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Agent-Based Modeling and Simulation of Coordination by Airline Operations Control

Soufiane Bouarfa, Henk A. P. Blom, Ricky Curran

***Abstract*— Motivated by the need to understand and further optimize coordination processes in the socio-technical air transportation system, this paper implements and compares four coordination policies through agent based modelling and simulation (ABMS). Three policies are based on established practices, while a fourth is based on the joint activity coordination theory from the psychology research domain. For each of these four policies, the relation with the literature on coordination is identified. The specific application of the four policies concerns Airline Operations Control (AOC), which core's functionality is one of coordination and taking corrective actions in response to a large variety of airline operational disruptions. In order to evaluate the four policies, an agent based model of the AOC and crew processes has been developed. Subsequently, this agent based model is used to assess the effects of the four AOC policies on a challenging airline disruption scenario. For the specific scenario considered, the joint-activity coordination based AOC policy outperforms the other three policies. More importantly, the simulation results provide novel insight in operational effects of each of the four AOC policies, which demonstrates that ABMS allows to analyze the effectiveness of different coordination policies in the highly complex socio-technical air transportation system.**

***Index Terms*—Airline Operations Control, Coordination, Joint Activity, Complex Large Socio-Technical Systems, Agent-Based Modelling and Simulation, Airline Disruption Management, Decision-Making.**

I. Introduction

COORDINATION is well developed in multi-agent systems research [1-6], with prominent application examples that include the framework for environment centered analysis and design of coordination mechanisms of Decker [7], the programmable coordination architecture for mobile agents of Cabri et al. [8], and the decentralized Markov decision process framework of Bernstein et al. [9]. Despite all these advances, important aspects that a human team can handle are not yet well understood in terms of multi-agent coordination models [10, 11]. A deeper, formal understanding of coordination in human teams could help researchers develop new insights and more efficient coordination strategies.

In order to contribute to this development, the aim of this paper is to conduct an Agent-Based Modelling and Simulation (ABMS) study of coordination in the highly complex socio-technical air transportation system. ABMS has proven to be of great use in identifying emergent behavior in the complex socio-technical air transport system [12]. Key ABMS application examples are in non-nominal air traffic response to air traffic control instructions [13], network-wide air traffic delay analysis [14, 15], agent-based safety risk analysis [16, 17], and artificial phase transitions in air traffic [18]. However, to the best of the author's knowledge, using ABMS for gaining a better understanding of the role of coordination in the socio-technical air transport system is novel.

Due to its open nature, the air transportation system is subject to daily disruptions from outside such as severe weather or volcano eruption. These external events may add to or interfere with various internal disruptions, such as an aircraft mechanical failure during operation. The management of these unforeseen airline disruptions requires ample coordination by the Airline Operations Control (AOC) centre.

Pujet and Feron [19] have investigated the dynamic behavior of an AOC center of a major airline using a discrete event model. In their model, each agent was represented as a multi-class queuing server, and the AOC as a multi-agent, multi-class queuing system. Since then several other AOC studies, e.g. [20-24], have focused on developing decision-support tools rather than studying the socio-technical challenges of the operation.

There are also a few studies addressing AOC as a socio-technical system [25-28]. Kohl et al. [25] have studied numerous aspects of airline disruption management, and argue that realistic approaches to disruption management must involve humans in the key parts of the process. Feigh [26] has examined the work of airline controllers at four US airlines of varying sizes, and applied an ethnographic approach for the development of representative work models. Bruce [27, 28] has examined many aspects of decision-making by airline controllers through conducting multiple case studies at six AOC centers. Although these socio-technical studies provide valuable insight into the challenges of an AOC center, this has not yet led to a significant improvement in the performance of the socio-technical AOC system.

The current paper studies how well multi-agent

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coordination models for socio-technical systems compare to established AOC practices. To accomplish this, the paper uses agent-based modelling and simulation to compare four specific AOC disruption management policies P1-P4 for a challenging airline disruption scenario. Policies P1-P3 are based on established AOC practices [27, 28], and policy P4 is based on the joint activity coordination theory of Klein et al. [29]. Policy P1 forms the basis for P2-P4 and makes use of several approaches from the general coordination literature, such as organization, planning, supervision, routines and protocols. Complementary to the coordination approaches of P1, policy P2 also makes use of negotiation protocols between team members. Policy P3 is similar to Policy P2, though makes use of team meetings instead of negotiation protocols. Policy P4 is an extension of Policy P3 with Team Situation Awareness [30, 31] and with the higher level coordination elements of Klein et al. [29] replacing the dedicated routines and protocols of P3.

Section II of the paper reviews the literature on coordination approaches for teams of software agents and human agents respectively. Section III provides an overview of AOC, its embedding in the larger air transportation system, and its disruption management challenges. Section IV develops the four policies P1-P4 and explains their relation with the coordination approaches reviewed in Section II. Section V describes the challenging airline disruption scenario considered. Section VI explains the development of the ABMS environment. Section VII provides the simulation results obtained for the considered airline disruption scenario and finally, Section VIII draws some key conclusions of the work.

II. COORDINATION APPROACHES IN THE LITERATURE

This section first gives an overview of coordination approaches in software agent systems, followed by a review of complementary coordination approaches in human teams.

A. Coordination by Software Agents

One of the classic coordination approaches is the **master/ slave technique** that is typically used for task and resource allocation among slave agents by a master agent [2]. The master agent plans and distributes fragments of the plans to the slaves. The slaves may or may not communicate among themselves, but must ultimately report their results to the master agent. Another classic coordination technique is the **contract net protocol** [32]. In this approach, agents assume two roles: 1) A manager who breaks a problem into sub-problems and searches for contractors to solve them, as well as to monitor the problem's overall solution, and 2) A contractor who does a sub-task. However, contractors may recursively become managers and further decompose the sub-task and sub-contract them to other agents.

Other coordination approaches include, **multi-agent planning** [2], **negotiation protocols** [33, 34], and **voting methods** [35]. In multi-agent planning, agents build and maintain a multi-agent plan that details all of the future actions and interactions required to achieve their goals, and furthermore interleave execution with more planning and re-planning. Due to the re-planning feature, multi-agent planning is particularly useful in dynamic situations. Negotiation is defined by Bussmann and Muller [34] as the communication process of a group of agents in order to reach a mutually accepted agreement on some matter. Sycara [33] has explained that to negotiate effectively, agents must reason about beliefs, desires, and other agents. Voting methods refer to various techniques that are used to describe decision-making processes involving multiple agents. Although originating from political science, they are currently used within a number of domains such as gaming theory and pattern recognition.

The various coordination approaches presented have their relative advantages and disadvantages and there is no universally best method. In general, the theoretical methods produce good results for narrowly defined coordination problems but many of their underpinning assumptions have limitations in developing real-world systems [11].

B. Complementary approaches in Human Teams

Various complementary coordination approaches are of use in human teams, ranging from routine and psychological approaches, to ecological, socio-technical and integrative approaches; i.e. a fusion of multiple different approaches [36].

Thompson [37] identified two basic complementary coordination approaches in human teams, namely **routines/protocols** and **mutual adjustment**. The first approach involves the establishment of rules which constrain the action of each unit or position into paths consistent with those taken by others in the interdependent relationship. An important assumption in coordination by routine is that the set of rules be internally consistent, and this requires that the situations to which they apply must be relatively stable, repetitive, and few enough to permit matching of situations with the appropriate rules. The second approach, mutual adjustment, involves the transmission of new information during the process of action. March & Simon [38] refer to this as "coordination by feedback". The more variable and unpredictable the situation, the greater the reliance on coordination by mutual adjustment [38].

Gittell [39] identified two other approaches, namely **team meetings** and **supervision**. Team meetings give participants the opportunity to coordinate tasks directly with one another. According to organization theory, they increase the performance of interdependent work processes by facilitating interaction among participants and are increasingly effective under conditions of high uncertainty. Supervisors, also known as boundary spanners, are individuals whose primary task is to integrate the work of other people.

Socio-technical coordination approaches include the **team situation awareness** model by Endsley & Jones [30, 31], and the **joint activity model** by Klein et al. [29]. The team situation awareness model conceptualizes how teams develop high levels of situationawareness (SA) across members and includes four crucial elements on which team SA is built. These include an understanding of what constitutes SA requirements in team settings, devices, and mechanisms that

are important for achieving high levels of shared SA and the processes that effective teams use.

The joint activity model [29] identifies three types of process phases that are required for effective coordination namely: 1) **Criteria for joint activity**; 2) **Requirements for joint activity**, and 3) **Choreography of joint activity** (see Fig. 1). The criteria for joint activity are that participants intend to work together (known as the basic compact) and their work has to be interdependent. The basic compact constitutes a level of commitment for all parties to support the coordination process, e.g. the commitment to some degree of goal alignment, and commitment to try and detect and correct any loss of common ground that might disrupt the joint activity. If these criteria are satisfied, the parties have to fulfill certain requirements such as making their actions predictable, sustaining common ground, and being able to redirect each other. The form for achieving these requirements (the choreography) is a series of activities that are guided by various signals and coordination devices.

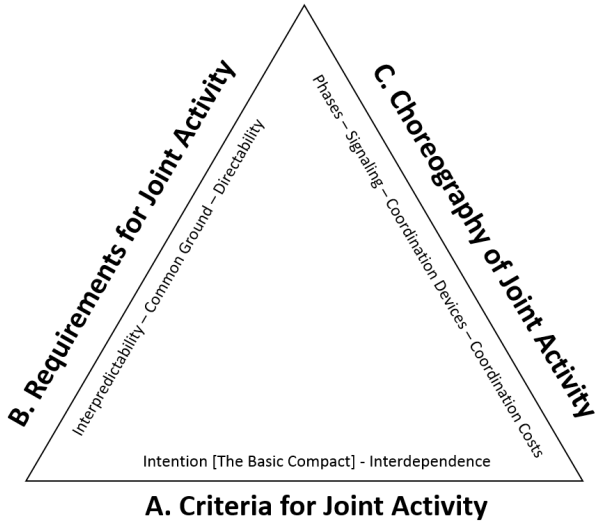

Fig. 1: Joint activity theory of Klein et al. [29]

III. AIRLINE OPERATIONS CONTROL

A. AOC embedded in the larger air transportation system

Each airline comprises of interactions between a variety of facilities, human operators, technical systems, regulations and procedures, and is embedded in the larger air transportation system that is comprised of airports, other airlines, and ATC centers. Each day of operation, the system is subject to a multitude of disruptions ranging from deteriorating weather, passenger delays, to aircraft and crew-related problems. The current practice of recovering from disruptions in commercial aviation involves multiple teams of collaborating human operators, such as:

- Flight crews on board of each commercial aircraft, who work together with teams in ATC centers, AOC centers and at airports.
- Air traffic controller teams in various ATC centers working together to allow aircraft to safely and efficiently share the same airspace.
- Airline operational controller teams working together in one of the many AOC centers to resolve any disruption affecting the schedules and plans, and to facilitate in the delivery of passengers at their destinations.
- Ground-side teams at each airport, who are responsible for handling a wide variety of ground based operations to ensure an efficient and safe boarding and debarkation of passengers and their luggage.

If a disruption affects flight plans, then human operators at the AOC center take corrective actions in real-time in order to manage the disruption. Possible actions include the cancelling or delaying of flights and swapping aircraft or crew, and are often the result of a coordination process that involves many AOC operators.

Current AOC practice consists of a coordination process between many human operators, each of which plays an essential role in disruption management. The specific organization of an AOC center depends on multiple factors. These factors include the airline size, type of airline operations, location, and airline culture. However, despite the different organization types, it is possible to identify human agents that are common to AOC centers [19, 23, 25, 40]. Fig. 2 gives an overview of a typical AOC center showing the human agents, the technical systems, and the interactions between the AOC agents and their external world (while the exact terminologies may vary per airline). It should be noted that in addition to the agents shown in Fig. 2, there exist other services in AOC centers which provide support for AOC operators (e.g. operational engineering). In addition, a crisis center which coordinates activities after an accident or incident is often an integrated part of an airline's AOC center.

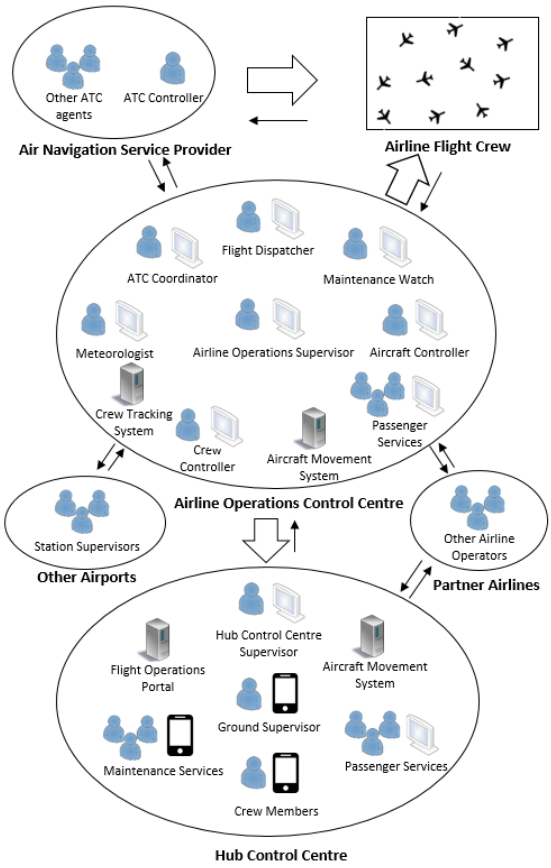

Fig. 2: AOC agents and their interactions.

B. Disruption management by an AOC center

It is important to develop a basic understanding of typical operational problems that might arise for an airline. In many cases, these problems can have a significant impact on the airline's operations, resulting in substantial deviation from the planned schedule of services. Problems originating because of a local event (e.g. aircraft mechanical failure) can trigger other problems and easily propagate to other flights [22, 40, 41]. Examples of such problems are:

- General ATC restriction related.
- Weather related: Wind, thunderstorm, low visibility, ATC restrictions.
- Equipment related: Aircraft mechanical failure or ATC system outage.
- Crew related: Misconnect violation, rest violation, duty limit violation, open position.
- Long embarking/disembarking times or delayed connecting passengers.
- Delay in ground handling operations: Cargo/baggage loading delays due to lack of resources.
- Airport capacity shortage at a given time due to traffic volume or runway unavailability, e.g. due to construction, surface repair, or broken aircraft.

In order to deal with disruptive events and reduce their impact, major airlines have established AOC Centers, an example of which is shown in Fig. 3. These Centers gather an extensive array of operational information and data, with the purpose of maintaining the safety of operations, and efficiently managing aircraft, crew, and passenger operations. When disruptions occur operators at the AOC centers adjust in real-time the flight operations by selecting and implementing the best possible actions (See table I). This is known as airline disruption management.

The main objective of airline disruption management is to ensure that operations adhere as closely as possible to the airline published schedule and the shorter-term planning of fleet assignment, aircraft routing and crew assignment (see Fig. 4). Kohl et al. [25] present the airline disruption management process that is in use by many airlines. The process has six steps namely:

1) *Operation monitoring:* in this step, the operations are monitored to check if there is anything that is not going according to plan. The state of operations is defined by the planned events (time table, fleet and tail assignment, crew scheduling, etc.)

2) *Assessment:* if an event happens (e.g. departure delay) a quick assessment is performed to see if an action is required. If not, the monitoring continues. If an action is necessary, then there is a problem that needs to be solved.

3) *Identify possible solutions:* having all the information regarding the problem, AOC operators need to identify solutions that are most appropriate for the problem (see table I).

4) *Evaluate possible solutions:* This phase involves evaluations from the passenger, crew, and aircraft perspective and possibly other perspectives. These evaluations may result in proposed changes to the solutions.

5) *Take decision:* Based on the agreed solution, one can decide whether it is necessary to implement it directly or postpone taking the decision.

6) *Implement decision:* Once a decision has been taken, it must be implemented. Consequently the operational plan needs to be updated accordingly, and the monitoring must continue.

According to Castro and Oliveira [23], for steps 2-5, AOC centers rely heavily on the experience of their controllers who use some rules-of-thumb (a kind of hidden or tacit knowledge) that exist in the AOC centers.

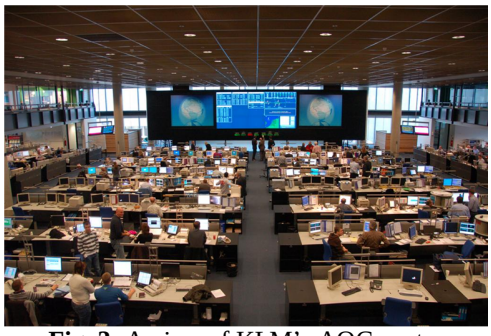

Fig. 3: A view of KLM's AOC center

TABLE I: POSSIBLE AOC ACTIONS

Problem dimension	Possible actions
	Exchange aircraft

Aircraft	Combine flights to free up aircraft Delay flight Ferry aircraft from nearby airport Lease aircraft Request high cruise speed to compensate for delay Reroute flight Cancel flight
Crew	Use crew at airport Use nearest crew to airport Exchange crew from other flights Seek extensions to crew duty time Use crew with free time Position crew from other airport Delay crew for signing in duty Use crew with vacation/ day-off Proceed without crew Propose aircraft change Accept delay/ await crew from inbound aircraft Cancel flight
Passenger	Rebook pax. to other flight at own airline Rebook pax. to other flight at other airline Keep pax. on delayed flight

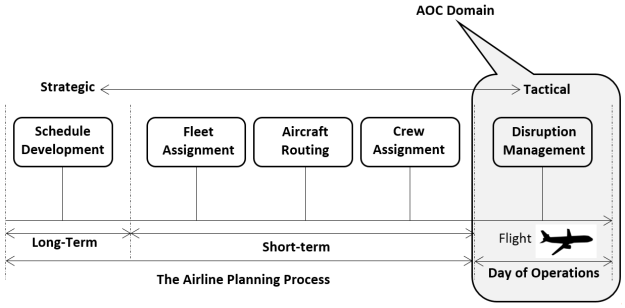

Fig. 4: Airline planning and airline disruption management

IV. AOC Disruption Management Policies

In this section we define four specific AOC disruption management policies P1-P4. Policies P1-P3 are based on established AOC practices [27, 28]. Policy P4 is based on the joint activity coordination theory of Klein et al. [29]. It is also explained how these four policies are related to the coordination approaches reviewed in Section II.

A. Established AOC Policies P1-P3

In order to select representative AOC policies and make a clear distinction between them, a critical element is the understanding of how AOC operators make their decisions in relation to various aspects during disruption management. Bruce [27] has systematically studied the decision-making processes of 52 controllers in six AOC centers. Advice was sought from an expert panel of AOC management staff to ensure that: a) the considered AOC centers were representative of airline AOC centers around the world; and 2) the participating controllers were representative of AOC operators (e.g. in terms of gender, age, years of experience in the airline industry, years of experience in the AOC domain, and previous occupation). Simulations of real life airline disruptions were conducted with each individual controller and data was collected using think-aloud protocol and observation. All comments made were recorded and transcribed verbatim. The data was classified into categories by Bruce [28] with support from an expert panel. The findings indicate that airline controllers use policies with different levels of performance. In this study, we distinguish between three AOC policies P1-P3 that correspond to these three performance levels. The details of these three policies are given in table II and explained below:

AOC policy P1 – Elementary level of performance: airline controllers identify various basic level considerations such as aircraft patterns and availability, crew commitments and maintenance limitations. For example, when a maintenance problem is reported, controllers at this level appear to acknowledge the information provided and begin considering the basic consequences of the scenario. They also identify opportunities to replace the aircraft or rebook passengers on alternative flights.

AOC policy P2 – Core level of performance: airline controllers have a greater comprehension of the problem. They take into account the more complex consequences of the problem than those evident at the elementary level. Several constraints such as crew restrictions, slot times, and curfews are identified at this level. Controllers, would for instance negotiate maintenance requirements and crew limitations in order to overcome the risk of breaching the curfew.

AOC policy P3 – Advanced level of performance: airline controllers demonstrate thinking beyond the immediacy of the problem. They examine creative ways to manage the disruption. For instance, controllers at this level would consider more complex crewing alternatives such as positioning a crew from one airport to another airport where the flight crew is needed. Also, in the case of a maintenance problem, controllers at this level would seek alternative information and recheck the reliability of information, e.g. through organizing a conference call with the maintenance watch people.

Table II: OVERVIEW OF THE THREE AOC POLICIES P1-P3 IN RELATION TO VARIOUS DISRUPTION MANAGEMENT ASPECTS

Aspect	AOC policy P1	AOC policy P2	AOC policy P3
Maintenance Information	Accept information source and content and act on information given about a maintenance situation	Challenge/ query information about a maintenance situation	Seek alternative information and recheck source and reliability.
Crewing	Await crew from inbound aircraft	Challenge crew limits/ Seek extensions to crew duty time	Seek alternative crew (e.g. from nearby base or other aircraft)
Curfews	Curfews are not taken into	Identify curfews and	Seek curfew dispension

	account	work within them	
Aircraft	Seek first available aircraft	Request high speed cruise	Combine flights to free up aircraft

B. AOC joint activity policy P4

The fourth AOC policy P4 is based on the joint activity framework developed by Klein et al. [29]. As depicted in Fig. 1, this framework identifies three types of process phases that are required for effective coordination, namely: (1) criteria for joint activity processes; (2) satisfying requirements for joint activity, and (3) choreography of joint activity. The criteria for joint activity are that the participants in the joint activity agree to support the coordination process and prevent its breakdown. If these criteria are satisfied, the parties have to fulfill certain requirements such as making their actions predictable, sustaining common ground, and being directable. The way of achieving these requirements (the choreography) is a series of activities that are guided by various signals and coordination devices. In a preceding study the potential of this joint activity theory for AOC has been identified [42].

In order to apply the joint activity based approach to AOC disruption management, Table III presents a more specific sets of rules that are defined for each of the three types of joint activity process phases [29]; which AOC agents should adhere to in order to have effective coordination.

Table III: COORDINATION RULES FOR EACH OF THE THREE TYPES OF JOINT ACTIVITY PROCESS PHASES (A,B,C) OF AOC POLICY P4

ID	Informal Coordination Rules
A 1	▪ All AOC agents are committed to support the coordination process, and carry out the required responsibilities: - Acknowledging the receipt of signals. - Transmitting construal of the signal back to sender and indicating preparation for consequent acts. - Repairing common ground. ▪ AOC agents should relax their local goals in order to permit more global (shared) goals to be addressed.
A 2	If agent A does something, it must depend in some way on what agent B does.
B 1	Each AOC agent has to make his actions predictable, e.g. estimates of time needed to complete a certain task.
B 2	To support common ground AOC agents have to: ▪ Establish routines for use during execution. ▪ Insert various clarifications and remainders, whether just to be sure of something or to give team members a chance to challenge assumptions. ▪ Update others about changes that occurred outside their view or when they were engaged. ▪ Monitor other team members to gauge whether common ground is breaking down. ▪ Detect and repair loss of common ground.
B 3	As priorities and conditions change a team member should be able to change the actions of other partners.
C 1	AOC agents should accomplish coordination one phase at a time in a joint activity, each phase having an entry, body of action, and an exit.
C2	AOC agents should constantly provide cues for coordination, e.g. they should signal to each other about a phase completion. They may also signal their understanding of a situation, their intentions, and the difficulties they are facing.
C3	▪ AOC agents should explicitly communicate their intentions (Coordination by Agreement). ▪ AOC agents should act according to rules and regulations (Coordination by Convention). ▪ As conditions change, AOC agents should decide about the interpretation of events, and adopt new norms if necessary (Coordination by Precedent). ▪ AOC Agents should observe how the ongoing work is unfolding so that the next action becomes apparent within the many actions that could conceivably be chosen (Coordination by Salience).
C4	To reduce coordination costs, AOC agents should improve their common ground and invest in adequate signaling and coordination devices (e.g. using abbreviated forms of communication while still being confident that signals will be understood).

C. Coordination approaches of P1-P4

In Table IV an overview is given of which coordination approaches reviewed in Section II apply for each of the four policies P1-P4. This shows that almost all coordination approaches of Section II (except Voting methods) are used within one or more of the four AOC policies P1-P4.

Table IV: APPROACHES FROM THE COORDINATION LITERATURE USED BY AOC POLICIES P1-P4.

Coordination Approach	Simulated Coordination Policies			
	P1	P2	P3	P4
Master/ Slave technique	+	+	+	+
Contract net protocol	+	+	+	+
Multi-agent planning	+	+	+	+
Negotiation protocol	-	+	-	-
Voting methods	-	-	-	-
Routines/ protocols	+	+	+	+
Mutual adjustment	+	+	+	+
Supervision	+	+	+	+
Team meetings	-	-	+	+
Criteria for joint activity	+	+	+	+
Requirements for joint activity	-	-	-	+
Choreography of joint activity	-	-	-	+
Team Situation Awareness	-	-	-	+

The four AOC policies P1-P4 have several of the coordination approaches from Section II in common, i.e.

master/slave, contract net protocol, multi-agent planning, routines/protocols, mutual adjustment, supervision and criteria for joint activity. This commonality stems from the typical airline manner of flight planning (Figure 4) and their AOC organization (Figure 2). Policy P1 has only one coordination approach complementary to this common set, i.e. dedicated routines/protocols in resolving a disruption. Policy P2 also makes use of negotiation protocols between team members as a complementary approach. Policy P3 is similar to Policy P2, though makes use of team meetings instead of negotiation protocols. Policy P4 is an extension of Policy P3 with Team Situation Awareness [30, 31] and a replacement of the dedicated routines/protocols of P3 by the higher-level rules in table III.

V. Airline Disruption Scenario

In order to assess the impact of the four policies (P1-P4) we will consider a challenging AOC scenario that is well described and evaluated in [27], and includes details of other ongoing flights (see Fig. 5). The scenario concerns a mechanical problem with an aircraft at Charles de Gaulle (CDG) airport, aiming for a long-haul flight (flight number 705) to a fictitious airport in the Pacific, which is indicated by the code PCF. The scenario is briefly described below:

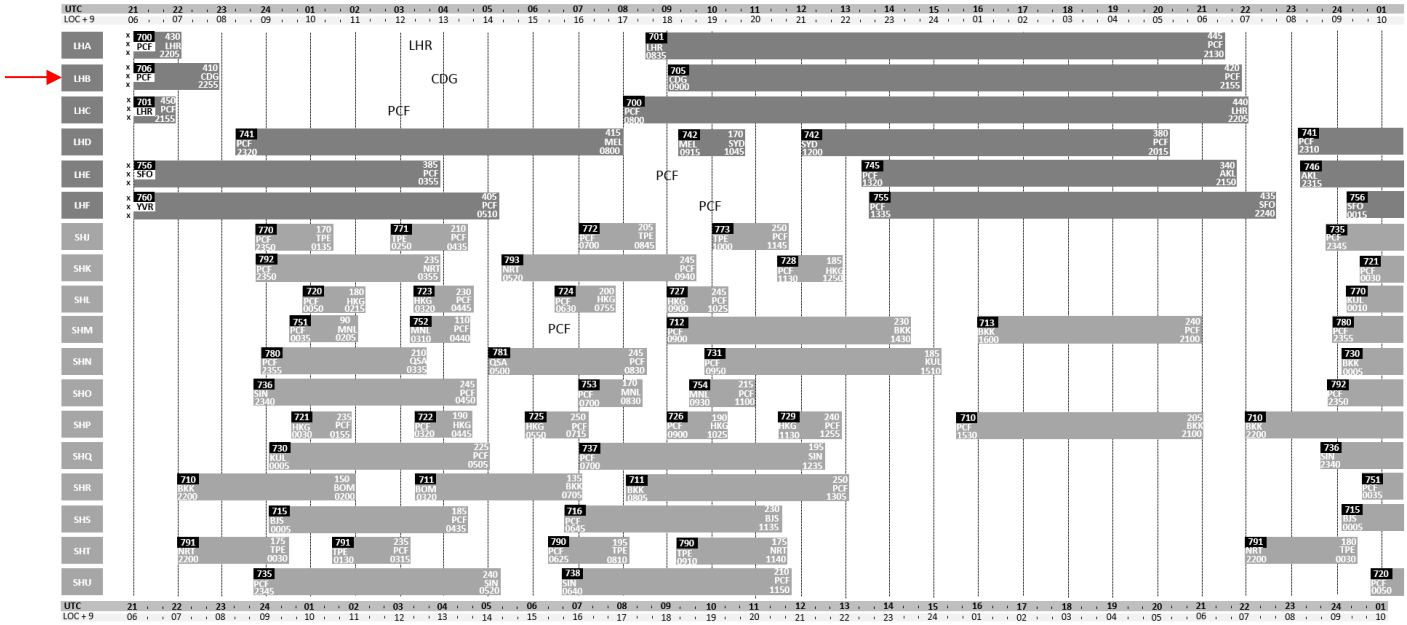

Fig. 5: A printout of the screen image at the time of disruption 06:55 Coordinated Universal Time (see top horizontal UTC time-scale). A secondary horizontal time-scale showed local time (UTC + 9 hours). The horizontal blocks (called puks) represent the flights and include relevant information such as the flight number, actual passenger loading, departure and arrival airport, and departure and arrival time. The background color of each flight block was designed to represent a type of aircraft (a darker block represents a large aircraft and a light block represents a medium sized aircraft. The longer the flight duration, the larger the size of the block. The vertical axis on the left side shows the aircraft registrations that identify each aircraft in the fleet. In this scenario the aircraft with the mechanical problem is designated by registration code LHB 'Lima Hotel Bravo' to the left of the second row highlighted by the arrow.

The time is 0655. Flight 705 is unserviceable in Paris (CDG). The engineers report that it has a hydraulic leak such that it may require a hydraulic pump change. If so, then they expect the pump change to take two hours. On this advice, the staff at CDG have stopped checking passengers in for Flight 705. After participants were given time to consider this situation, subsequent information was provided that confirmed the hydraulic pump change and advised that due to inclement weather, the maintenance work would be done in the hangar, delaying a possible departure considerably more than initial advice.

This scenario requires participants to consider strategies and consequences to resolve the delay caused by the unserviceable aircraft. The flight was progressively delayed at CDG for 3 hours due to mechanical unserviceabilities, to the extent that the operating crew were eventually unable to complete the flight within their legal duty time.

In [27], this scenario was considered by a panel of AOC management experts. They developed several alternatives, and subsequently identified the best solution, which was to re-route the flight from CDG to PCF and to include a stop-over in Mumbai (BOM). In parallel, a replacement flight crew was flown in as passengers on a scheduled flight from PCF to BOM in order to replace the delayed crew on the flight part from CDG to PCF (see Fig. 6). The question therefore is how

well the outcome of the agent-based modelling and simulation of the

AOC center compared to the expert panel in finding a best solution?

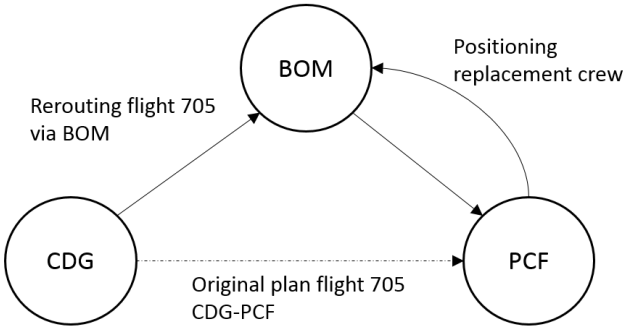

Fig. 6: The expert panel identified best solution of the scenario considered

VI. AGENT-BASED MODELLING

A. *Identifying the agents and their interactions*

In order to develop the agent-based model, a first step is to identify the main agents involved and their role in the disruption management process. The agents involved in the aircraft mechanical breakdown scenario and captured in the ABM are presented in table V.

Table V: AGENTS CAPTURED IN THE ABM

Agent	Abbreviation
Airline Operations Supervisor	AOS
Aircraft Controller	ACo
Crew Controller	CCo
Maintenance Services	MS
Airport Engineer	AE
Station Supervisor	SS
Aircraft Movement System	AMS
Crew Tracking System	CTS
Flight Crew	FC

B. *Workflow schemes and communication prescripts*

The rules of each policy are captured in the ABM through two approaches: workflow schemes and communication prescripts. Workflow models capture the role of agents, communication paths, and authority relationships between agents in the ABM. The workflows corresponding to the four policies are distinctive in terms of the agents involved, information being exchanged, and sequence of activities. For instance, when the airline operations supervisor receives a message about the aircraft mechanical problem, he can either accept the information received and seek the first available aircraft using support from the aircraft controller (Policy P1); challenge and query the information about the mechanical breakdown (Policy P2); or consult maintenance services about the mechanical breakdown (Policy P3); or apply the joint activity framework (Policy P4). Fig. 7 shows an example of the workflow corresponding to AOC policy P3.

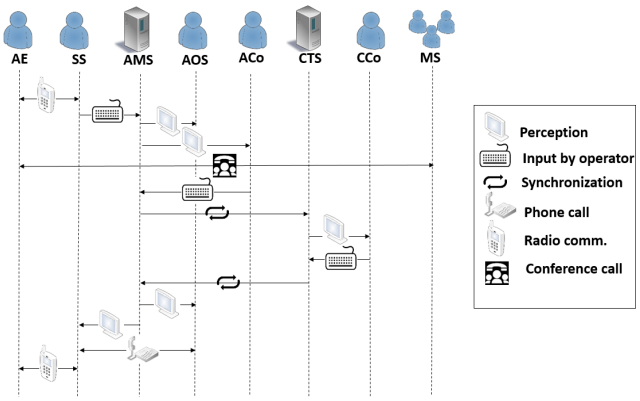

Fig. 7: Operational workflow for AOC policy P3

To formally capture the dynamic properties of socio-technical systems in an agent-based model, a formal agent-based modelling language is needed. For this purpose, the Temporal Trace Language (TTL) [43] is used. TTL has been developed for the purpose of specifying and analysing dynamic properties in multi-agent systems. Within TTL communication between two agents R_{src} and R_{dst} is expressed in the following type of predicate:

$$communication_from_to_(R_{src}, R_{dst}, C_{type}, I_{content})$$

where:

- R_{src} models the source.
- R_{dst} models the destination.
- C_{type} models the type of communication (e.g. request, inform, declare, approve, etc.).
- $I_{content}$ indicates the content of the information being communicated.

As an example the predicate:

$communication_from_to_(AE, SS, inform, leak)$ states that the Airport Engineer (AE) informs the Station Supervisor about a hydraulic leak, as a means to formalizing the communication

C. *Rule-based multi-agent modeling environment*

To implement interaction rules using the TTL communication prescripts, the authors made use of the LEADSTO simulation environment [44, 45]. LEADSTO consists of two programs: a Property editor and a Simulation tool (see Fig. 8). The first is a graphical editor for constructing and editing LEADSTO specifications, and the second is for performing simulations of the LEADSTO specifications; generating data-files containing traces for further analysis, and visualizing these traces. Fig. 8 gives an overview of the simulation tool architecture and shows its interactions with the property editor. The bold rectangular borders define the two separate tools while the arrows represent the data flow, with the dashed arrows representing control.

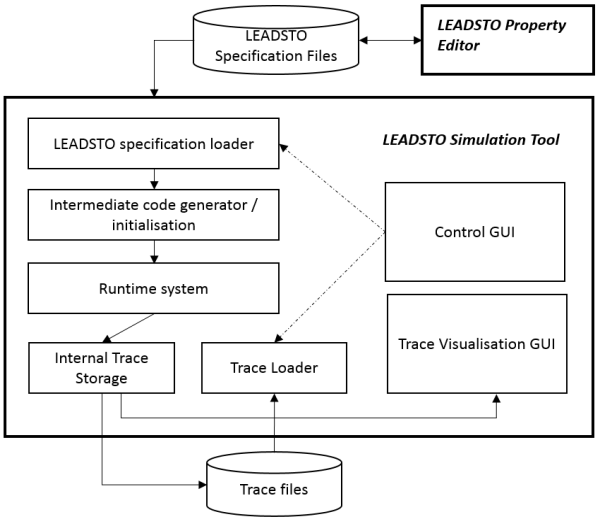

Fig. 8: LEADSTO architecture [45]

LEADSTO enables one to model direct temporal dependencies between two state properties in successive states (i.e. dynamic properties). The LEADSTO format is defined as follows: let α and β be predicates, and e, f, g, h be non-negative real numbers. Then $\alpha \rightarrow_{e, f, g, h} \beta$ means:

If predicate α holds for a certain time interval with duration g, then after some delay (between e and f) predicate β will hold for a certain time interval of length h

An example of a dynamic property in the LEADSTO format is $\alpha \rightarrow_{0.25, 1, 1, 2} \beta$ where α represents the predicate *communication_from_to_(external_world,AE,observe,leak)* and β represents the predicate *communication_from_to_(AE,SS, inform,pump_change_required)*. This property expresses the fact that, if the airport engineer AE observes that there is a hydraulic leak during 1 time unit, then after a delay between 0.25 and 1 time unit, AE will inform the station supervisor R_{SS} about the problem during 2 time units. Such a rule can be implemented using LEADSTO editor as illustrated in Fig. 9.

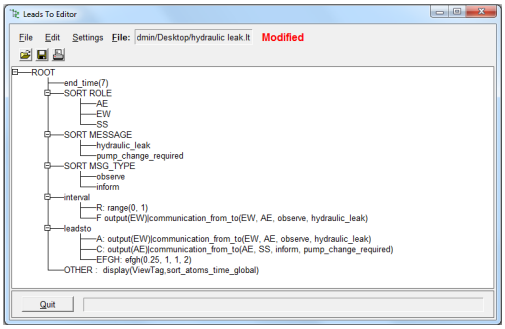

Fig. 9: LEADSTO editing

By executing this rule a trace of predicates holding true or false can be generated and visualized as can be seen in Fig. 10. In this example trace, the horizontal axis depicts the time frame while the vertical axis depicts the predicates. A blue box on each line indicates that the predicate is true.

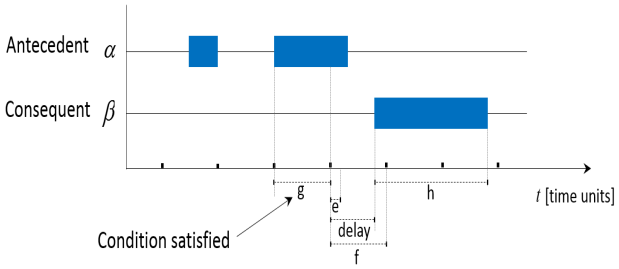

Fig. 10: Visualizing traces in LEADSTO

D. *Model Verification*

After implementing all the rules corresponding to the various AOC policies in LEADSTO, the next step is to test if these rules are implemented correctly. For this purpose, a special software environment named the TTL checker [43] was used. The TTL checker takes a rule and one or more (empirical or simulated) traces as an input and checks whether the rule holds for the trace(s). Using this environment, the formal rules can be automatically checked against the simulated trace. Traces are represented by sets of PROLOG factors of the form: $\text{holds}(\text{state}(m_1, t_2), a, \text{true})$. Here, m_1 is the trace name, t_2 time point 2, and a is a state formula in the ontology of the component's input. The above holds-statement indicates that state formula a is true in the component's input state at t_2. The programme for temporal formula checking uses PROLOG rules that reduce the satisfaction of the temporal formula to the satisfaction of the atomic state formulae at certain time points, which can be read from the trace representation.

VII. SIMULATION RESULTS

The four AOC policies introduced in Section III have been implemented and simulated in the presented agent-based model. For each of these four policies various results have been collected such as related to aircraft, crew, passengers, and the minimum time needed to manage the disruption. Table VI presents the simulation results obtained for the four AOC policies.

The outcome of policy P3 concurs with the best solution identified by the expert panel. However the outcomes of P1 and P2 are significantly worse, and the outcome of P4 even outperforms the expert panel result. In order to understand the background of these differences, the agent-based simulation results have carefully been analyzed.

Under policies P1 and P2, AOC operators make decisions based on limited coordination, as a result of which the disruption considered is not efficiently managed. The aircraft mechanical problem was eventually fixed, however the flight was cancelled. As a result, the 420 passengers were accommodated in hotels (i.e. greatly inconvenienced). This unfavorable outcome can be explained as a result of the possible actions identified by the crew controller i.e. "await crew from inbound aircraft" and "see extensions to crew duty time." Crew controllers mainly considered crew sign-on time and duty time limitations and tried to work within these

constraints. In this scenario, none of the possible actions solves the crew problem.

Under policy P3, AOC controllers consider complex crewing alternatives such as flying-in a replacement crew from another airport. Therefore, under P3 the decision was made to reroute the flight via BOM and fly-in a replacement crew from PCF into BOM. Here, both the delayed crew and replacement crew were able to operate in one tour of crew duty time. In comparison to policies P1 and P2, policy P3 is much better from both the airline and the passenger's perspectives. Regarding the minimum time required for managing the disruption policy, P3 takes more time than P1 and P2.

Table VI: SIMULATION RESULTS

AOC policy	Flight	Aircraft mechanical problem	Crew problem	Passengers problem	Minimum disruption mgmt time	Costs for the airline [Euros]		Costs for the passengers: time lost
						Operating costs	Legal pax. compensation	
P1	Cancelled	Fixed	Not resolved	Pax. accommodated in hotel (i.e. distressed)	26 min	326 kEUR	168kEUR	24h
P2	Cancelled	Fixed	Not resolved	Pax. accommodated in hotel (i.e. distressed)	30 min	326 kEUR	168 kEUR	24h
P3	Diverted	Fixed	Resolved	Pax. significantly delayed due to fixing aircraft and diverting	33 min	360 kEUR	126 kEUR	8h
P4	Delayed	Fixed	Resolved	Pax. delayed until aircraft is fixed	20 min	326 kEUR	0 kEUR	3h

Under policy P4, AOC agents make lower level decisions, like P1-P2, though under the joint-activity coordination regime. Therefore the aircraft, crew, and passenger problems were resolved with minimum disruption. The main difference between P4 and the other policies P1-P3 is that the AOC agents now act according to joint activity coordination rules (Table III). Thus, for instance, when the crew controller can't find a crew, he signals his understanding about the situation and the difficulties he is facing. Likewise, the airline operations supervisor signals his understanding back to the crew controller just to be sure of the crew situation, or to give the crew controller a chance to challenge his assumptions. Such a process of communicating, testing, updating, tailoring, and repairing mutual understandings is aimed at building common ground prior to starting the choreography phase [29]. By updating the crew controller on changes outside their information base, and coordinating by agreement (precedent and salience) they managed together with the crew controller to solve the crew problem before moving to the next coordination phase. In the scenario considered, P4 was therefore able to identify a possibility that had not been identified by any of the other three policies, and neither by the expert panel. The flight crew that had landed the aircraft at CDG had received sufficient rest to fly the delayed aircraft directly to PCF instead of enjoying their scheduled day-off in Paris. Passengers had a minimum delay compared to the previous policies (P1-P3) as they only had to wait for the aircraft to be fixed. Another relevant difference between P4 and the other policies P1-P3 is the shorter minimum time needed to manage the disruption.

VIII. CONCLUSION

Coordination is well developed in multi-agent systems research. Despite all these advances, important aspects that a human team can handle are not yet well understood in terms of multi-agent coordination models. This raised the question how well coordination methods from the literature compare to established coordination policies in a complex socio-technical system like air transportation. This question has been studied in this paper for the problem of airline disruption management by an airline operational control (AOC) center.

The approach taken has been to run agent-based simulations for agent-based models of four airline disruption management policies P1-P4. The policies P1-P3 were based on established AOC practices, and policy P4 was based on the joint activity coordination theory of Klein et al. [29]. Each of these four policies has been characterized in terms of the various coordination techniques that have been developed in the literature. This characterization showed that all but one coordination techniques identified in the literature apply to one or more of the four policies P1-P4. This supports the view that coordination techniques in the literature have reached a remarkably high level of development.

For each of the four policies an agent-based model simulation has been conducted on a challenging airline disruption scenario. This challenging scenario had previously been evaluated by an expert panel. The outcomes of the agent-based simulations showed that the performance of policy P3 was the same as the best possible outcome identified by the expert panel. The outcomes of policies P1 and P2 were significantly less good than P3. Quite unexpectedly, policy P4 even had a better outcome then policy P3. Hence P4 outperformed both the three established policies P1-P3, and the best outcome identified by the expert panel. This leads to the following three conclusions:

- There are disruptions for which established AOC coordination policies as well as expert panels may fail to identify the best solution.
- Airline disruption management can learn from the insight that is gained through taking an ABMS approach.
- For the challenging airline disruption scenario considered it would be best to make use of policy P4, i.e. the policy that is from the psychology domain.

In view of these three findings, there also are three directions for follow-up research. The first direction is to also evaluate some other airline disruption management policies through an ABMS approach, e.g. the fully automated policy of Castro et al. [24]. The second follow-up research direction is to test the different AOC policies also on other challenging airline disruption scenarios. The third follow-up research direction is to support AOC centers in improving their AOC disruption management policies

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