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Concept of separation method between aircraft in the transition period

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Abstract: The current concept of air traffic control based on human work was created many years ago and is now approaching the limit of its performance. Therefore, new concepts for air traffic control are being sought. One of the ideas is to delegate the responsibility for ensuring separation between aircraft to aircraft crews. The issue of self-separation is quite a difficult task. Analysis of the literature concludes that the transition from one phase to another will occur in stages. This paper focuses on the transition period. The concept of ensuring separation when changing traffic organization was proposed. A vital element of the separation method in the transition period is to define the negotiation and communication process between aircraft, which was presented in this paper.

Keywords: Airborne Separation Assurance System, distributed air traffic control, new concepts of air traffic control, multi-agent systems

1. Introduction

Air traffic is increasing all the time and is expected to double over the next two decades. With the increased air traffic, there is a problem of growing congestion levels. This increases the likelihood of collision situations in the air and increases air traffic controllers' workload. Another consequence is delayed flight operations. Therefore, new solutions are sought that will change the current situation and alleviate the effects of growing congestion in air traffic management. The modern concept of air traffic control, based on the work of machine-supported humans, was created many years ago, and in the era of increasing air traffic is approaching the limit of its efficiency. The problem is the concentration of decisions and responsibility in the person of an air traffic controller, who is subject to restrictions typical for the operator of a complex anthropotechnical system. Therefore, work is underway to create new concepts of air traffic control. One of them is to delegate the responsibility for ensuring separation between aircraft to the aircraft crews. This, in turn, requires the expansion of on-board collision avoidance systems, from simple last-resort emergency

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systems to the complex assistance of Airborne Separation Assurance Systems with extensive modules for obtaining information on aircraft flight trajectories, processing them to detect potential collisions and developing solutions based on modification further trajectory. Therefore, the question arises of how to ensure separation between aircraft during the transition period, when only some of the aircraft will be equipped with systems enabling their own separation, and some of the aircraft will continue to be centrally controlled (as before) to maintain the required level of safety of flight operations.

2. New Concepts of Air Traffic Control

There are many ideas in the literature on new concepts for air traffic control, including the self-separation concept. They concern both organizational and technical issues, i.e., ASAS on-board systems. The very concept of self-separation appeared already in the 1990s. Consideration was given to delegating responsibility for ensuring separation to aircraft crews to reduce the workload of the air traffic controller, thereby increasing the capacity of airspace sectors.

The first aspect that is taken into consideration when creating such a concept is to ensure an adequate level of safety. Therefore, the first idea of delegating air traffic control to aircrews consisted of creating a new dedicated airspace in which the solution was implemented. In the study [24], a solution was proposed in which corridors were created between points with the highest traffic intensity, where aircraft with similar flight trajectories were collected. All aircraft fly in one direction. There are designated areas (lanes) in which airplanes can move. These aircraft are equipped with appropriate equipment and software, enabling them to ensure self-separation. The safety area is cylindrical with a 5 NM radius and a height of 1,000 ft. Similar solutions are also in [1] and [25]. An exciting idea for safety areas was presented in [7]. The protected zone in the presented model is a rectangular zone with dimensions *l*, which is the length of the protected zone, and *w*, which is the width of the protected zone. The mathematical model (called Rectangular Model) presented in the paper is intended to compare different alternatives of an intersection configuration of air traffic service routes based on the average number of potential conflicts per hour at route intersections, index of conflict intensity, and intersection capacity. Similar research was conducted in the paper [18], where Minimum Distance Model was presented.

The paper [3] proposes a complete separation of two types of traffic in two different sectors of airspace. The first is Managed Airspace, where air traffic follows the existing air traffic control method. The second is Free Flight Airspace, where aircraft follow optimal routes, and the responsibility for providing separation between aircraft has been delegated to aircraft crews. A transition zone of defined dimensions is provided between the different spaces, the main purpose of which is to prevent loss of separation between aircraft moving from one zone to another.

Many studies relate their assumptions to multi-agent systems [6], [9]. Multi-agent systems are systems composed of communicating and cooperating units, called agents, pursuing common goals. The paper [6] proposed a solution using multi-agent systems in distributed artificial intelligence. A set of aircraft that navigate under the concept of free flight is defined. These aircraft are modeled as intelligent agents with shared responsibilities to establish a specific common goal of providing separation between them. The common goal is achieved through joint conflict resolution (jointly outlining a plan to resolve the conflict). In most cases, multi-agent systems are used to establish distributed air traffic control, but studies [8] and [20] present the use of MAS systems as a solution to assist the controller in processing landing requests or in collision detection and avoidance. Another solution was presented in the paper where the concept of Automatic Commercial Aircraft Formation Flight was described [16]. The main goals of that paper were to bring concepts that would increase the airport runway capacity, increase airspace capacity and create an idea of how the future air transport could look. The new modes of the autopilot responsible for maintaining the minimum separation between aircraft were also described.

Recently, unmanned aerial vehicles (UAVs) have been increasingly used, which was described in [4] and [12]. UAVs can be operated autonomously or can be controlled by a pilot using an advanced remote control system. For autonomous or semi-autonomous flights, operations are based on onboard sensors, including vision and ultrasound, control signals, and positioning systems. The algorithms used, often using artificial intelligence, allow conflict situations to be detected based on the signals received. There is a similarity here to the ASAS concept, where aircraft can fly arbitrary routes and must provide their own separation.

Few studies take into account the transition period, so this paper's focus. The study [17] shows different levels of delegation of responsibility for providing separation between aircraft. The works [1], and [10-11] propose a solution in which the air traffic controller is not completely excluded from providing separation between aircraft. The work presents the allocation of responsibility for providing separation as a function of the time remaining before the conflict situation arises. According to the concept, the pilot should provide separation, but if his reaction time is too long, the responsibility for providing separation is assumed by the controller.

The issue of self-separation is quite a difficult task. Analysis of the literature leads to the conclusion that the transition from centralized air traffic control to decentralized air traffic control will occur in stages. In this situation, particular attention is necessary for effectively separating traditionally controlled air traffic and air traffic flying by the ASAS concept. Appropriate methods of negotiation and communication between conflicting aircraft must be provided.

3. The Concept of Separation Method During the Transition Period

The subject of the study is the transitional period in providing air traffic control (transition from a centralized system to a distributed system). Currently, international air traffic regulations require [13-14] that only one type of air traffic takes place in the designated airspace defined by the sector. In a given sector, the air traffic controller is responsible for ensuring separation between aircraft. Many studies (see section 2) suggest the separation of a fragment of the airspace in which aircraft could move following the idea of ASAS. To increase the level of safety of operations, a separate zone for ASAS ships is surrounded by a protection zone constituting a safety buffer. Nevertheless, it is a concept similar to the current one - only one type of traffic can take place in one traffic sector. This work will propose a new solution, the main assumption of which is that two types of traffic take place in one airspace sector. The following subsections of the chapter will discuss the assumptions regarding airspace structure, air traffic rules, and the necessary data to ensure the safe performance of operations.

3.1. The Structure of the Analyzed Airspace

It was assumed that two types of air traffic would take place in one sector, i.e., some aircraft would be centrally controlled, and some would be independent and could ensure their own separation. The sector will consider transit traffic. Individual types of traffic will have separate levels of traffic on which they should move. Still, there will be no clear boundary separating the two types of traffic from each other (see Fig. 1). In Managed airspace, aircraft are separated from each other by an air traffic controller. The FF airspace (Free Flight airspace) is intended for aircraft that can ensure their separation. MIXED airspace is intended for both types of traffic, where appropriate systems support inter-system separation.

Fig. 1. Vertical section of the analyzed airspace (source: own elaboration)

3.2. Air Traffic Rules

There are two types of traffic in MIXED space - centrally controlled air traffic and distributed air traffic. Distributed air traffic is all aircraft flying under the ASAS concept. Their routes run directly from an entry point to an exit point in a given sector. Centrally controlled traffic corresponds to the current air traffic organization, where the controller ensures separation between aircraft.

For both traffic types, the current separation standard, which is 5 NM in the horizontal plane and 1000 feet in the vertical plane, is maintained.

A solution based on access to traffic situation data was used to ensure the integration of both traffic types. Centrally controlled aircraft transmit their position and velocity data but do not receive data from the outside, and therefore, ASAS aircraft are not visible to conventionally flying aircraft. Centrally controlled aircraft are visible to ASAS aircraft; therefore, ASAS aircraft can separate themselves from conventional traffic. For this solution, it is necessary to ensure adequate communication between the participants of different types of traffic. A simplified diagram of how this situation is handled is shown in Fig. 2. Aircraft operating under the ASAS concept transmit data about their status but can also receive data from other traffic participants, which allows them to detect a conflict situation and propose a solution. The solution proposals are sent to the air traffic controller, with whom negotiations are conducted on the choice of a solution for the conflict situation.

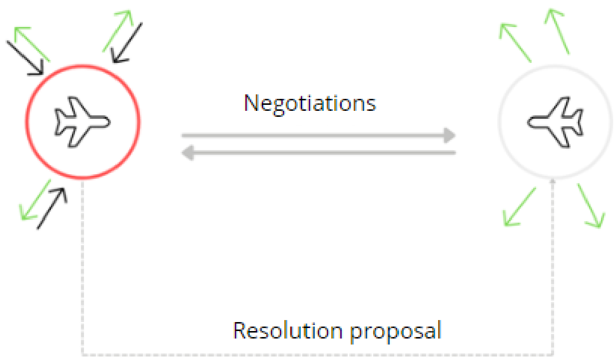

Fig. 2. Integration of two types of air traffic (source: own elaboration)

When air traffic control is delegated to aircraft crews that are supported by appropriate systems, the technical limitations of the operation of these systems (operating range) must be taken into account. Therefore, tactical planning must be introduced here. Therefore, a time horizon of 5 minutes was assumed for the analysis. Since the adopted time horizon is quite short, it is necessary to adapt the execution of evasive maneuvers in pairs to accelerate the process of conflict resolution.

This paper defines four types of available maneuvers to resolve the conflict situation: turn right, turn left, climb, and descend. In natural conditions, maneuvers in the speed change category are also used; however, given the adopted time horizon for analyzing the traffic situation, which is 5 minutes, and air traffic control practices in which speed control separation provision is made 10 minutes before the anticipated event, this solution will not be considered further.

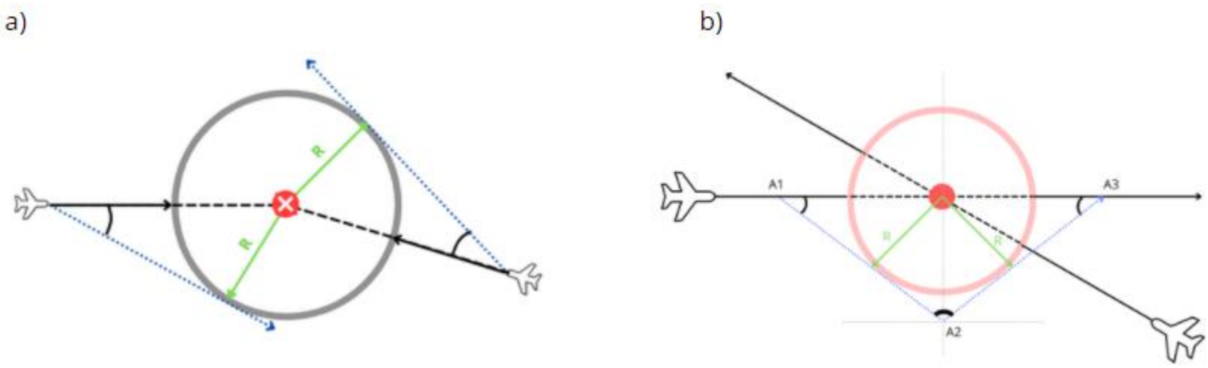

Fig. 3. (a) general diagram of the heading change maneuver to avoid a collision, (b) heading change – return to the original route, (source: own elaboration)

In the case of a heading change, the maneuver is to be performed so that the aircraft is a minimum of 5 NM from the conflict place. This boils down to deflecting the heading so that the new route is tangent to a circle with a center at the point of conflict and a radius equal to 5 NM (see Fig. 3a). The value of the heading deviation for each aircraft may vary. Execution of the maneuver shall occur at the earliest 90 seconds and the latest 60 seconds before the occurrence of the anticipated conflict. The entire route modification is symmetric concerning the conflict, as shown in Fig. 3b. If the modification started at point A_1, upon reaching point A_2, the ship returns to the original route at point A_3, which is symmetrically aligned to point A_1 relative to the conflict location.

4. Negotiation between aircraft

It is assumed that detecting a conflict situation and initiating the resolution process is the responsibility of the aircraft crew, who can ensure their own separation. This requires defining clear traffic rules allowing for an unambiguous resolution of the conflict. It is required to develop clear rules of communication and negotiation between aircraft.

Negotiation is a complex communication process involving at least two parties with partially divergent interests. These parties seek to reach a solution that satisfies each of them. Two main negotiation strategies can be found in the literature [2]: noncooperative and cooperative. In the first one, the adversaries adopt certain positions (positions) towards each other related to what they would like to achieve and then urge each other to make concessions. An agreement is concluded when the negotiators' positions converge and reach a mutually acceptable value [23]. In the cooperative strategy, the conflict situation is resolved to the satisfaction of both parties.

It can be observed that the proposed separation method adopts the characteristics of multi-agent systems. Since, for this paper, it is assumed that conflict resolution is performed in pairs, the Monotonic Concession Protocol (MCP) proposed by Rosenchein and Zlotkin [21] and also described in [5], [15], [22] is implemented for the inter-agent negotiation process. This protocol is dedicated to negotiation between two agents.

The following designations are assumed:

$A = \{A_i, A_j\} -$ set of two agents

X – a finite set of proposals for solutions to conflict situations

Each agent belonging to set A has a certain utility function defined as $u_i : X \to \mathbb{R}_0^+$.

Furthermore, there is a specific agreement between the agents in set X that will yield a utility function equal to 0 for both agents, which is the worst possible solution because it will end the negotiation process without resolving the conflict situation.

The negotiation takes place in rounds where each agent simultaneously gives its proposal from set X. In the first round, each agent can give any proposal from set X. In each subsequent trial, each agent can accept the proposal but also offer a solution that the other party more prefers. Each agent may also reject the rival's proposal and stay with their own. Agreement (and thus the resolution of the conflict) is reached when one agent proposes a solution his opponent rates at least as highly as his own current proposal, which can be written as:

$$u_i(x_i) \le u_i(x_j) \quad \text{or} \quad u_j(x_j) \le u_j(x_i) \tag{1}$$

It is assumed that a solution proposal consists of two elements: an evasion maneuver for the agent proposing and an evasion maneuver for the rival. Having the above in mind, the situation when in a given round, both agent *i* and agent *j* find that the above-written equation is true has been considered. Which proposition should be chosen, then? Should the agent *i* stay with his proposal? Or should the agent *j's* suggestion be selected? Should the solution be selected by drawing lots? For this circumstance, a solution that is used when a conflict arises in the negotiation process is applied to this paper. In the protocol of monotonic concessions, a conflict is defined as a situation when, in a given round, both agents stay with their proposals. It is necessary here to define the strategy of the agents. Zeuthen, in his book [26], proposed that each agent should determine its willingness to take the risk of a conflict situation in a negotiation. The agent who receives a lower value of this parameter should concede in the next round. In case of the same values of this parameter for both agents - both agents should give up (the protocol ends the action, and the conflict remains unresolved). The risk willingness *Z* of agent *i* was defined as:

$$Z_i = \frac{u_i(x_i) - u_i(x_j)}{u_i(x_i)} \tag{2}$$

where:
$u_i(x_i)$ – the utility function of agent *i* at its proposal x_i
$u_i(x_j)$ - the utility function of agent *i* at agent *j*'s proposal x_i

For the purposes of this paper, it is assumed that if the agents' proposals are equally good, or both proposals are rejected, then a given round remains undecided, and the next round proceeds. If it is the last round, the parameter *Z* should be calculated. The agent, whose parameter *Z* has a smaller value in a given round, should concede and accept the opponent's proposal. In case of the same values of this parameter for both agents - according to the assumption above - both of them should give up (the protocol ends the action, and the event remains unsolved).

The protocol ends the action when an agreement is reached or a conflict occurs. Another important piece of information is that the protocol does not last indefinitely; the number of rounds in which the negotiation takes place is specified [21], so it was assumed that the negotiation would take place in up to 5 rounds. The negotiation process is shown in Fig. 4.

The following designations have been adopted for the symbols used in the diagram:

$U_1(1)$	–	utility function for aircraft AC1 at solution proposal from AC1
$U_2(1)$	–	utility function for aircraft AC2 at solution proposal from AC1
$U_2(1)$	–	utility function for aircraft AC1 at solution proposal from AC2
$U_1(2)$	–	utility function for aircraft AC2 at solution proposal from AC2
Z_1	–	Risk willingness of AC1
Z_2	–	Risk willingness of AC2

The actions for each case are color-coded:

– blue - during the negotiation, it was agreed that the proposal of the agent labeled AC1 would be selected (based on the utility function);
– green - in the course of negotiations, based on the utility function, it has been agreed that the proposal of the agent marked as AC2 will be selected;

– pink - the scheme of action when:

a) both solution proposals are satisfactory to both agents, but the choice of the proposal is not explicitly indicated

b) both agents reject each other's proposals.

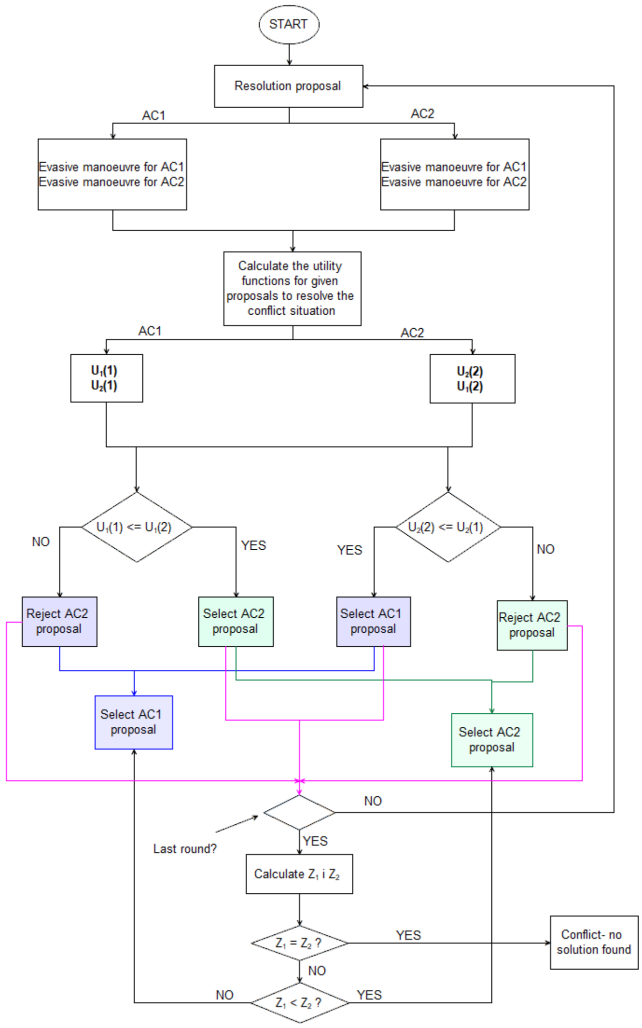

Fig. 4. Negotiation scheme (source: own elaboration)

It has been assumed that the utility function will reflect the efficiency of the traveled route, which boils down to an analysis of the distance traveled and a comparison with the original plan. The goal is to modify the route as little as possible. In the case of flight level change, the goal is to make as few altitude change maneuvers as possible. Therefore, the utility function takes the form:

$$(x) = \frac{T_z}{T_p} + H_z \rightarrow min \tag{3}$$

where:

$T_p -$ total distance flown according to the original flight plan

$T_z -$ total distance flown after trajectory modification

$H_z -$ total flight level change

During the negotiation in selecting a solution, it is aimed that the trajectory modification is at most 15% of the original plan.

The final solution will be generated in 5 iterations to reduce the negotiation time. The assumed conflict prediction time horizon is 5 minutes. Therefore, analyzing the situation and negotiating should be contained in a time frame that allows for the safe execution of maneuvers. This was assumed to be a maximum of 3 minutes from the collision detection time. The remaining two minutes are left for collision resolution, of which 30 seconds of safety buffer is left. The remaining 90 seconds are allocated for the execution of the maneuvers. This scheme is shown in Fig. 5.

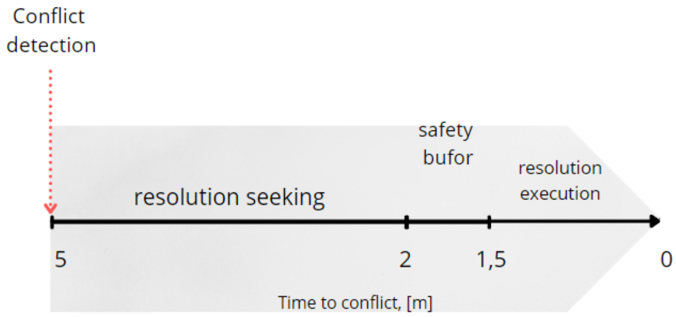

Fig. 5. The action time horizon of a proposed solution (source: own elaboration)

The communication process involves exchanging information between a sender and receiver through a specific channel and means of communication. This paper proposes the automation of communication processes, which is greatly accelerated by the progressive standardization of data scope and format [19]. An unambiguous interpretation of information is important for effective negotiation. Messages between negotiators were assumed to be sent, as shown in Table 1. AC is the aircraft that suggest a solution. The evasion maneuver is a maneuver for a specific Aircraft suggested by the second one being in conflict. *U* is the utility function for a given solution. Based on the utility function, the resolution can be selected. If based on the utility function, both proposals should be selected or both proposals should be rejected, the solution should be chosen according to the algorithm shown in Figure *X*. If there is no solution in this round, proceed to the next round. If there is no solution in the last round, determine the parameter *Z* on the basis of which a solution will be selected.

Table 1. Negotiation message template, (source: own elaboration)

AC	**Resolution**	**U**	**Resolution (based on U)**	**Resolution (based on negotiation algorithm)**	**Z**	**Resolution (based on Z)**
AC1	Evasion maneuver for AC1	$U_1(1)$	Select/reject the proposal from AC1/AC2	The select proposal from AC1/AC2 or Next round or Set a risk willingness (Z)	Z_1	AC1/AC2 or Conflict
	Evasion maneuver for AC2	$U_2(1)$				
AC2	Evasion maneuver for AC1	$U_1(2)$	Select/reject the proposal from AC1/AC2		Z_2	
	Evasion maneuver for AC2	$U_2(2)$				

5. Experiments

The proposed method was tested in a series of simulations for which 3 test scenarios were prepared. In the first scenario, 1000 flights were randomly generated, in the second scenario, 2000 flights; and in the third scenario, 3000 flights. Origin and destination were randomly selected for each aircraft. The heading was also selected randomly for each aircraft. To simplify calculations, it was assumed that all planes are of the same type and fly at the same altitude.

The experiment looked at how many of the total conflicts were unresolved to assess how effective the proposed solution was. As the traffic volume increases, there are more incidents left unresolved, indicating that the effectiveness of the proposed solution decreases and its safety decreases. See table 2.

Table 2. Total unresolved conflicts

	Scenario 1	**Scenario 2**	**Scenario 3**
Unresolved conflicts	5%	5,8%	6,9%

The experiment also analyzed how long it took to find a solution to the conflict. It can be noticed that with the amount of traffic, the time to find a solution increases, which is influenced by the much higher complexity of the traffic (the solution that will not cause another conflict will be chosen). The results are shown in Table 3.

Table 3. Time to find a resolution

	Scenario 1	**Scenario 2**	**Scenario 3**
Time to find a resolution [s]	118	135	149
Standard deviation	33,98	25,68	17,18

6. Conclusions

This paper presents a concept for assuring separation between aircraft during a transitional period between centralized and distributed air traffic control. Relevant literature suggests that the decentralized system of air traffic control is capable of dealing with the current problem of increasing congestion in airspace sectors. Delegating the responsibility for maintaining separation between aircraft to their crews probably will allow reducing and lessening of the workload of the air traffic controllers. Flying along the preferred trajectories will increase the effectiveness of operations which in turn saves time and fuel. However, it is necessary to maintain at least the current safety level of operations. When two types of air traffic are integrated, communication between them must be adequately ensured. Automating the communication will speed up the search for conflict resolution and avoid misunderstandings due to inappropriate interpretations of the message received. The proposed solution was able to resolve conflicts for 95% of the cases, which allows to evaluate it as quite safe. Nevertheless, further modeling and simulation research is necessary to improve the proposed solution.

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