A new concept for disruption management in airline operations control

A J M Castro* and **E Oliveira**
LIACC-NIAD&R, FEUP, DEI, University of Porto, Porto, Portugal

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Abstract: The Airline Operations Control Centre (AOCC) of an airline company is the organization responsible for monitoring and solving operational problems. It includes teams of human experts specialized in solving problems related with aircrafts, crewmembers, and passengers, in a process called disruption management or operations recovery. In this article, the authors propose a new concept for disruption management in this domain. The organization of the AOCC is represented by a multi-agent system (MAS), where roles that correspond to the most frequent tasks that could benefit from a cooperative approach, are performed by intelligent agents. The human experts, represented by agents that are able to interact with them, are part of this AOCC-MAS supervising the system and taking the final decision from the solutions proposed by the AOCC-MAS. The authors show the architecture of this AOCC-MAS, including the main costs involved and details about how the system takes decisions. They tested the concept, using several real airline crew-related problems and using four methods: human experts (traditional way), the AOCC-MAS with and without using quality-costs, and the integrated approach presented in this article. The results are presented and discussed.

Keywords: disruption management, operations recovery, airline operations, multi-agent systems, intelligent agents, quality costs

1 INTRODUCTION

1.1 Overview

Controlling the operation is one of the most important tasks that an airline company have. It does not matter much to produce an optimal or near-optimal schedule of flights if, later, during the execution of the operational plan, the changes to the plan caused by disruptions are too far from the original schedule. Unfortunately, the majority of the disruptions are difficult to predict (for example, those caused by meteorological conditions or by aircraft malfunctions). Airline companies developed a set of operations control mechanisms to monitor the flights (and crewmembers) to check the execution of the schedule. During this monitoring phase, several problems may appear related to aircrafts, crewmembers, and passengers [1]. According to Kohl *et al.* [2], disruption management (DM) is the process of solving these problems. To be able to manage disruptions, airline companies have an entity called Airline Operations Control Centre (AOCC). This entity is composed of specialized human teams that work under the control of an operations supervisor. Although each team has a specific goal (for example, the crew team is responsible for having the right crew in each flight), they all contribute to the more general objective of minimizing the effects of disruption in the airline operational plan. In this article, the authors propose a new concept for DM in this domain. They see the AOCC as an organization not only with local goals (for example, minimizing the costs with aircraft, crew, and/or passengers when solving a specific disruption) but also with global goals like minimizing delays and costs in a given period of time. The objective is to make the AOCC more efficient, quicker when solving disruptions and with better global decisions and performance. The authors believe that human experts should be managers and not controllers. In their opinion, repetitive or frequent tasks are better performed by software agents and

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*Corresponding author: Faculty of Engineering, Informatics Engineering Department, University of Porto, Porto 4200-465, Portugal. email: ajmc@fe.up.pt

tasks with a high degree of uncertainty are performed better by humans. For that they propose to represent the AOCC as an organization of agents, a multi-agent system (MAS), where the roles that correspond to the most frequent tasks that could benefit from a cooperative approach are performed by intelligent agents. The human experts, represented by agents who are able to interact with them, are part of this AOCC-MAS supervising the system and taking the final decision from the solutions proposed by the AOCC-MAS.

1.2 Literature review and current systems classification

In this section, the authors present a comparative summary of related work regarding operations recovery and a classification of current systems. Most of the work in operations recovery has been done using operation research (OR) methods. For the interested reader, Barnhart *et al.* [3] give an overview of OR air transport applications. Section 1.2.1 presents a descendent chronological order of research regarding airline DM. Section 1.2.2 proposes a classification for current systems and tools related with airline DM and section 1.2.3 briefly establishes a link between the approach presented by the authors in this article and the related work on operations recovery.

1.2.1 State of the art regarding airline disruption management

Most of the information presented in this section was collected from references [4] and [5], and, for detailed information about each work, the authors recommend

Table 1 Comparative summary of research regarding operations recovery

Author(s)	Year	Main strategies/objectives	Main model/solver	Aircraft recovery	Crewcraft recovery	Integrated recovery
Abdelghany *et al.* [6]	2008	Resource reschedule; flight cancellations; departure delays	Mixed integer	—	—	Yes
Zhang and Hansen [7]	2008	Ground transportation (pax)	Integer with non-linear objective function	—	—	Yes
Mei Yang [8]	2007	Flight schedule modifications	Tabu search	Yes	No	No
Zhao and Zhu [9]	2007	Surplus aircraft; delay; cancellations; cost	Grey programming; local search heuristic	Yes	No	No
Eggenberg *et al.* [10]	2007	Recovery plans; cancellations; flight, delay, maintenance cost.	Set partitioning; resource constraint shortest path	Yes	No	No
Zhao *et al.* [11]	2007	Flight schedule modifications; crew, flight delay cost; individual roster	Grey programming; local search heuristic	No	Yes	No
Castro and Oliveira [12]	2007	Crew and aircraft swap, reserve crew and aircraft; crew cost; individual roster	MAS system; hill climbing and simulated annealing	No	Yes	No
Medard and Sawhney [13]	2007	Assumes recovery flight schedule first; Illegal crew, uncovered flights and affect crew; individual roster	Set covering model; depth-first search or reduced cost column generator	No	Yes	No
Liu *et al.* [14, 15]	2006/8	Flight connections and swaps; total flight delay; cancellations; assignment	Multi-objective genetic algorithm (meta-heuristics)	Yes	No	No
Bratu and Barnhart [16]	2006	Delay, cancel, assign reserve crew, and aircraft	Flight schedule network	—	—	Yes
Andersson [17]	2006	Cancellations, swap, and fleet swap	Tabu and simulated annealing (meta-heuristics)	Yes	No	No
Nissen and Haase [18]	2006	Assumes recovery flight schedule first; duty-based formulation; modifications original schedule; individual roster	Branch-and-price; set covering; resource constrained shortest path	No	Yes	No
Stojkovic and Soumis [19]	2005	Departure delays; reserve pilots; modifications, uncovered flights, flight delays; individual roster	Multi-commodity network flow; column generation	No	Yes	No
Love *et al.* [20]	2005	Cancellations; revenue minus costs	Meta-heuristics	Yes	No	No
Andersson and Varbrand [21]	2004	Cancellations, swap, and fleet swap	Set packing problem with generalized upper bound (GUB) constraints; Lagrangian relaxation-based heuristic and Dantzig–Wolfe decomposition	Yes	No	No
Abdelgahny *et al.* [22]	2004	Deadheading, stand-by, swap, flight delay costs; individual roster	Mixed-integer program	No	Yes	No

(*continued*)

Table 1 (continued)

Author(s)	Year	Main strategies/objectives	Main model/solver	Aircraft recovery	Crewcraft recovery	Integrated recovery
Guo [23]	2004	Assumes recovery flight schedule first; stand-by, modifications, operating costs; individual roster	Set partitioning problem; column generation with LP relaxation or hybrid heuristic based in a genetic algorithm with a local search	No	Yes	No
Kohl *et al.* [2]	2004	Flight swaps, cancellations, crew swaps, stand-by, up/downgrading crew; passenger delay costs at destination, value of passenger based on the booked fare class, and frequent flyer information	Dedicated aircraft solver (extension local search heuristic [20]); dedicated crew solver (differential column-generation/constraint integer problem); dedicated passenger solver (multi-commodity flow problem); integrated recovery layer (intelligent messaging system)	—	—	Yes
Yu *et al.* [24]	2003	Cancellations; deadheading, modifications, uncovered flight costs	Depth-first search; *CrewSolver* optimization	No	Yes	No
Rosenberger *et al.* [25]	2003	Delay and cancellation	Set partitioning model; preprocessing heuristic; CPLEX 6.0.	Yes	No	No
Andersson [26]	2001	Delay, cancel, assign reserve crew, and aircraft	Flight schedule network	—	—	Yes
Bard *et al.* [27]	2001	Delay and cancellation	Integer minimum cost flow model with additional constraints	Yes	No	No
Thengvall *et al.* [28, 29]	2001/3	Cancellations; multi-fleet; revenue minus cost	Three mixed-integer program models	Yes	No	No
Stojkovic and Soumis [30]	2001	Modifications, uncovered flights, and flight departure delays; individual roster	Multi-commodity network flow with additional constraints; column generation	No	Yes	No
Lettovsky *et al.* [31]	2000	Cancellation; pairing, cancel flight costs	Set covering with decision variables; LP relaxation and branch-and-bound	No	Yes	No
Thengvall *et al.* [32]	2000	Cancellations, swaps, delays; revenue minus costs	Integer programming; LP relaxation with heuristic	Yes	No	No
Luo and Yu [33]	1998	Delayed flights	Assignment problem with side constraints; heuristic	Yes	No	No
Stojkovic *et al.* [34]	1998	Assumes recovery flight schedule first; pairing, deadheading, undercovering costs; Individual roster	Integer non-linear multi-commodity flow network problem; columns generation, branch-and-bound	No	Yes	No
Lettovsky [35]	1997	Cancellation, delays, equipment assignment; maximizes total profit	Linear mixed-integer mathematical problem; benders decomposition	—	—	Yes
Wei *et al.* [36]	1997	Assumes recovery flight schedule first; pairing cost	Integer multi-commodity network flow problem; depth-first search	No	Yes	No
Arguello *et al.* [37]	1997	Cancellations; multi-fleet; flight route augmentation, partial route exchange; route cost and cancellation cost	Meta-heuristics (GRASP – greedy randomized adaptative search procedure)	Yes	No	No
Luo and Yu [38]	1997	Number delayed flights under GDP (Ground Delay Program)	Assignment problem with side constraints; heuristic	Yes	No	No
Cao and Kanafani [39, 40]	1997	Cancellations; revenue minus costs	Minimum cost network flow; network flow algorithms	Yes	No	No
Yan and Tu [41]	1997	Cancellations; multi-fleet; costs minus revenues	Network flow model with side constraints; Lagragian relaxation with subgradient method, Lagragian heuristic	Yes	No	No
Clarke [42, 43]	1997	Cancellations; multi-fleet; costs minus revenues	Set partitioning, column generation, extra constraints; tree-search heuristic and a set packing-based optimal solution	Yes	No	No
Yan and Yang [44]	1996	Cancellations; costs minus revenues	Minimum cost network flow; network flow algorithms	Yes	No	No
Talluri [45]	1996	Multi-fleet; swaps when exchanging aircraft type	Classifies swap opportunities; polynomial time algorithm	Yes	No	No

(continued)

Table 1 (continued)

Author(s)	Year	Main strategies/objectives	Main model/solver	Aircraft recovery	Crewcraft recovery	Integrated recovery
Mathaisel [46]	1996	Cancellations; revenue loss, operating cost	Minimum cost network flow; network flow algorithms	Yes	No	No
Teodorovic and Stojkovic [47]	1995	Cancellation and delay minutes; crew considerations; minimize total passenger delays	Heuristic	Yes	No	No
Johnson *et al.* [48]	1994	Pairing, stand-by, deadheading costs; cancellations	Set covering problem with decision variables; *MINTO* [49] (mixed integer optimizer)	No	Yes	No
Jarrah *et al.* [50]	1993/6	Cancellations; delay, swap and ferrying	Minimum cost network flow; network flow algorithms	Yes	No	No
Rakshit *et al.* [51]	1993/6	Cancellations; delay, swap and ferrying	Minimum cost network flow; network flow algorithms	Yes	No	No
Teodorovic and Stojkovic [52]	1990	Cancellation and delay minutes	Heuristic	Yes	No	No
Teodorovic and Guberinic [53]	1984	Delay minutes	Heuristic	Yes	No	No

reading the above-mentioned articles. Table 1 presents a descendant chronological order of research regarding airline DM. The authors also classify each work according to the dimensions they are able to deal with, that is, aircraft recovery, crew recovery, or integrated recovery. They classify a work as integrated when it is able to deal with, at least, two of the dimensions (for example, aircraft and passenger or aircraft and crew).

1.2.2 *Classification of current systems and tools*

This section will help the reader to understand some of the links that the authors are going to establish between their approach and the current state of the art regarding operations recovery (section 1.2.3).

In a previous work [54], they classified the current tools (or systems that provide those tools) in use at AOCCs into one of these three categories.

1. Database query systems (DBQS).
2. Decision support systems (DSS).
3. Automatic or semi-automatic systems (ASAS).

The DBQS (the most common situation at airlines) allows the AOCC human operators to perform queries on the existing databases to monitor the airline operation and to obtain other data essential for decision making. These systems are useful and relatively easy to implement and/or acquire, but they have some important disadvantages, for example, to find the best solution and to take the best decision is completely dependent on the human operator. As explained in reference [54], there are two problems when airline companies use only this type of systems:

(a) the solution quality is dependent on knowledge and experience of the human operator;
(b) due to the usual difficulty of the human being in leading with large volumes of data simultaneously, they do not use all the necessary information (variables) to take the best decision.

The DSS, besides having the same characteristics of the DBQS, also include additional functionalities to support the human operators on the decision making. For example, after a request made by a human operator, these systems are able to recommend the best solution to solve a problem related with a delayed aircraft. Some of them may just recommend a flight re-scheduling but others are able to justify the candidate solution as well as to present the solution cost. DSS eliminate some of the disadvantages of the DBQS. Namely, they are able to analyse large volumes of data and, because of that, propose solutions that take into consideration more information (variables). The decision making still is on the human operator side but, now, he is able to take better decisions.

The goal of the third type of systems, ASAS, is to automate as much as possible the AOCC, replacing the functional part by computerized programs. Specifically, these systems try to automate the repetitive tasks and also the tasks related with searching for the best solution (problem solving). In a totally automatic system, decision making is also taken by the system. In a semi-automatic system, the final decision is taken by the human operator. In ASAS type of systems, the AOCC does not need as much human operators as in the previous ones, to operate correctly. Usually, roles or functions related to operation monitoring, searching for solutions related with aircraft, crew or passenger problems, and re-allocation of resources, are performed by specialists agents [12] replacing the human specialists. The final decision regarding the application of the solution found by these systems on the environment (for example, making the necessary changes on the airline operational plan database) depends on the human supervisor. According to references [55] and [56], the agent and MAS paradigm is more appropriate to be used in this domain than any other paradigm.

1.2.3 A general comparison of the authors' approach

This section tries to establish the differences that exist between the authors' approach presented in this article and the current work as presented in section 1.2.1. Considering the high number of related work they have presented, it is not feasible to present a detail comparison of their approach with each of the mentioned works. Nevertheless, it is possible to present the main differences. In their opinion, their work is different from the previous ones regarding the following main characteristics:

(a) scope;
(b) technology;
(c) integration;
(d) quality costs.

Regarding the scope and using the classification presented in the previous section, the authors' work is classified as an ASAS. They want to automate as much as possible the AOCC, replacing the most repetitive tasks with computerized systems and leave to the human user the final decision. To the best of their knowledge, none of the related works presented in section 1.2.1 has this scope. Most of them or even all of them should be classified as DSS.

On the technology side and to the best of the authors' knowledge, they were the first to propose the agent and multi-agent paradigm to represent the AOCC as an organization of agents [**12**, **56**]. The organization environment of the AOCC is naturally modelled as a society of agents that cooperate with each other to solve the problems. In their opinion, this paradigm has some advantages over other paradigms. In section 3.2, the authors present the reasons that make them adopt this paradigm. As far as they know, none of the related works presented (with the exception of their own previous work [**12**]) follows this paradigm.

In the operations recovery domain, there are three dimensions: aircraft, crew, and passengers. The authors have classified the related work according to these dimensions and they consider an integrated approach when it is able to deal with two of these dimensions. The authors' work differs from the previous ones in the sense that it considers explicitly the three dimensions of the domain. In this sense and to the best of their knowledge, their approach is fully integrated.

In one of the authors' previous works [**5**] they argue that it is important to capture the costs of delaying or cancelling a flight, from the point of view of the passenger and not only from the point of view of the airline company. The related works that consider the cost of delaying a flight (not all of them do as it is possible to see in Table 1) assign a cost to each minute of delay. In the authors' opinion, this only captures the cost from the point of view of the airline company because that cost is defined by the airline and it is valid for all flights, without considering the profiles of the passengers in the specific flight being affected by a disruption. The authors' approach uses quality costs that considers the opinion of the passengers on the specific flights and that is one of the biggest differences regarding the related work published so far. For more information regarding the approach used to calculate the quality costs, please consult reference [**5**].

1.3 The use of agents on other application domains

The agent and multi-agent paradigm has been used in several application domains, including in other air transportation problems. As stated before and to the best of the authors' knowledge, they believe that they were the first to use this paradigm to represent the AOCC as an organization of agents [**12**, **56**].

Regarding the use of agents in other domains a very brief list follows: Jonker *et al.* [**57**] propose a MAS for Air Traffic Control (ATC) Tower operations. In the aviation domain, but in a different context, Tumer and Agogino [**58**] present a MAS for traffic flow management. Another use of agents in the context of collaborative traffic flow management is reported by Wolfe *et al.* [**59**]. Here, agents are used to compare routing selection strategies. As a last example and in a completely different domain, Ouelhadj [**60**, **61**] developed an integrated dynamic scheduling system of steel production based on the multi-agent paradigm.

As the authors said in the beginning of this section, the examples above are an incomplete and very brief list of the use of the MAS paradigm, just to give an idea that this technology is able to deal with very complex and critical problems.

1.4 Document structure

This article is organized as follows: section 2 introduces the AOCC, including typical organizations and problems, the current DM process and a description of the main costs involved. Section 3 is the main section of this article and presents the authors' new concept for DM in AOCC, including details about how they built the agent-based approach to this problem. This section presents:

(a) the reasons that made them adopt the software agents and MAS paradigm;
(b) the MAS architecture including the specific agents, roles, and protocols as well as some relevant agent characteristics like autonomy and social awareness;

(c) decision mechanisms, including costs criteria and negotiation protocols;
(d) examples of the problem solving algorithms used.

In section 4, the authors present the experimental set-up and, in section 5, they evaluate their approach, presenting and discussing the results. Finally, in section 6, they conclude and give some insights on the future work.

2 AIRLINE OPERATIONS CONTROL

In this section, the authors introduce the airline operations control problem (AOCP; also known as airline DM problem). To contextualize, they start by briefly introducing the AOCP preceding problem known as the airline scheduling problem (ASP). Then they explain what an AOCC is and present some typical AOCC organizations. The typical problems, the current DM process, as well as the main costs involved are also introduced.

2.1 Airline scheduling problem

According to Kohl *et al.* [2] the scheduling process of an airline company is composed by the long- and short-term phases presented in Fig. 1. The scheduling process has three main dimensions or views:

(a) passenger view;
(b) aircraft view;
(c) crew view.

The first one represents the seats available to be sold to the airline customers. The other two views, represents resources that will be allocated.

Everything starts with *publishing the flights' timetable* for a specific period of time (usually 6 months). After publishing the timetable, the *revenue management* phase starts. Here the goal is to maximize the revenue-obtained selling tickets. At the same time, the scheduling of the two most important resources starts: aircrafts and crew. Regarding the aircraft, the first step is the *fleet assignment*. Here, the goal is to assign the aircraft type or aircraft fleet that will perform the flights. It is an important step because the aircraft type/fleet will define the number of available seats in each flight. Near to the day of operations, the assignment of the specific aircraft to each flight is performed. This step is known as *tail assignment*. After the fleet assignment step, it is possible to start to schedule the crew. The first step is the *crew pairing*. The goal is to define the crew duty periods (pairings) that will be necessary to cover all the flights of the airline for a specific period of time (typically 1 month). Having the pairings, it is possible to start the *crew rostering* step, that is, assign crewmembers to the pairings. The output of this step is an individual crew roster that is distributed or published in the crew web portal. Finally and until the day of operations, it is necessary to change/update the crew roster (*roster maintenance*), to include any changes that might appear after publishing the roster. The ASP is composed of all the previous phases and steps and ends some hours or days (depends on the airline policy) before the day of operation. The global objective of the ASP is to maximize the airline operating profit. For more detailed information, please consult reference [62] specially sections 2.1 to 2.4.

2.2 AOCC organization

The AOCP starts where the ASP stops. If everything goes as planned, the airline just needs to monitor the execution of the plan. Unfortunately, several unexpected events appear during this phase that can disrupt the plan. To monitor those events and solve the problems that arise from these, it is necessary to define and follow a DM process. Airline companies have an entity called AOCC that is responsible for the DM process. There are three main types of AOCC organizations [54].

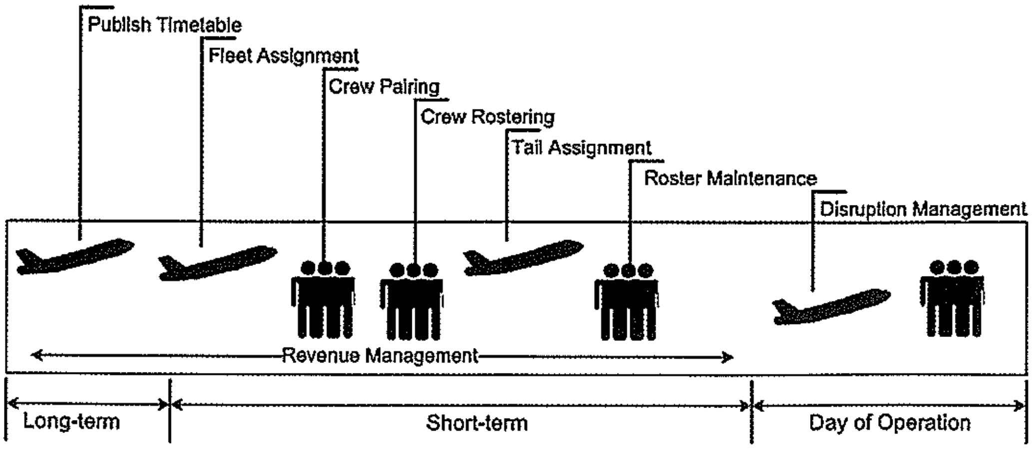


Fig. 1 The airline scheduling process

1. *Decision centre*: The *aircraft controllers* share the same physical space. The other roles or support functions (crew control, maintenance service, etc.) are in a different physical space. In this type of *collective organization*, all roles need to cooperate to achieve the common goal.
2. *Integrated centre*: All roles share the same physical space and are hierarchically dependent of a supervisor. For small companies, we have a *simple hierarchy organization*. For bigger companies, we have a *multi-dimensional hierarchy organization*. Figure 2 shows an example of this kind of AOCC organization.
3. *Hub control centre* (*HCC*): Most of the roles are physically separated at the airports where the airline companies operate a hub. In this case, if the aircraft controller role stays physically outside the hub, we have an organization called *decision centre with a hub*. If both the aircraft controller and crew controller roles are physically outside the hub, we have an organization called *integrated centre with a hub*. The main advantage of this kind of organization is to have the roles that are related with airport operations (customer service, catering, cleaning, passengers transfer, etc.) physically closer to the operation.

The organization adopted depends on several factors like airline size, airline network type (for example, hub-and-spoke), and geographic distribution of the operation, as well as, tradition and/or company culture.

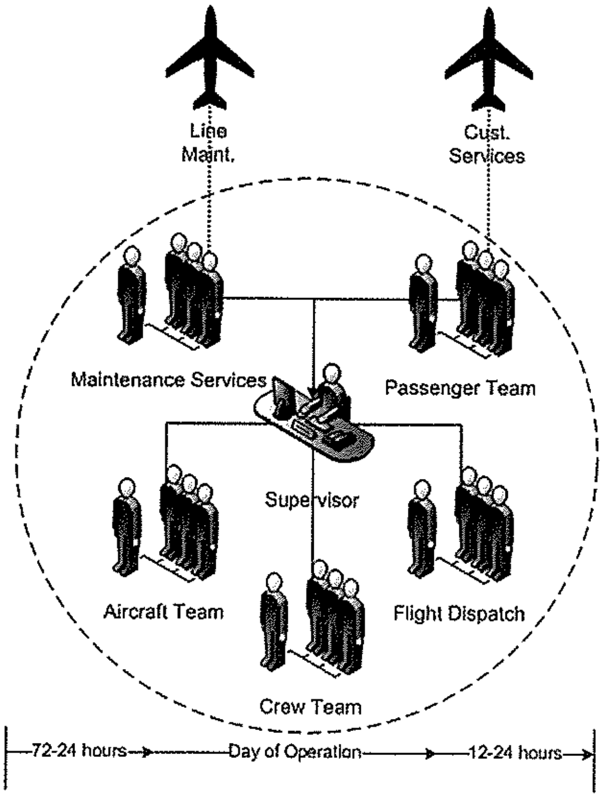


Fig. 2 Integrated airline operational control centre

In Fig. 2, the authors present the organization of a typical *integrated operational control centre*. It is important to point out the role of the supervisor, a characteristic that makes this organization hierarchical and, also, the operation time window that marks the responsibility boundaries of the AOCC. This operation time window is different from airline to airline but, usually, ranges from 72–24 h before to 12–24 h after the day of operation.

The roles or support functions more common in an AOCC, according to Kohl *et al.* [2] and Castro [54], are the following.

1. *Flight dispatch*: Prepares the flight plans and requests new flight slots to the ATC entities (Federal Aviation Administration (FAA) in North America and EUROCONTROL in Europe).
2. *Aircraft control*: Manages the resource aircraft. It is the central co-ordination role in the operational control. In a disruptive situation, tries to minimize the delays by changing aircrafts and rerouting or joining flights, among other actions. Usually, uses some kind of computer system to monitor the operation that, in some cases, might include some decision supports tools. Much more common is the use of *rules-of-thumb* based on work experience (a kind of hidden knowledge).
3. *Crew control*: Manages the resource crew. Monitors the crew check-in and check-out, and updates and changes the crew roster according to the disruptions that might appear during the operation. Like the previous role, it uses some kind of system with or without decision support tools. The experience and the use of rules-of-thumb are still the most common decision tools. To use reserve crew and exchange crewmembers from other flights, are among the possible actions used to solve crew problems.
4. *Maintenance services*: Responsible for the unplanned maintenance services and for short-term maintenance scheduling. Changes on aircraft rotations may impact the short-term maintenance (maintenance cannot be done at all stations).
5. *Passenger services*: Decisions taken on the AOCC will have an impact on the passengers. The responsibility of this role is to consider and minimize the impact of the decisions on passengers, trying to minimize the passenger trip time. Part of this role is performed on the airports and for bigger companies it is part of the HCC organization.

2.3 Typical problems

In the previous section, the authors presented typical AOCC organizations and the roles that exist on those organizations. Now, it is important to understand the typical problems that appear during the execution of the airline operation. From the authors' observations in a real AOCC, and from reference [63], they found the typical problems presented in Fig. 3. In this diagram, the authors have also included the impact that each problem might have on flight arrival or departure delays as well as the relation that exist between them. The diagram also shows that the problems might propagate due to the relation between them and generate new problems on different flights. This propagation characteristic makes the problem more difficult to be solved optimally in a real time and dynamic environment, like the one on the AOCC.

As one can see in Fig. 3, there is an obvious relation between *flight arrival delays* and *flight departure delays*. Most of the flights are performed by aircrafts that are used in previous flights. If the flight has an arrival delay and the aircraft turn-around time at the airport is not enough, then, if the AOCC does not find an alternative solution, the next flight of that aircraft will also have a departure delay. From the diagram, one can also see that the main reasons for flight arrival delay (besides the delay on departure) are: *en-route air traffic, en-route weather, en-route aircraft malfunction*, and *flight diversion*. In the previous cases and to minimize the arrival delay, cooperation between the pilot, the AOCC, and ATC is necessary. Regarding departure delays, the main reasons are: *crew delays, cargo/baggage loading delays*, and *passenger delays* as a consequence of an *arrival delay*. Crewmembers who do not report for duty, air traffic control reasons, aircraft malfunctions, and weather conditions (at departure or at arrival) are the other main reasons for departure delays.

2.4 Current disruption management process

As one can see from the previous section, there are several problems that might cause flight delays. AOCCs have a process to monitor the events and solve the problems, so that flight delays are minimized with the minimum impact on passenger and, preferably, with the minimum operational cost. In Fig. 4, the authors present the current DM process in use at most of the airlines. This process has five steps.

1. *Operation monitoring*: In this step, the flights are monitored to see if anything is not going according to the plan. The same happens in relation to crewmembers, passenger check-in and boarding, cargo and baggage loading, etc.
2. *Take action*: If an event happens, like, for example, a crewmember is delayed or an aircraft malfunction, a quick assessment is performed to see if an action is required. If not, the monitoring continues.

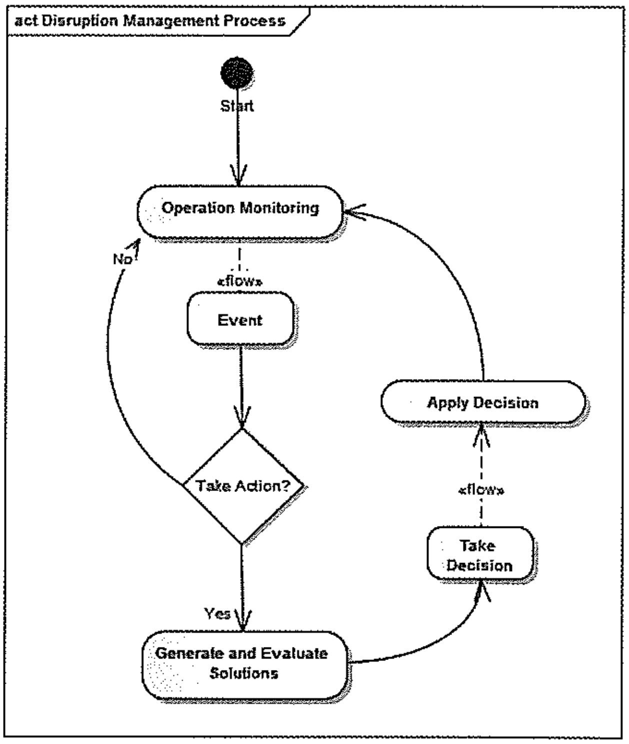


Fig. 4 AOCC DM process

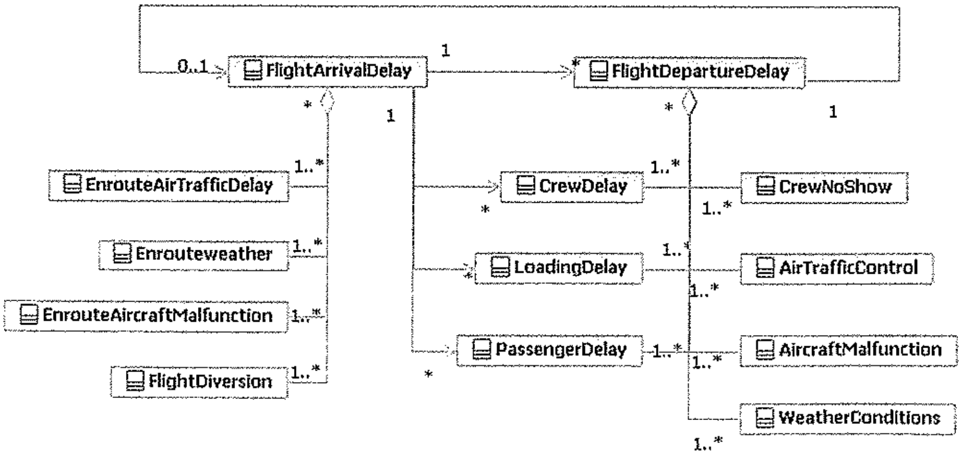


Fig. 3 Typical AOCC problems and relations

If an action is necessary, then there is a problem that needs to be solved.
3. *Generate and evaluate solutions*: Having all the information regarding the problem the AOCC needs to find and evaluate the candidate solutions. Usually, a sequential approach is adopted when generating the solutions. First, the aircraft problem is solved; then, the crew problem, and finally, the passengers. It is understandable that the AOCC adopts this approach. Without good computer tools, it is difficult to take care of the problem, considering three dimensions (aircraft, crew, and passengers) simultaneously. Although there are several costs involved in this process, it was found that the AOCC relies heavily on the experience of their controllers and in some rules-of-thumb (a kind of hidden knowledge) that exist on the AOCC.
4. *Take decision*: Having the candidate solutions, a decision needs to be taken.
5. *Apply decision*: After the decision, the final solution needs to be applied in the environment, that is, the operational plan needs to be updated accordingly.

In the authors' opinion, this process can greatly benefit from an intelligent agent-based approach to the problem, as will be explained in section 3.

2.5 Main costs involved

In the step generate and evaluate solutions of the DM process on the previous section, the main costs involved in generating and choosing from candidate solutions should be considered. According to the authors' observations, these are the main costs involved when generating and evaluating a solution for a specific disruption.

1. *Crew costs*: the average or real salary costs of the crewmembers, additional work hours, and *perdiem* days to be paid, hotel costs and extra-crew travel costs.
2. *Flight costs*: airport costs (approach and taxing taxes, for example), service costs (cleaning services, handling services, line maintenance, etc.), and average maintenance costs for the type of aircraft, ATC en-route charges, and fuel consumption.
3. *Passenger costs*: passenger airport meals, passenger hotel costs, and passenger compensations.

Finally, there is a less easily quantifiable cost that is also included: the cost of delaying or cancelling a flight from the passenger point of view. Most airlines use some kind of rule-of-thumb when they are evaluating the impact of the decisions on passengers. Others just assign a monetary cost to each minute of delay and evaluate the solutions taking into consideration this value. A different way of calculating this cost component is proposed.

3 A NEW CONCEPT FOR DM IN AIRLINE OPERATIONS CONTROL

In section 3, the authors introduced the ASP and the AOCP (or DM problem). They have described the AOCC organization and roles as well as the typical problems that appear during the execution of the operational plan. The DM process used by airlines was presented as well as the main costs involved in generating and evaluating the solutions. In this section, the authors present their new concept for DM in the airline domain, including how they represent the AOCC using an MAS, an organization of intelligent agents. To implement the MAS, the authors have used Java (http://www.java.com) and JADE [**64**]. These tools provide the necessary development framework and runtime environment for their agents.

3.1 Introduction

Looking at the current roles in the AOCC (Fig. 2), the authors see that some of them correspond to very repetitive tasks. For example, the aircraft controller (a member of the aircraft team) is constantly checking the computer system (including email, *datalink* system, telex, etc.) to see if there is any problem that might affect the departure or arrival of a flight. A similar routine regarding monitoring crewmembers is performed by the crew controller (a member of the crew team). When a problem is detected, the process of solving it is also very repetitive. For example, if a flight is delayed, the possible and general actions than an aircraft controller has to solve the problem are (the applicability of each action depends on the specific problem at hand):

(a) use an aircraft from a later flight (change aircrafts);
(b) reroute the flight (helpful when the delay is related with slots);
(c) join flights (use one aircraft to also perform the flight of the broken aircraft);
(d) freight an aircraft and crew from another company;
(e) delay the flight;
(f) cancel the flight.

The crew controller also performs very repetitive tasks when trying to solve crew problems. For example, the general actions he can use to solve the problems are (the applicability of each action depends on the specific problem at hand):

(a) use a reserve crew at the airport;
(b) use a reserve crew that lives near the airport;
(c) use another crew from another flight;
(d) invite a day off crew;
(e) propose to change the aircraft to a different aircraft type;
(f) proceed without the crewmember;

(g) delay the flight;
(h) cancel the flight.

Taking into consideration the above as well as the characteristics of the agent and multi-agent paradigm (see next section), the authors propose to represent the AOCC by a MAS, replacing the monitoring, aircraft controller, crew controller, and part of the passenger role, by intelligent agents as represented in Fig. 5.

In this new approach, the aircraft team will be replaced by a suborganization of agents (represented as *aircraft manager*). The same will happen to the crew team (represented as *crew manager*). Regarding the passenger services, the authors propose to replace by software agents the task of finding the best solutions to the problems with passengers (usually a plan of alternative flights to each disrupted passenger) and keep the other tasks to be performed at the airports by human operators (represented as *passenger manager* in Fig. 5). The supervisor interacts with the software agents through an interface agent.

3.2 Why an agent and multi-agent system paradigm?

Before presenting the architecture of the authors' MAS, it is important to point out the characteristics of this paradigm, according to references [55] and [65], which make them adopt it to model this problem. Table 2 summarizes the characteristics. For the interested reader, more details are available in reference [5, section III].

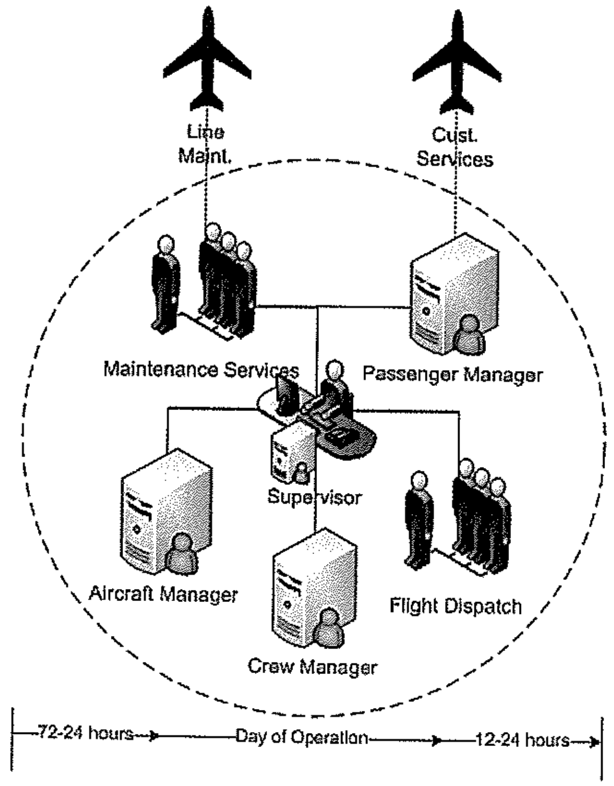


Fig. 5 New concept for integrated airline control centre

3.3 MAS architecture

To develop a software system it is important to follow a methodology. MAS are not an exception. The architecture presented here is the result of following an agent-oriented methodology, specifically an adaptation of GAIA according to references [66] and [67]. The base for this architecture was the service and agent model that resulted from following the methodology.

Figure 6 shows the architecture of the authors' MAS approach. The boxes represent agents, the solid lines represent interactions between agents and the dashed lines represent actions in the environment. The cloud represents the negotiation at the managers' level. In this figure, the authors represent only one instance of the system. All agents can be replicated with the exception of the *Supervisor* agent. Each agent performs one or more roles in the AOCC. The *monitor* agent looks

Table 2 Summary of the MAS paradigm characteristics

Characteristic	Main reason
Autonomy	Problems are modelled as autonomous interacting components. The CrewManager, PaxManager, and A/CManager in Fig. 6 are example of that. They respond to the requests according to their objectives
Natural metaphor	The AOCC modelled as an organization of cooperating agents is a natural metaphor
Reactivity	The *Monitor* agent in Fig. 6 is an example of how agents are able to perceive and react to changes
Resource distribution	Depending on the size of the airline, one might want to treat this problem in a more distributed way. The MAS paradigm allows distributing computational resources and the MAS can be designed so that the agents are able to distribute their tasks among other agents. The *social-awareness* characteristics of their agents are an example of that
Scalability and modularity	In systems of this dimension and complexity, all characteristics that promote reuse are very important. Extensibility, robustness, maintainability, flexibility, and scalability are some of those characteristics presented in MAS
Parallelism/ concurrency	These characteristics are important if one wants a fault-tolerant system and to speed up computation. The authors' *Specialist* agents in Fig. 6 are examples of that
Legacy systems	Legacy systems can be wrapped in an agent layer to be able to interact with other systems. In the air transportation domain, most likely, the interaction with older but functional systems is necessary. Therefore, this characteristic is very important

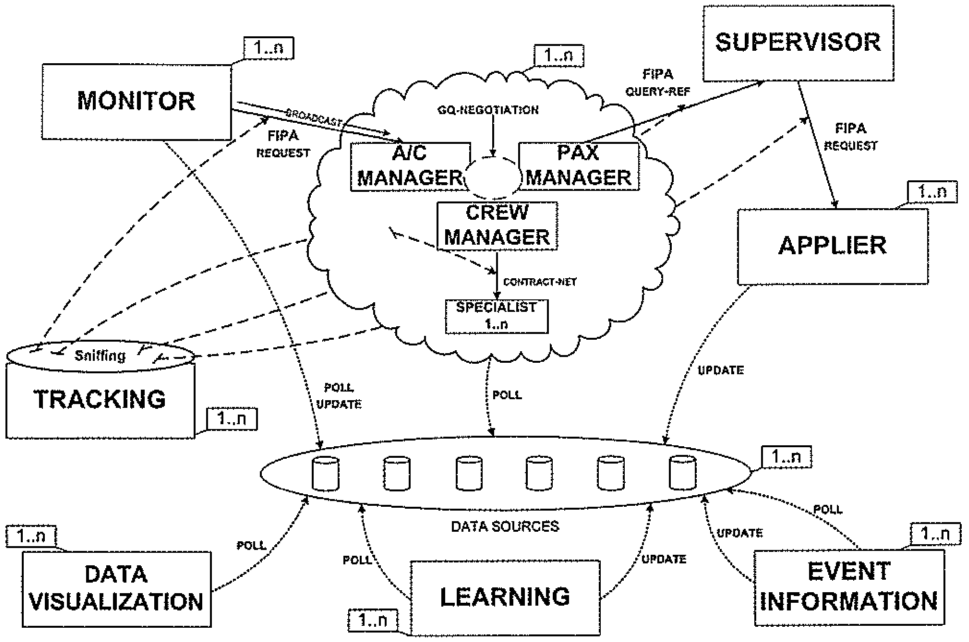


Fig. 6 MAS architecture

for events on the operational plan that may trigger any aircraft/flight, passenger, and/or crew problem. This agent has social-awareness characteristics in the sense that it is able to recognize and interact with other agents with the same role, splitting the tasks. For example, if each monitor agent instance corresponds to a different hub, they will monitor the corresponding hub operational plan. This agent, like others in the system, is autonomous because it is able to consider an event as a problem only when specific conditions or characteristics are present.

The *CrewManager* and *A/CManager* agents are responsible for crew and aircraft/flight problems, respectively. They manage a team of expert agents [12] with the role of finding solutions for the problems in their area of expertise. The expert or specialist agents implement different heterogeneous problem solving algorithms and are able to run in parallel. The managers are autonomous, because they only respond to requests related to their area of expertise. The task of the PaxManager agent is to find the best solution regarding passenger problems.

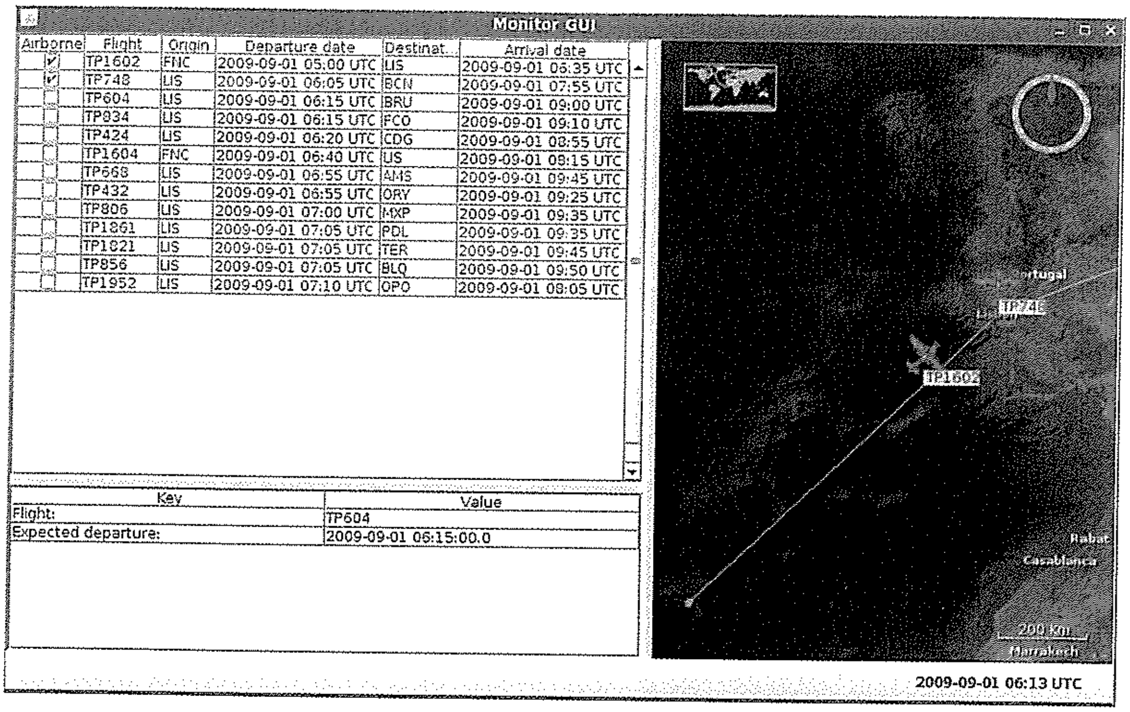
The agent *supervisor* and agent *EventInformation* are the only ones that interact with a human user of the AOCC. The solutions selected by the supervisor are presented to the human. It includes solution details (and the rationale behind the solution) to help the human decide, which are ranked according to the criteria of the airline company. After getting approval from the human supervisor, the Supervisor agent requests the *Applier* agent to apply it on the environment.

In Fig. 6, *data sources* represent the environment that all agents are able to observe and act upon. All the necessary information is included in the data sources. For example, company and airport information, flight schedule, aircraft and crew rosters, etc.

Additional information to support some characteristics of the MAS like learning is also included on the data sources. The *tracking* agent supports the tracking characteristics of the system and the *data visualization* agent supports the visualization of the information (flight movements, delays, problems, etc.) showing what is happening at the AOCC. Figure 7 shows a partial Graphical User Interface (GUI) updated by the *data visualization* agent.

There is also a *learning* agent that will support the advanced learning characteristics of the system (not implemented yet). In section 6, the interested reader can find more information about the way the authors expect to apply learning in their MAS. Finally, the protocols used are the following (the first three are FIPA (http://www.fipa.org) compliant ones).

1. *Fipa-request*: It is used between *monitor* and *crew*, *pax*, and *A/C manager* interactions.
2. *Fipa-query*: It is used in interactions between the *supervisor* and the *managers* as well as in interactions between the supervisor and *EventInformation* and *applier*. Finally, it is used between *EventType* and *monitoring* agent.
3. *Fipa-Contract.net* [68]: A simplified version of this protocol is used in the interactions between the *managers* and the *expert/specialized* agents.
4. *GQ-negotiation*: This negotiation protocol is a generalization of the Q-negotiation protocol as presented in reference [69]. The authors use it at the manager agents' level so that the best integrated



Airborne	Flight	Origin	Departure date	Destinat...	Arrival date
☑	TP1602	FNC	2009-09-01 05:00 UTC	LIS	2009-09-01 06:35 UTC
☑	TP748	LIS	2009-09-01 06:05 UTC	BCN	2009-09-01 07:55 UTC
☐	TP604	LIS	2009-09-01 06:15 UTC	BRU	2009-09-01 09:00 UTC
☐	TP834	LIS	2009-09-01 06:15 UTC	FCO	2009-09-01 09:10 UTC
☐	TP424	LIS	2009-09-01 06:20 UTC	CDG	2009-09-01 08:55 UTC
☐	TP1604	FNC	2009-09-01 06:40 UTC	LIS	2009-09-01 08:15 UTC
☐	TP668	LIS	2009-09-01 06:55 UTC	AMS	2009-09-01 09:45 UTC
☐	TP432	LIS	2009-09-01 06:55 UTC	ORY	2009-09-01 09:25 UTC
☐	TP806	LIS	2009-09-01 07:00 UTC	MXP	2009-09-01 09:35 UTC
☐	TP1861	LIS	2009-09-01 07:05 UTC	PDL	2009-09-01 09:35 UTC
☐	TP1821	LIS	2009-09-01 07:05 UTC	TER	2009-09-01 09:45 UTC
☐	TP856	LIS	2009-09-01 07:05 UTC	BLQ	2009-09-01 09:50 UTC
☐	TP1952	LIS	2009-09-01 07:10 UTC	OPO	2009-09-01 08:05 UTC

Key	Value
Flight:	TP604
Expected departure:	2009-09-01 06:15:00.0

2009-09-01 06:13 UTC

Fig. 7 User interface (partial) updated by the data visualization agent

solution can be obtained. The next section gives more information about this protocol.

3.4 Decision mechanisms

The MAS uses two levels of negotiation. The *manager agents level*, that is, between *A/CManager*, *CrewManager*, and *PaxManager*. At this level, the agents cooperate to find an integrated solution, that is, one that includes the impact on passengers, crew, and aircraft.

The *team level* (or *specialist agents level*), that is, between each manager and the expert/specialist team agents. In the following sections, both decision mechanisms are explained.

3.4.1 *Manager agents level negotiation*

At this level, the authors are using a generalization of the *Q-negotiation* protocol present in references [**69**] and [**70**]. Rocha and Oliveira propose a negotiation mechanism in the context of an agent-based virtual organization (VO) formation process, which selects the optimal group of organizations that satisfies the VO needs. In this scenario, each organization has the objective to maximize its own profit and, for that, the negotiation process takes into account the rationality and self-interestedness of the agents. The *Q-negotiation* includes a multi-attribute negotiation with several rounds and qualitative feedback. Additionally, the agents are able to learn (adapt) their strategies during bid formulation, due to the inclusion of a Q-learning algorithm. According to the authors '(...) Q-learning enables on-line learning, which is an important capability (...) where agents will learn in a continuous way during all the negotiation process, with information extracted from each one of the negotiation rounds, and not only in the end with the negotiation result'. The authors believe that the Q-negotiation protocol can be useful in their domain, given that they perform the necessary adaptation.

Figure 8 shows the *GQ-negotiation* protocol (Generic *Q-negotiation*) that results from the adaptation of Rocha and Oliveira protocol, applied to their domain.

The *monitor* agent sends the problem to the *supervisor* agent, including information about the dimension affected (aircraft, crew, or passenger) as well as the schedule time and costs (flight, crew, and passenger). The agent supervisor assumes the role of *organizer* and using the information about the problem, prepares a call-for-proposal (cfp) that includes the problem, a range of preferred values for delay, flight costs, crew costs, passenger costs, passenger trip time, and a negotiation deadline. After the cfp, the first round of negotiation starts. The ACManager, CrewManager, and PaxManager agents (*respondent* agents) present the proposal according to their interests. For example, the ACManager wants to minimize the flight costs and delay, and the PaxManager wants to minimize the passengers trip time and cost.

It is important to point out that the proposals presented by the *respondent* agents are based on the candidate solutions found by their specialist agents as explained in sections 3.4.2 and 3.5. The proposals are evaluated by the supervisor and qualitative feedback is sent to the *respondent* agents. At this time, the

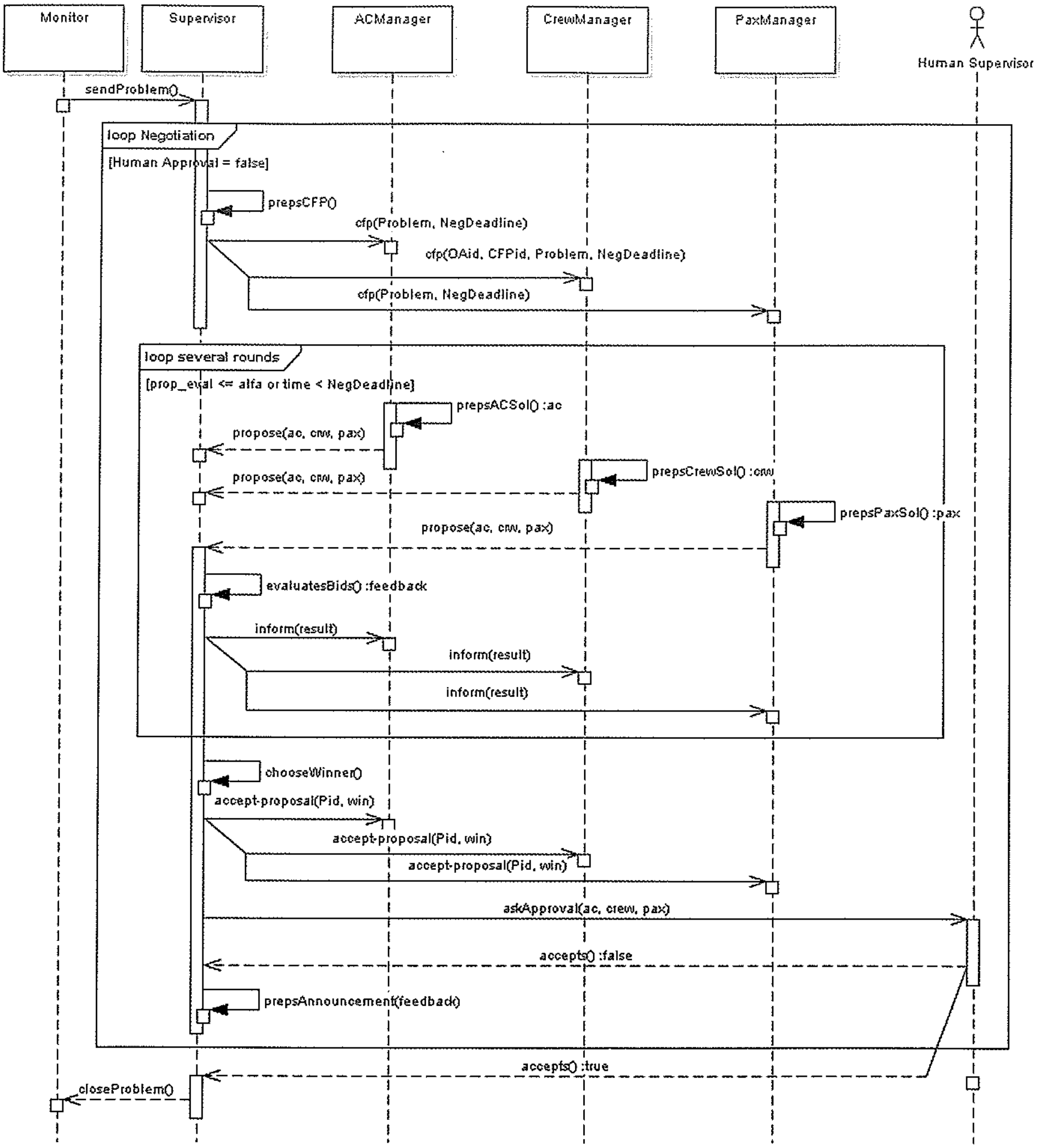


Fig. 8 GQ-negotiation protocol

supervisor agent uses a simple function to evaluate the proposals as indicated in equation (1)

$$ev = \frac{\begin{array}{c}\alpha(\mathrm{da}/\max(\mathrm{DA})) + \beta(\mathrm{dc}/\max(\mathrm{DC}))\\ + \gamma(\mathrm{tt}/\max(\mathrm{TT})) + \delta/3(\mathrm{ac}/\max(\mathrm{AC})\\ + \mathrm{cc}/\max(\mathrm{CC}) + \mathrm{pc}/\max(\mathrm{pc}))\end{array}}{\alpha + \beta + \gamma + \delta} \qquad (1)$$

In this equation, da, dc, and tt, represent the aircraft delay, crew delay, and passenger trip time; ac, cc, and pc represent the aircraft cost, crew costs, and passenger cost of a specific proposal. The set of aircraft delay from all proposals is represented by DA and a similar approach is followed for the other equation components. Each component has a weight represented by α, β, γ, and δ with values between 0 and 1.

Using the feedback, the *respondent* agents change their proposals. The bid formulation process uses a Q-learning algorithm endowing the agent with the capability to learn on-line along with the negotiation process. This loop of proposals and feedback ends when the supervisor agent founds a proposal that satisfies its preferences. The *respondent* agents are informed of the result.

After having the best solution, the upervisor agent shows the *human supervisor* the solution and the rationale behind it. The *human supervisor* can choose to apply it or not. If he chooses to not apply the solution, some feedback is given. For example, and for a specific problem, it might be better to have lower passenger costs even if it means higher flight costs. Using this feedback, the supervisor agent (the one with the *organizer* role in the negotiation process) improves the range of preferences included in the cfp and the negotiation process restarts.

Before concluding this section, it is important to point out that Ehlers and Langerman [**71**] proposed the use of an intelligent interface agent that uses a hybrid approach (combination of an expert system and a Q-learning system) to learn the preferences of the users when solving disruptions in airline schedules. Although there are some similarities (starting with the domain), the authors believe that their approach differs considerably. For example, the authors use an MAS that represents the AOCC and in this context, the agents are able to negotiate and learn autonomously. There are other differences but this one, by itself and in the authors' understanding, shows the main difference between the two approaches.

3.4.2 Team level negotiation

At the team level, the MAS uses a fipa-contract.net [**68, 72**] protocol with some modifications. Figure 9 presents this protocol applied to the CrewManager team.

The *Monitoring* agent requests a solution to a specific problem. If the CrewManager agent (*organizer*) has the expertise to propose a solution, he can decide to reply. For that, he issues a cfp to start the negotiation process. On the cfp, information about the problem as well as deadlines for receiving an answer (refuse/propose) and for receiving the candidate solution from the *responder agent* is included (*CrewSimmAnneal* in the example).

The *respondent* agent answers back with refuse or propose. If he answers with propose, it means that he will seek for a possible solution according to the cfp conditions. The *organizer* agent answers back with an accept-proposal. To speed up the communication, it was here that the authors simplified the protocol. In the authors' approach, they do not need to select from the received answers, because they want all available agents to work in parallel. That is the reason why the answer from the *respondent* agents is 'yes' or 'no', meaning that they are available (or not) to seek for candidate solutions. If the *respondent* agent finishes the task with success, it will send the candidate solution included in the inform-result performative. If he fails, the reasons are included in a failure performative.

After receiving all the candidate solutions, the *organizer* agent needs to select the best one. This process is explained in reference [**5**] and is based on the *Total Operational Cost* criteria. Table 3 summarizes the costs involved.

3.5 Problem solving algorithms

As seen in Fig. 6 (section 3.3), the aircraft and crew dimension have, each one, a team of specialist agents. Each agent should implement a heterogeneous problem solving algorithm on the team they belong to. Preliminary results show that a single problem solving algorithm is not able to solve, dynamically and within the required time restriction, all types of problems that the authors have identified during their observations (see section 2.3). Taking advantage of the modularity, scalability, and distributed characteristics of the MAS paradigm, the authors are able to add as many specialist agents as required, so that all types of problems are covered. As seen in sections 4.3 and 4.4.2, the idea is to have all specialist agents of a team looking for solutions concurrently.

In this section, the authors are going to show how they have implemented one of the specialist agents of the crew team, namely *CrewHillClimb*. This agent implements a hill climb algorithm. For more details regarding how the authors have implemented this and other specialist agents, please see reference [**73**].

The hill-climbing agent solves the problem iteratively by following the steps.

1. Obtains the flights that are in the time window of the problem. This time window starts at the flight date, and ends at a customizable period in the future. This will be the initial solution of the problem. The crew members' exchanges are made between flights that are inside the time window of the problem.
2. While some specific and customizable time has not yet passed, or a solution below a specific and customizable cost has not been found, repeats steps 3 and 4.
3. Generates the successor of the initial solution (the way a successor is generated is described below).
4. Evaluates the cost of the solution. If it is smaller than the cost of the current solution, it accepts the generated solution as the new current solution. Otherwise, it discards the generated solution. The way a solution is evaluated is described below.
5. Send the current solution to the CrewManager agent following the protocol as seen in section 3.4.2.

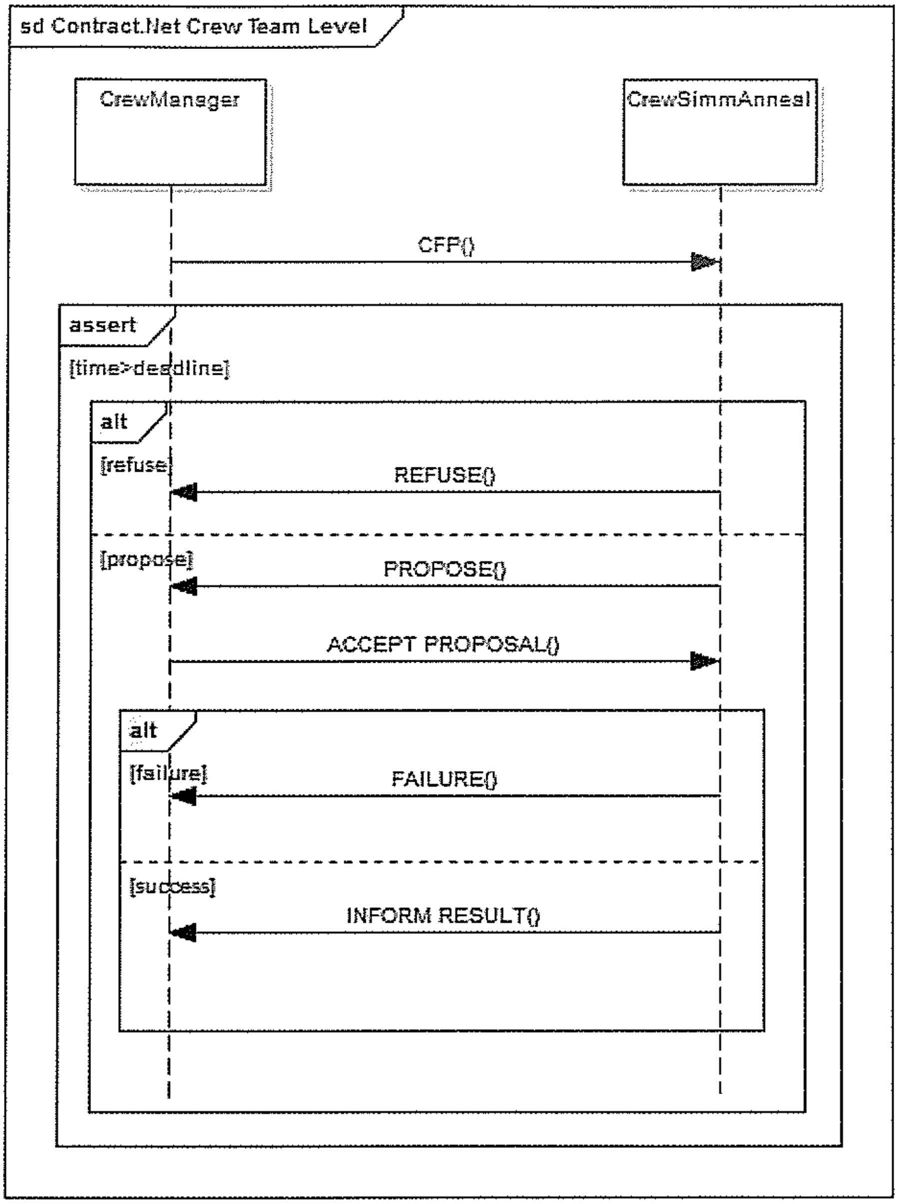


Fig. 9 Contract net protocol (simplified)

The generation of a new solution is made by finding a successor that distances itself to the current solution by one unit, that is, the successor is obtained by one, and only one, of the following operations:

(a) swap two crewmembers between flights that belong to the flights that are in the time window of the problem;
(b) swap a crewmember of a flight that belongs to the flights that are in the time window of the problem with a crewmember who is not on duty, but is on standby.

When choosing the first element to swap, there are two possibilities:

(a) choose randomly;
(b) choose an element that is delayed.

The choice is made based on the probability of choosing an element that is late, which was given a value of 0.9, so that the algorithms can proceed faster to good solutions (exchanges are highly penalized, so choosing an element that is not late probably would not reduce the cost, as a possible saving by choosing a less costly element probably would not compensate the penalization associated with the exchange).

If the decision is to exchange an element that is delayed, the list of flights will be examined and the first delayed element is chosen. If the decision is to choose randomly, then a random flight is picked, and a crewmember or the aircraft is chosen, depending on the probability of choosing a crewmember, which was given a value of 0.85. When choosing the second element that is going to swap with the first, there are

Table 3 Summary of costs involved

No.	Equations	Description
2	$tc = dc + \beta qc \quad \beta \in R, \beta \geqslant 0$	Total operational cost includes direct operational costs (dc) and quality operational costs (qc)
3	$dc = cc + fc + pc$	Direct operational costs included crew costs, flight costs, and passenger costs
4	$cc = \sum_{i=1}^{\lvert F\rvert}\sum_{j=1}^{\lvert C\rvert}(\mathrm{Salary}_{\{i,j\}} + \mathrm{Hour}_{\{i,j\}} + \mathrm{Perdiem}_{\{i,j\}} + \mathrm{Hotel}_{\{i,j\}} + Dhc_{\{i,j\}})$ where $i \in F; F = \{\text{all flights in solution}\}$ $j \in C; C = \{\text{all crewmembers in flight}\}$	Crew cost includes salaries, extra hours, perdiems, hotel, and extra-crew travel costs
5	$fc = \sum_{i=1}^{\lvert F\rvert}(\mathrm{Airp}_i + \mathrm{Service}_i + \mathrm{Ma\,int}_i + \mathrm{Atc}_i + \mathrm{Fuel}_i)$ where $i \in F; F = \{\text{all flights in solution}\}$	Flight cost includes airport costs, service costs, average maintenance costs, ATC en-route charges, and fuel
6	$pc = \sum_{i=1}^{\lvert F\rvert}\sum_{d=1}^{\lvert D\rvert}(\mathrm{Meals}_{\{d,i\}} + \mathrm{PHotel}_{\{d,i\}} + \mathrm{Comp}_{\{d,i\}})$ where $i \in F; F = \{\text{all flights in solution}\}$ $d \in D; D = \{\text{all delayed passengers in flight}\}$	Passenger cost of disrupted passengers includes airport meals, hotel costs, and compensations
7	$qc = \alpha \sum_{i=1}^{\lvert F\rvert}\sum_{p=1}^{\lvert PP\rvert}(P_{\{p,i\}} * C_{\{p,i\}})$ where $i \in F; F = \{\text{all flights in solution}\}$ $p \in PP; PP = \{\text{flight passengers profiles}\}$ P = number of passengers of profile p C = delay cost of each passenger on profile p α = coefficient to convert to momentary costs	Quality costs are related with passenger satisfaction. For more information about this topic please consult references [74] and [5]

two possibilities:

(a) swap between elements of flights;
(b) swap between an element of a flight and an element that is not on duty.

The choice is made based on the probability of choosing a swap between elements of flights, which was given a value of 0.5.

The evaluation of the solution is done by an objective function that measures the following types of costs:

(a) the crew cost according to equation (4) in Table 3;
(b) the penalization for exchanging elements;
(c) the penalization for delayed elements. The cost associated with this aspect is the highest, because the goal is to have no delayed elements.

The hill-climbing objective function (hc) is given by equation (8)

$$hc = cc + excW * nExc + delayW * nDelay \tag{8}$$

In this equation, cc represents the crew cost calculated according to equation 3, excW represents the

```
GregorianCalendar currentDate = new GregorianCalendar();
int secondsExecution = (int) ((currentDate.getTimeInMillis() - startDateResolution.getTimeInMillis()) / 1000);
while(!Shared.to(problem.getNumSeconds(), secondsExecution, problem.getMaxCost(), currentSolutionCost))
{
// get successor
successor = Shared.generateSuccessor(Shared.copyArrayList(currentSolution));
// checks if successor has an inferior solution cost
successorCost = Shared.calculateCost(successor, initialPlainSolution);
System.out.println(“Successor Cost:” + successorCost + “\n”);
if(sucessorCost < currentSolutionCost)
{
currentSolution = successor;
currentSolutionCost = successorCost;
}
currentDate = new GregorianCalendar();
secondsExecution = (int) ((currentDate.getTimeInMillis() - startDateResolution.getTimeInMillis()) / 1000);
}
```

Fig. 10 Implementation of the hc algorithm in Java penalization for crew exchanges, nExc represents the number of crew exchanges, delayW represents the penalization for delaying crewmembers, and nDelay the number of delayed crewmembers.

Figure 10 shows the implementation of the hill-climbing algorithm in Java.

4 EXPERIMENTAL SET-UP

To evaluate the authors' approach, a scenario that includes three operational bases (A, B, and C) has been set up. Each base includes their crewmembers, each one, with a specific roster. The data used corresponds to a real airline operation of June 2006 of base A. A scenario was simulated where 15 crewmembers, with different ranks, did not report for duty in base A. In Table 4, the authors present the collected information for each event.

Each event corresponds to a crewmember who did not report for duty in a specific day. The data for each event are presented in Table 5. As an example, event 15 corresponds to the following: Allan, a crewmember with number 65 and rank OPT (first officer), belongs to crew group 1 (flight crew), did not report for duty with ID 4LIS50A with briefing time at 14:20 on 25 June 2006. This flight has 83 economy passengers and two business passengers and it did not delay on departure. The new crewmember must have the same rank and belong to the same group. The duty ends at 19:40 on 28 June 2006 and the rest period end at 07:40 on 29 June 2006. For the payroll, the duty will contribute with 219 min. Solutions were found after setting up the scenario, using four different methods.

Table 4 Description of the information collected for each event

Attribute	Description
Event ID	A number that represents the ID of the event. For tracking purposes only
Duty date time	The start date and time of the duty in UTC for which the crew did not report
Duty ID	A string that represents the ID of the duty for which the crew did not report.
Flight delay	Flight delay in minutes
C Pax	Number of passengers in business class
Y Pax	Number of passengers in economy class
End date–time	The end date and time of the duty in UTC for which the crew did not report
Ready date–time	The date and time at which the crew member is ready for another duty after this one
Delay	The delay of the crewmember. The authors have considered 10 min in their scenario
Credit minutes	The minutes of this duty that will count for payroll
Crew group	The crew group (Technical = 1; Cabin = 2) that the crewmember belongs to
Crew rank	CPT = Captain; OPT = First Officer; CCB = Chief Purser; CAB = Purser
Crew number	The employee number
Crew name	The employee name
Base ID	The base where the event happened. The authors considered all events in base A
Open positions	The number of missing crews for this duty and rank. The authors used a fixed number of 1

UTC, Coordinated Universal Time.

The first three methods, named *human (M1)*, *agent-no-quality (M2)*, and *agent-quality (M3)* are explained in reference [5]. Basically, in the *human* method, the authors have used a human controller from the AOCC, using current tools, to find the solutions. In the *agent-no-quality* method, an agent-based approach was used without considering the quality costs as presented in equation (7) in Table 3. In the *agent-quality* method, the quality costs were considered. For more information, please see reference [5].

In the fourth method, the authors have used the approach presented in section 4, but without the user feedback (see section 3.4.1). Table 6 presents the collected data.

5 RESULTS AND DISCUSSION

The discussion that compares method 1 (*human*), method 2 (*agent-no-quality*), and method 3 (*agent-quality*) was presented in the authors' previous work [5]. A summary of the main results as presented in their previous work follows.

1. On average, the *agent-quality* method decreases the flight delays in approximately 36 per cent.
2. The *agent-quality* method is, on average, 3 per cent slower than *agent-no-quality* in finding solutions and produces solutions that represent a decrease of 23.36 per cent on the total operational costs.
3. The *agent-quality* method decreases the direct operational costs in 41 per cent and the *agent-no-quality* method in 45.5 per cent when compared with the *human* method.
4. The *agent-quality* method has a higher direct operational cost (8 per cent) than *agent-no-quality*, because it uses the quality operational costs in the decision process.

In Table 7, the authors compare the approach presented in this article (*integrated*) with all the previous ones, using five indicators:

(a) flight delays;
(b) quality costs;
(c) direct operational costs;
(d) total operational costs;
(e) time to find a solution.

The reference values were extracted from the experimentation results as presented in Table 8. As it is possible to see, information regarding flight delays, quality costs, and total operational costs was not available for the *human* method. In the *integrated*

Table 5 Events used (testing)

	Duty date–time	DutyID	Flight delay	C Pax	Y Pax	End date–time	Ready date–time	Credit minutes	Crew group	Rank	Crew number	Crew name
1	05-06 07:25	1ORY149S	0	7	123	05-06 13:35	06-06 01:35	370	2	CAB	80	John A
2	05-06 07:25	1ORY149S	10	11	114	05-06 13:35	06-06 01:35	370	2	CAB	45	Mary A
3	05-06 07:25	1ORY85P	0	10	112	05-06 13:35	06-06 01:35	370	1	CPT	35	Anthony
4	15-06 04:10	2LIS24X	30	0	90	16-06 16:15	17-06 04:15	1757	2	CAB	99	Paul M
5	15-06 04:10	3LIS25X	25	3	77	15-06 09:20	15-06 21:20	632	2	CAB	56	John B
6	15-06 12:50	2LHR63P	5	25	85	16-06 20:45	17-06 08:45	1549	1	CPT	57	Paul S
7	15-06 12:50	2LHR63P	0	20	95	16-06 20:45	17-06 08:45	1549	1	OPT	53	Mary S
8	15-06 14:15	1LHR31P	0	23	52	15-06 20:55	16-06 08:55	843	2	CCB	23	Sophie
9	15-06 15:25	2LHR19P	10	27	105	16-06 20:45	17-06 08:45	1341	2	CCB	34	Angel
10	15-06 15:25	1ZRH12X	0	5	115	17-06 09:30	17-06 21:30	1318	1	CPT	32	Peter B
11	25-06 05:20	1LIS16S	20	3	97	25-06 15:05	26-06 03:05	585	2	CAB	20	Paul G
12	25-06 05:20	1LIS16S	5	2	108	25-06 15:05	26-06 03:05	585	2	CAB	10	Alice
13	25-06 05:20	1LIS158T	0	4	92	25-06 15:05	26-06 03:05	585	2	CAB	15	Daniel
14	25-06 06:15	3LIS174S	0	1	129	27-06 16:15	28-06 04:15	1258	2	CAB	71	George
15	25-06 14:20	4LIS50A	0	2	83	28-06 19:40	29-06 07:40	219	1	OPT	65	Allan

Table 6 Partial data for method 4

	Duty ID	Base ID	Crew group	Rank	Hour pay	Perdiem pay	Quality operational cost	Direct operational cost
1	1ORY149S	B	2	CAB	0.00	72.00	0	86.40
2	1ORY149S	A	2	CAB	0.00	72.00	501.31	72.00
3	1ORY85P	C	1	CPT	0.00	106.00	0	148.40
4	2LIS24X	B	2	CAB	637.77	144.00	838.11	938.12
5	3LIS25X	B	2	CAB	0.00	72.00	1021.42	86.40
6	2LHR63P	C	1	CPT	102.90	212.00	272.10	440.86
7	2LHR63P	B	1	OPT	37.22	144.00	0	217.46
8	1LHR31P	B	2	CCB	229.17	72.00	0	361.40
9	2LHR19P	C	2	CCB	0.00	144.00	788.78	201.60
10	1ZRH12X	B	1	CPT	0.00	212.00	0	254.40
11	1LIS16S	C	2	CAB	0.00	80.00	426.98	112.00
12	1LIS16S	A	2	CAB	0.00	80.00	144.34	180.00
13	1LIS158T	C	2	CAB	0.00	31.00	0	43.40
14	3LIS174S	B	2	CAB	985.00	216.00	0	1081.20
15	4LIS50A	A	1	OPT	152.72	288.00	0	440.72
	Total				1844.77	1945.00	3993.02	4564.36

Table 7 Integrated method versus all the previous

	Integrated (M4) (reference values)	Human (M1) (on average)	Agent-no-quality (M2) (on average) (%)	Agent-quality (M3) (on average) (%)
Flight delays	6	NA	↓ 45.00	↓ 14.30
Quality costs	3993.02	NA	↓ 48.73	↓ 16.48
Direct operational costs	4564.36	↓ 35.16 %	↑ 18.88	↑ 10.51
Total operational costs	8557.38	NA	↓ 26.40	↓ 3.95
Time find a solution	28	↓ 72.27 %	↑ 12.00	↑ 7.69

approach, the authors use the two levels of negotiation as explained in section 3.4 but without the user feedback.

These results are encouraging. The authors see that the flight delays, quality costs, and total operational costs decrease. However, the direct operational costs are higher than *agent-quality* method (10.51 per cent) and higher than *agent-no-quality* method (18.88 per cent) although lower than the *human* method (35.16 per cent). If the authors read this figure as-is, they have to consider that they did not achieve an important goal. In the authors' opinion, this result should be interpreted together with the flight delay result. Although the *integrated* method increases the direct operational costs in 10.51 and 18.88 per cent, it was able to select solutions that decrease the flight delays in 14.30 and 45 per cent, respectively. Therefore, when there are several solutions to the same problem, the *integrated* method is able to select the solution with less quality costs (corresponds to better passenger satisfaction), less operational cost and, due to the relation between flight delays and quality costs, the solution with less flight delays.

Considering the above conclusion, how does it compare with a method that uses the criteria of minimizing the direct operational cost and the expected flight

Table 8 Results summary

	Human (M1)		Agent-no-quality (M2)		Agent-quality (M3)		Integrated (M4)	
	Total	%	Total	%	Total	%	Total	%
Event base:								
From base A	7	47	3	20	3	20	3	20
From base B	6	40	7	47	7	47	6	40
From base C	2	13	5	33	5	33	6	40
Time to find solution (average seconds)	101	100.00	25	24.75	26	25.74	28	27.72
Flight delays (average minutes)			11	100.00	7	63.64	6	54.54
Base A (average)			14	40	7	30	5	29
Base B (average)			9	26	4	17	6	35
Base C (average)			12	34	12	52	6	35
Direct operational costs	7039.60	100.00	3839.36	54.54	4130.07	58.67	4564.36	64.84
Total by base								
Base A	4845.55	92.42	288.00	11.23	578.83	14.02	592.72	12.99
Base B	1796.40	34.26	1275.80	49.77	1429.54	34.61	3025.38	66.28
Base C	397.60	7.58	2275.56	88.77	2121.70	51.37	946.26	20.73
Quality operational cost			7788.47	100	4781.53	61.39	3993.02	51.27
Total by base								
Base A			1649.57	21.18	593.30	12.41	645.65	16.17
Base B			3617.66	46.45	1562.19	32.67	1859.52	46.57
Base C			2521.24	32.37	2626.04	54.92	1487.86	37.26
Total operational costs			11 628.01	165	8911.60	126.6	8557.38	121.6
Total by base								
Base A			1937.57	16.66	1172.13	13.15	1238.37	14.47
Base B			4088.42	35.16	2991.73	33.57	4884.90	57.08
Base C			4796.80	41.25	4747.74	53.28	2434.12	28.44

delay? It is a reasonable question, because the flight delay is the variable that has the biggest impact on passenger satisfaction and the authors could expect that the results were the same. Therefore, in general, the authors may say that this assumption is true. However, what should happen when the authors have two solutions for the same problem, with the same delay and direct operational cost? Which one should be chosen? For the authors, it depends on the on-board passenger profiles and the importance that they give to the delays. It is an important value that the authors capture with their quality operational cost. The authors' approach uses all these criteria to achieve the best integrated solution and, and because of the GQ-Negotiation protocol, they were able to decrease the quality operational costs in 16.48 and 48.73 per cent when compared with the *agent-quality* (that also uses quality operational costs in the decision process) and *agent-no-quality* approach, respectively.

Regarding the time to find a solution, the *integrated* approach took 7.69 per cent more time than the *agent-quality*, 12 per cent more time than the *agent-no-quality* and 72.27 per cent less time than the *human* approach. Considering the comparison between the methods that use agents and the *integrated* one, the fact that the authors are using a negotiation protocol at the *managers level* explains this figure. However, the average time (28 s) is still within the acceptable values, and so this increase has a minor impact on the proposed approach.

It is important to point out that the authors need to evaluate a higher number of scenarios with data from all year round. The air transportation domain has seasonal behaviours and that might have an impact on the results the authors have found in their work. Nevertheless, they believe that these results are encouraging.

6 CONCLUSION AND FUTURE WORK

The authors have introduced the AOCP as well as the AOCC, including typical organizations and problems, the current DM process, and a description of the main costs involved.

The authors proposed a new concept for DM in airline operations control, where the most repetitive tasks are performed by several intelligent software agents, integrated in a MAS that represents the AOCC. The authors found that the multi-agent paradigm is very adequate to model this type of problem and, as such, the authors presented the reasons that make them adopt it. A description of the proposed solution with agents and some of their characteristics (social awareness and autonomy, for example), as well as their roles and protocols used, was included. The authors presented the costs criteria as well as the negotiation algorithms used as part of the decision mechanisms.

Four different methods were used to test the authors' approach using data from an airline company. The results show that with the authors' approach and when compared with methods that minimize direct operational costs, it is possible to have solutions with shorter flight delays while contributing to better passenger satisfaction.

Several improvements are expected in a very short term. Among them, the authors would like to point out the following.

1. Complete the implementation of the GQ-Negotiation protocol as described in section 3.4.1, especially, the inclusion of the user feedback and the associated learning mechanisms. By including knowledge provided by the user as well as from the other specialist agents, the authors are improving the distributed characteristics of their approach.
2. Use the knowledge gathered from learning to improve robustness of future schedules.
3. Improve autonomy and learning characteristics of the *Monitor* agent, so that he is able to consider new events (or change existing ones) according to the experience he gets from monitoring the operation, without relying exclusively on the definition of events created by the human operator.

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