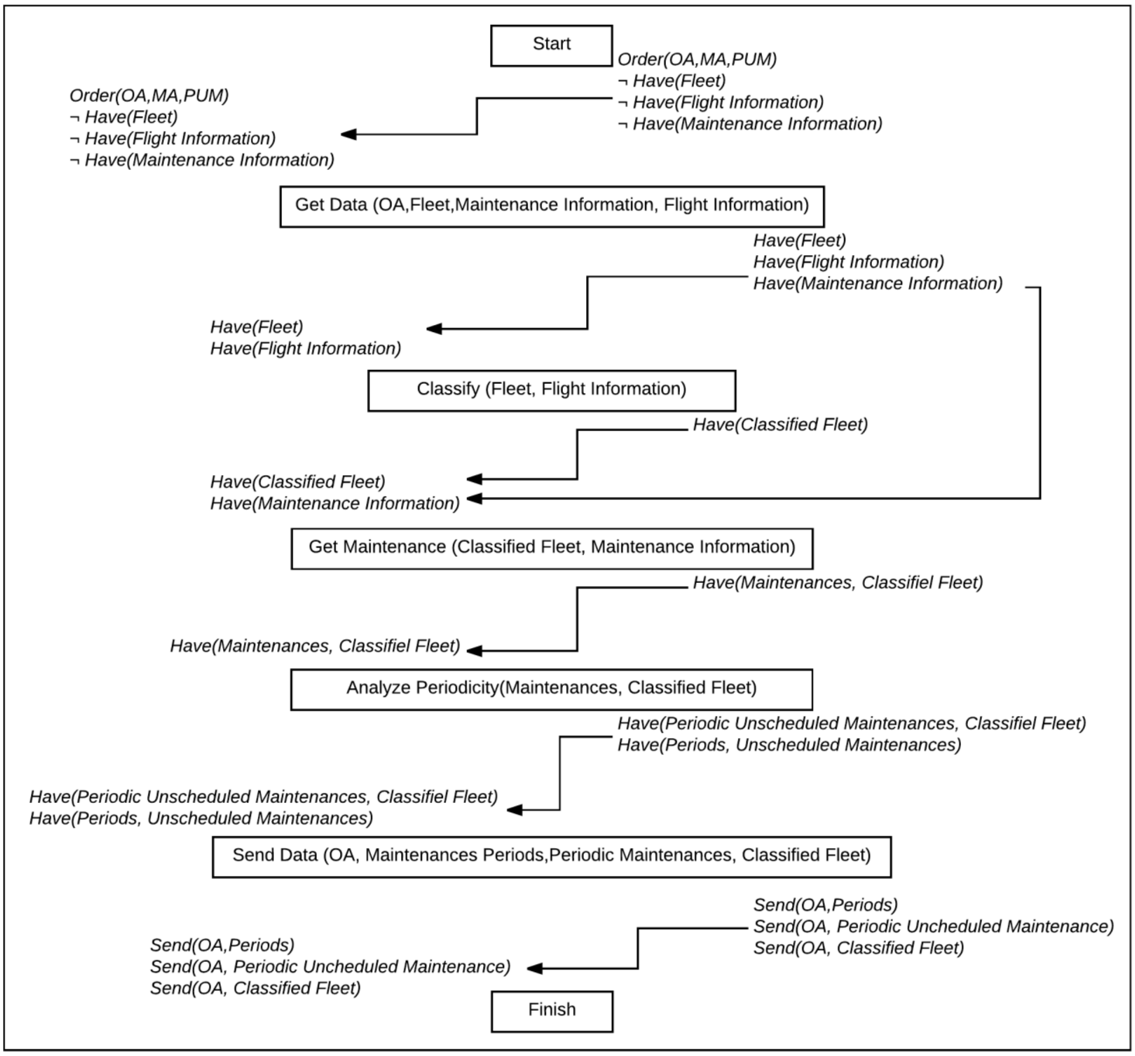

Figure 4.10 Predict Unscheduled Maintenance Planning

### 4.2.3. Inventory Management Agent

We have mentioned before that we are focusing on the aircraft component inventory management. In literature, there are many statistical methods for deciding ordering time of aircraft components’ orders. The stocking methods are changing according to the airline's policies. So that, the inventory agent only calculates order periodicity of each component of aircraft in the company’s fleet and send them to operation agents. While the agent was calculating the periodicity, it will use the classical statistical method and then it will integrate the result with the prediction of unscheduled maintenance prediction by getting information from operation agent.

The agent begins with the operation agent’s order to perform its tasks and it does not have order history and unscheduled maintenance information for managing the inventory in the initial state. The agent aims to send component information with their order periodicity and confidence interval (Risk) of periods. The agent will analyze all component periodicity by using analyze periodicity action and will integrate its result with the periodicity which is found at the unscheduled maintenance prediction task of the maintenance agent (See Figure 4.11 Inventory Management Description).

$Init(Order\ (OA, IMA, MI) \land \neg Have(Order\ History)$
$\land \neg Have(Unscheduled\ Maintenance\ Prediction)$
*Goal (Send (OA, Order Period, Component, Risk))*

*Action (Get Data (OA, Order History PAR, MR)),*
PRECOND: $Order\ (OA, IMA, MI) \land \neg Have(Order\ History)$
$\land \neg Have(Unscheduled\ Maintenance\ Prediction)$
EFFECT: $Have(Order\ History) \land Have(Unscheduled\ Maintenance\ Prediction)$

*Action (Analyze Periodicity (Component, Order History)),*
PRECOND: $Have(Order\ History)$
EFFECT: $Have(Component\_1, Period, Risk)$

*Action (Find (Component, Unscheduled Maintenance Prediction)),*
PRECOND: $Have(Unscheduled\ Maintenance\ Prediction)$
EFFECT: $Have(Component\_2, Period, Risk)$

Figure 4.11 Inventory Management Description

The first step of the inventory management process is to get an order from the operation agent (OA) to the inventory management agent (IMA) about managing inventory (IM). After this step, the agent gets necessary information for finding periodicity of order from the operation agent. There are two different sources to find periodicity and this method can find the order periodicity of the same aircraft component, so that, the agent integrates the periodicity of component order after analyzing periodicity and getting periodicity from the unscheduled maintenance prediction information. The final step is to send the components information with its periodicity and its periodicity confidence interval to the operation agent (See Figure 4.10 Predict Unscheduled Maintenance Planning).

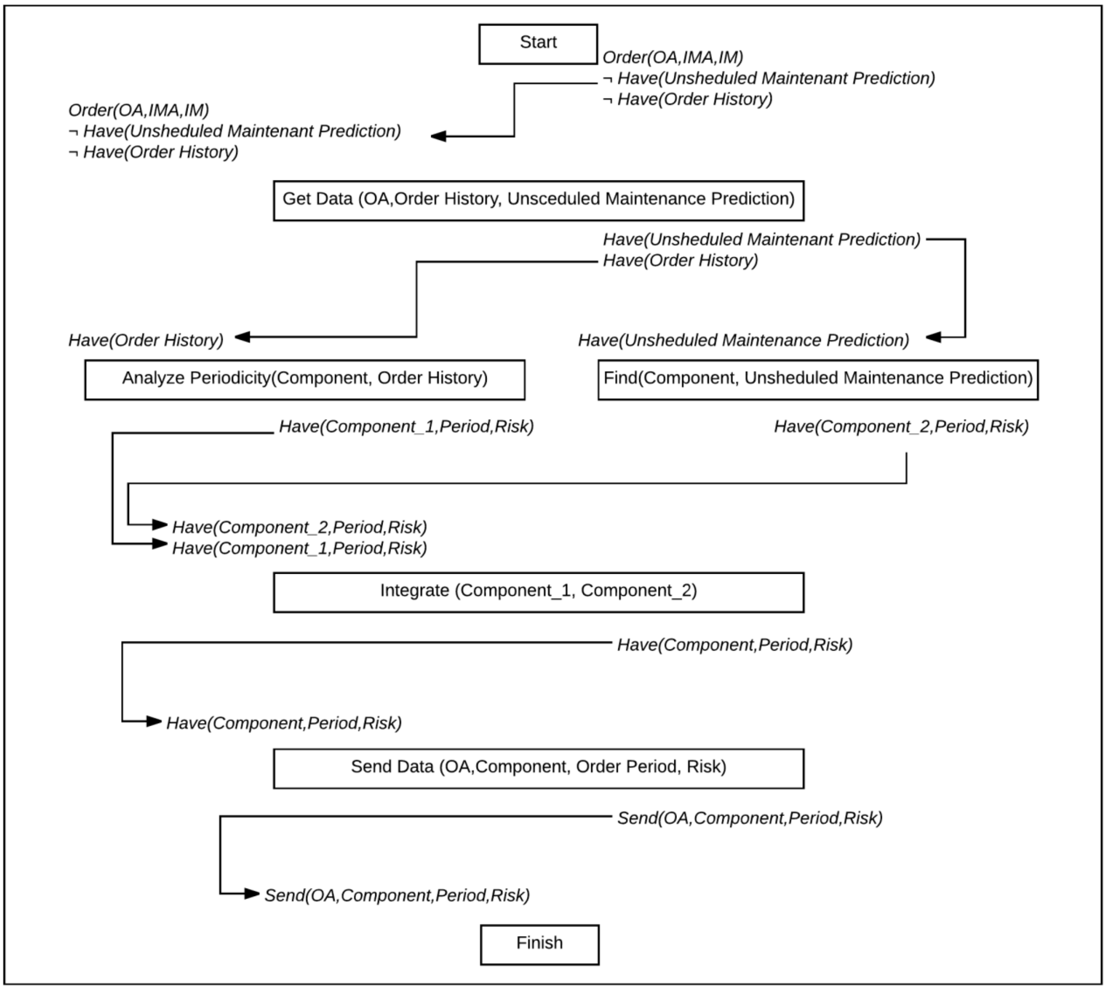

Figure 4.12 Inventory Management Planning

### 4.2.4. Staffing Management Agent

We mentioned before that airline companies spend the most for its staffing after the fuel. For this reason, it is important to managing staff for avoiding loss due to having more or less employees than needed. The staffing agent will use operation research method for allocating the staff to the necessary department according to their experience level and certification. The agent has two different tasks and these are to allocating staff to the department/maintenance and to decide to recruit new staffs according to their experience and certification. We will explain only the first task due to the time limit on the study.

$Init(Order\ (OA, SMA, AS) \wedge\ \neg Have(Maintenance\ Schedule)$
$\wedge \neg Have(Unscheduled\ Maintenance\ Prediction)$
$\wedge\ \neg Have(Staff\ Information)$
*Goal (Send (OA, Team, Maintenance))*

*Action (Get Data (OA, Maintenance Schedule, Unscheduled Maintenance Prediction, Staff Information)),*
PRECOND: $Order\ (OA, SMA, AS) \wedge\ \neg Have(Maintenance\ Schedule)$
$\wedge \neg Have(Unscheduled\ Maintenance\ Prediction)$
$\wedge\ \neg Have(Staff\ Information)$
EFFECT: $Have(Maintenance\ Schedule)$
$\wedge Have(Unscheduled\ Maintenance\ Prediction)$
$\wedge\ Have(Staff\ Information)$

*Action (Classify by Certification (Staff)),*
PRECOND: $Have(Staff\ Information)$
EFFECT: $Have(Certification,\ Staff)$

*Action (Classify by Experience (Staff)),*
PRECOND: $Have(Staff\ Information)$
EFFECT: $Have(Experience\ Level,\ Staff)$

*Action (Need (Maintenance, Team)),*
PRECOND: $Have(Maintenance\ Schedule)$
$\wedge Have(Unscheduled\ Maintenance\ Prediction)$
EFFECT: $Have(Maintenance, Team)$

*Action (Allocate (Staff, Team)),*
PRECOND: $Have(Experience\ Level,\ Staff) \wedge Have(Certification,\ Staff)$
$\wedge Have(Staff\ Information)$
EFFECT: $Have(Team)$

*Action (Allocate (Maintenance, Team)),*
PRECOND: $Have(Team) \wedge Have(Maintenance, Team)$
EFFECT: $Allocated(Team, Maintenance) \wedge Have(Free\ Team)$

*Action (Send Data (OA, Staff Allocation, Free Team)),*
PRECOND: $Allocated(Team, Maintenance) \wedge Have(Free\ Team)$
EFFECT: $Send(OA, Team, Maintenance) \wedge Send(OA, Free\ Team)$

**Figure 4.13 Staff Allocation Description**

The initial state of the agent is beginning with the order of operation agent about staffing allocation. The final state is to send the allocated teams of maintenance and unallocated teams to the operation agent. The agent has actions such as allocating staffs to teams by considering their experience level and certification; allocation teams to maintenance and sending them to the operation agent (See Figure 4.13 Staff Allocation Description).

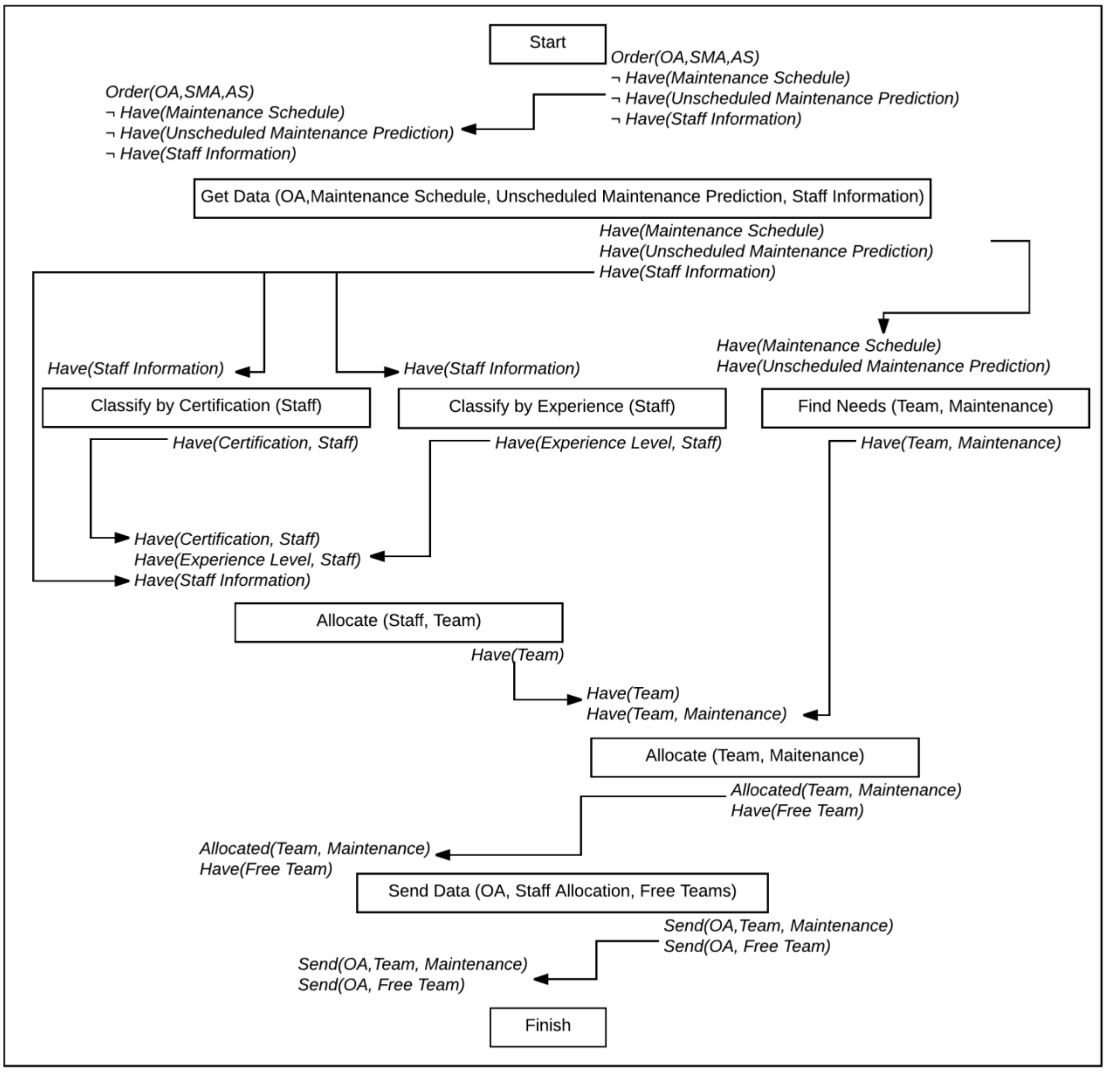

Figure 4.14 Staffing Allocation Planning

The staffing allocation agent planning begins with getting necessary data from the operation agent after its order about allocating staff. The agent classifies staffs according to their experience level and their certification. While the agent is allocating the staffs to the teams, it considers certification and experience level constraints (i.e. each team should contain one experienced staff and one certificated staff). In this step, the agent will use the operation research method for allocating staffs to the team by maximizing the experience level of each team and by satisfying the necessary certification. In the “find need” action, the agent finds how many teams are needed for each maintenance task to perform the maintenance. In the following step, the agent allocates the teams to the maintenance tasks by considering their needs. In the final step, the agent sends the result to the operation agent (See Figure 4.14 Staffing Allocation Planning).

# 5. CONCLUSION

## 5.1.Conclusion

In this study, we have presented a new agent based approach to integrated aircraft maintenance routing problem by considering crew management, inventory management, and operation management. The proposed model incorporates scheduling maintenance mandated by authorities, predicting unscheduled maintenance, managing aircraft component inventory, crew assignment to the scheduled/predicted maintenance by considering experience level and certifications of staffs for supporting the decision of operation managers and purchasing department of airline companies.

To effectively integrate the aircraft routing problem by considering unscheduled maintenance, scheduled maintenance, inventory, staffing, and operation management, we adopted an agent based system wherein the operation agent controls other agents named maintenance agent, inventory management agent and staffing management agent. Each agent has been developed for a set of tasks dedicated an aircraft maintenance routing sub-problem, and the operation agent has been developed for coordinating all agents and for coordinating with users.

Our study differentiates from other integrated aircraft routing models having operation research background such as Shao et al. (2015) study which integrates fleet assignment, aircraft routing, and crew pairing problem by using mixed integer programming. Because, while they were integrating the problem, they add a new objective to the objective function of their model and they add new constraints to the same model. In this case, the computation time for solving the problem increases dramatically, and they use linear relaxation or bender decomposition for decreasing the computation time which causes loss from the optimum solution. In addition, use of the linear relaxation is changing the structure of some constraints. When some regulations are changed by the authorities or the company, it is difficult to change relevant constraints to the changed regulations if their constraints contain some linear relaxation application. Even if these studies use some method for decreasing computation time by accepting the loss on the optimum solutions, the computation time take more than 6 hours for an airline having more than 300 aircrafts due to the examining all integrated problems in the same time.

Our study is separating each problem for solving them and coordinating them to performing a specific task. So that, the computation time does not increase, because our model does not need to solve all the problems in the same time. Adding new constraint or changing constraints is more flexible in our model by changing relevant agent action which solves the problem of the relevant changed constraints, so that, we do not need to change the entire model. Other differentiation of our model is to predict the unscheduled maintenance which facilitates handling the unscheduled maintenance before they occur, so that, our model may response in real time to the operation managers to avoid delay or cancellation according to maintenance timing.

Consequently, our study offers a new approach for integrating aircraft fleet maintenance processes which may uses less computation time and satisfy more optimum solution with a more flexible model according to the classical integrated models.

## 5.2.Limitations and Future Work

Despite the agent based model is a good solution for integrating aircraft maintenance management problems, the agent planning algorithm may cause the computation time due to its computation complexity. On the other hand, the agents may use classical research operation methods for affecting operation crews to maintenance and other optimization problem which have the polynomial complexity. Also, CIMPA SAS deep learning tools becomes more accurate according to increment on analysis duration, it can cause some loss when the model supported to user in real time.

In the future works on the subject, the examined problem can be extended to the all the aircraft routing problem such as fuel management, cabin crew pairing, passenger ingress/digress management, fleet assignment in the terms of the demands etc. On the other hand, a learning algorithm may be used for remembering user choice on previous decision for avoiding interaction between user and machine with cause bad effect on computation duration.

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