

Synthesis of the Collaborative Decision-making Models for the Remote Pilot during Flight Emergency

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Abstract—Taking into account the specifics of the unmanned aerial systems design and the lack of a crew onboard the unmanned aerial vehicle, to ensure safe joint flights, it is advisable to implement the possibility of interaction of the remote pilot not only with the air traffic controller but also with the crews of manned aircraft within the collaborative decision-making concept based on a distributed network of highly automated systems using application program interfaces. In this article, the technics of collaborative decision-making by the various aviation staff for selecting the optimum decision in uncertain conditions while the performance of unmanned aerial vehicle flight in non-segregated airspace are presented. An example of the synthesis of the collaborative decision-making models for choosing the optimum landing airfield by the remote pilot, air traffic controller, and the pilot of manned aircraft during flight emergency "Engine failure on the unmanned aerial vehicle" is given.

Keywords—*alternative decision, costs, decision matrix, interaction, landing airfield, objective factors, subjective factors, uncertainty*

I. INTRODUCTION

The world market for civil unmanned aerial systems (UAS) is growing rapidly. On the world statistics the capacity of the global civilian UAS market is growing with a Compound Annual Growth Rate (CAGR) of 12.6% and in the next decade will reach \$ 88.3 billion, having soared from \$ 4.9 billion in 2019 to \$ 14.3 billion by 2028 (Fig. 1). The market for commercial UAS applications in 2023 will surpass the consumer market and grow more than eightfold, reaching \$ 9.5 billion by 2028. In 2020, global shipments of commercial UAS amounted to about 526,000 units, which is 50% more than in 2019 and will reach more than 1.3 million units by 2023 [1], [2].

Estimates carried out by various research organizations show that the world market for UAS will be the subject of diversification of various segments of the economy. Not only the structure of the market will change, but also the needs of users, to which new pacesetters in the world competition will have to adapt [2].

At present, there are ongoing debates in international and regional organizations ICAO, RTCA, EUROCONTROL, EASA, EUROCAE, GUTMA, as well as in national aviation authorities, based on which regulatory technical solutions and technological requirements to execute safe and effective integration of UAS into non-segregated airspace. Satellite

and hybrid technologies for communication, navigation, surveillance, and flight information services are the basis for the secure integration of UAS into airspace and the evolution of mass-market for their commercial use [3] – [5].

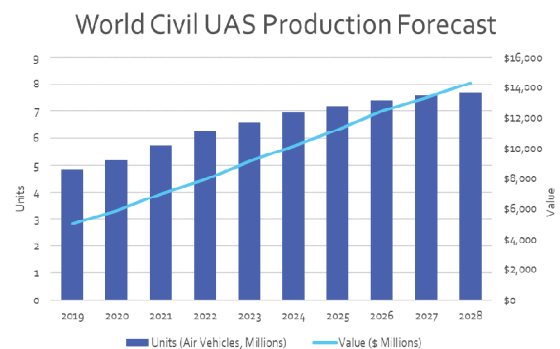


Fig. 1. World civil UAS production forecast [1].

The simultaneous operation of manned and unmanned aircraft requires novel approaches to the management of air traffic. Conceptually, unmanned aircraft systems traffic management (UTM) can be defined as a system that provides air traffic management for UAS through the association of personnel, technology, information, facilities, and services supported by air, ground, and space communications, air navigation, and surveillance [6]. A main issue of UTM is the need for such a system in areas with high air traffic density. It should be noted that airspace up to 1000 feet above ground level is already in use by low-level helicopters and other manned aircraft, which must also be identified by the UTM system.

Nowadays, UTM technology is impetuously developing in many nations and regions [6]. For example, in Europe, a high-level UAS conference held in Helsinki in November 2017 called for increased international regulatory collaboration with ICAO, JARUS, and non-EU states, and invited relevant European authorities to urgently make proposals for future regulatory plans that express the possible roles and responsibilities of operators operating drones, as well as the development and implementation of the U-Space concept.

The UTM concept for the European Union, called U-Space, is the creation and implementation of a set of novel services and particular procedures (e.g. registration, electronic identification, geofencing, flight permits, and

tracking) designed to provide safe, effective, and secure access to airspace for a significant number of small unmanned aircraft. Current work on the UTM also includes NASA activities in the USA, as well as pilot projects in China, the Russian Federation, Singapore, and Japan. Any UTM framework will need to include several components, three of which are basic [6]:

- a registration system from which data can be obtained in real-time to enable remote identification and tracking of each unmanned aerial vehicle (UAV), its operator, and remote pilot location;
- communication systems for monitoring UAVs and tracking all UAVs within the UTM zone;
- geofencing systems that will automatically update the 28-day aeronautical information regulation and control (AIRAC) cycle by national authorities to avert UAVs from flying in vulnerable and restricted areas or hazardous areas such as areas near airfields.

The specificity of UAS is characterized by the following points, which determine the number of additional requirements for ensuring flight safety and aviation security [7]:

- the lack of a pilot onboard and the transmission of control commands remotely from the ground control station using the C2 (Command and Control) communication channel;
- practical impossibility to perform flights according to the visual flight rules (VFR);
- unknown in advance whereabouts of the remote pilot operating or controlling the UAS.

The above-mentioned features give rise to new technological tasks:

- ensuring the safety of the C2 channel;
- prevention of possible collisions between unmanned and manned aircraft;
- ensuring uninterrupted communication between the air traffic controller (ATCO) and the remote pilot;
- ensuring compliance with the established requirements due to the UAS design feature;
- rational use of airspace;
- safe integration into controlled and uncontrolled airspace;
- provision of situational awareness of the remote pilot;
- introduction of technologies for automatic independent surveillance;
- determination of a special air layer for UAV.

Ensuring the established level of flight safety and reducing the risks associated with UAS flights is the highest priority for UAS integration into the airspace. UAS regulation should be based on a risk-based required performance approach, which is determined by the used technology. The risk-based approach assumes a proportional dependence of the level of access of a particular UAV into the airspace on the level of risk it creates when performing a particular flight.

The integration of UAS should not lead to a decrease in the existing level of flight safety for manned aircraft, a decrease in the level of aviation security, an increase in the risk for third parties in the air and on the ground, and ground infrastructure.

Taking into account the specifics of the UAS design and the lack of a crew onboard the UAV, to ensure safe joint flights, it is advisable to implement the possibility of interaction of the remote pilot not only with the ATCO but also with the crews of manned aircraft within the collaborative decision-making (CDM) concept [8] based on a distributed network of highly automated systems using application program interfaces (API) [9; 10].

In the process of interaction during the flight between the pilots of the manned and unmanned aircraft, and the ATCO there is a coordination of their actions, planning of joint activities, distribution of functions, etc. Interaction promotes mutual regulation, control, and assistance. At the same time, each of the participants of the interaction contributes to the joint task, adjusting their actions, taking into account previous experience, activating their capabilities and abilities of the partner.

The most relevant problem is CDM by the operators in uncertain conditions during flight emergencies (FE) [11–13].

The purpose of the work is the synthesis of the individual and collaborative decision-making models for the remote pilot, ATCO, and the pilot of manned aircraft in uncertainty for selecting the optimum landing airfield during FE.

II. THE TECHNIQS OF THE COLLABORATIVE DECISION-MAKING DURING FLIGHT EMERGENCY

The flight activity of pilots is characterized by a number of features, the most significant of which are [14]: constant danger during flight; the complexity of aircraft control; strict regulation of flight activity by instructions, regulations, and guiding documents; the impact on the pilot and crew of many flight factors; the need to perform in flight several time-combined actions; high requirements for interaction in crews; readiness to make quick decisions in extreme situations; high moral, social and material responsibility for the success of the flight.

The professional activity of ATCO is aimed at ensuring safe, orderly, regular, fast, and efficient air traffic [15]. It involves the processing of information obtained from various technical means (radar monitors, indicators, direction finders, and various boards), representation and forecasting of changes in the spatial position of the aircraft, timely informing crew members of dangerous changes in air traffic.

A feature of the remote pilot activity is the low situational awareness of the external environment due to his absence onboard the aircraft [5] therefore he must interact with both the ATCO and the pilots of manned aircraft.

The technics of the CDM by the various aviation staff for selecting the optimum landing airfield during FE during the performance of UAV flight in non-segregated airspace.

1) Computation of the direction of the route. Construction of the individual decision-making matrix with the alternative decisions $\{D\}$ – are the usable landing airfields; factors affecting decision-making $\{\mu\}$ – are the

conditions of natural factors during FE; outcomes $\{G\}$ – are the expected results of the selection of alternative landing airfields caused by factors affecting decision-making.

2) Alternative decisions $\{D\}$ – is a set of all usable airfields $\{D\} = \{DepA \cup DestA \cup \{UsA\}\} = \{D_1, D_2, \dots, D_i, \dots, D_n\}$, where $DepA = D_1$ – is a departure airfield and its specifications; $DestA = D_2$ – is a destination airfield and its specifications; $UsA = D_n$ – are the other usable airfields and their specifications according to the calculated route.

3) Factors affecting decision-making for the operators $\{\mu\} = \{\mu_1, \mu_2, \dots, \mu_j, \dots, \mu_m\}$, where μ_m – are the similar or unique factors.

4) Results $\{G\}$ – is a set of the possible outcomes caused by the selection of the usable airfields during FE $\{G\} = \{G_{11}, G_{12}, \dots, G_{ij}, \dots, G_{mn}\}$, where $\{G\}$ – is a set of the results of decision-making matrix $G_{ij} (i = 1, \dots, m; j = 1, \dots, n)$. The possible outcomes G_{ij} are defined based on the method of expert assessment in accordance with data from the regulations and reviews of O_i operators: O_1 – remote pilot, O_2 – ATCO, O_3 – pilot of the manned aircraft, O_i – other aviation staff.

5) Construction of the individual matrices of decisions for each operator. The matrix of decisions for the first operator (O_1 – remote pilot) is in Table I.

TABLE I. THE MATRIX OF DECISION-MAKING IN UNCERTAINTY FOR OPERATOR O_1

The matrix 1	$\{D\}$	Factors affecting decision-making for operator O_1 – remote pilot					
		μ_1	μ_2	...	μ_j	...	μ_n
Alternative decisions during FE	D_1	G_{11}	G_{12}	...	G_{1j}	...	G_{1n}
	D_2	G_{21}	G_{22}	...	G_{2j}	...	G_{2n}
	...	...	...	...	...	...	...
	D_i	G_{i1}	G_{i2}	...	G_{ij}	...	G_{in}
	...	...	...	...	...	...	...
	D_m	G_{m1}	G_{m2}	...	G_{mj}	...	G_{mn}

Analogically, decision-making matrices for the second operator (O_2 – ATCO), the third operator (O_3 – pilot of the manned aircraft), and other operators, who are involved in this situation, are constructing.

1) Consideration of conditions of decision-making in uncertainty (flight type). Selecting the criteria for solving the decision-making problem in uncertainty with maximum safety. If the flight is performed for the first time then Wald (minmax/maxmin) criterion is applied; if the flight is regular – Laplace criterion; if there is an optimism-pessimism flight situation – Hurwicz criterion.

2) Determination of the optimum decisions for each operator using the Wald, Laplace, Hurwicz criteria of decision-making in uncertainty: $D'_1 = D_j(O_1)$ – are the decisions of remote pilot $\{C_{01}\}$; $D'_2 = D_j(O_2)$ – are the decisions of ATCO $\{C_{02}\}$; $D'_3 = D_j(O_3)$ – are the decisions of the pilot of the unmanned aircraft $\{C_{03}\}$.

3) Construction of the collective matrix of decision-making (Table II), where $\{D\}$ – are the alternative landing airfields; $\{g\}$ – are the outcomes of the operators' optimum decisions based on the chosen criteria according to the conditions of flight from the individual matrices $D_j(O_i)$;

$D_j(O_2)$; $D_j(O_3)$; $D_j(O_i)$ (O_1 – remote pilot, O_2 – ATCO, O_3 – pilot of the unmanned aircraft, O_i – other aviation staff).

TABLE II. THE COLLECTIVE MATRIX OF DECISION-MAKING IN UNCERTAINTY

The collective matrix	$\{D\}$	Outcomes of optimum decisions by all operators					
		$D_j(O_1)$	$D_j(O_2)$	$D_j(O_3)$	$D_j(O_i)$	...	$D_n(O_n)$
Usable airfields	D_1	G'_{11}	G'_{12}	G'_{13}	...	...	G'_{1n}
	D_2	G'_{21}	G'_{22}	G'_{23}	...	...	G'_{2n}
	...	...	...	...	...	...	...
	D_i	G'_{i1}	G'_{i2}	G'_{i3}	G'_{ij}	...	G'_{in}
	...	...	...	...	...	...	...
	D_m	G'_{m1}	G'_{m2}	G'_{m3}	...	...	G'_{mn}

Calculation of the optimum decisions for all operators based on the Wald, Laplace, Hurwicz criteria of decision-making in uncertainty with minimal costs and maximum safety, for Wald criterion:

$$D' = \max_i \left\{ \min_l C_{oj}^l \right\}, \quad (1)$$

where $C_{oj}^l = \min_j \{G_{oj}^l\}$ are the optimum decisions from the operators' individual matrices;

- for Laplace criterion:

$$D' = \max_i \left\{ \frac{\sum_{l=1}^L C_{oj}^l}{L} \right\}, \quad (2)$$

where $C_{oj}^l = \min_j \left\{ \frac{\sum_{j=1}^n G_{oj}^l}{n} \right\}$ are the optimum decisions from the operators' individual matrices;

- for Hurwicz criterion; $0 \leq \beta \leq 1$:

$$D' = \max_i \left\{ \beta \max_l C_{oj}^l + (1-\beta) \min_l C_{oj}^l \right\}, \quad (3)$$

where $C_{oj}^l = \alpha \max_j G_{oj}^l + (1-\alpha) \min_j G_{oj}^l$ are the optimum decisions from the operators' individual matrices.

Depending on the flight conditions and decision-making priorities, a specific criterion is selected. It is important to take into account all circumstances when forming individual matrices: the identity of factors affecting decision-making in individual matrices (x_j, y_j, z_j).

III. ILLUSTRATIVE EXAMPLE OF SYNTHESIS OF THE MODELS OF COLLABORATIVE DECISION-MAKING DURING FLIGHT EMERGENCY "ENGINE FAILURE ON THE UAV"

There is presented an example of CDM by remote pilot/ATCO/pilot of the manned aircraft during FE "Engine failure on the UAV" while the monitoring flight along the route Bila Tserkva (D_1) – Konotop (D_2) with alternate airfields Berezan (D_{c1}), Vasylikiv (D_{c2}), Nizhyn (D_{c3}), and Pryluky (D_{c4}). The route of flight Bila Tserkva (D_1) – Konotop (D_2) is the schematic presented in Fig. 2.

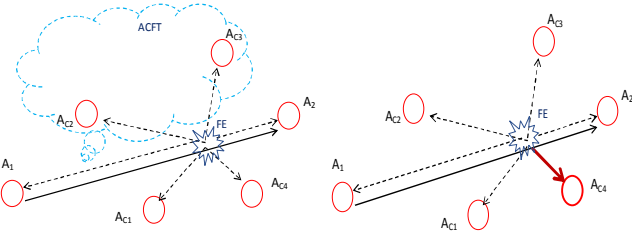
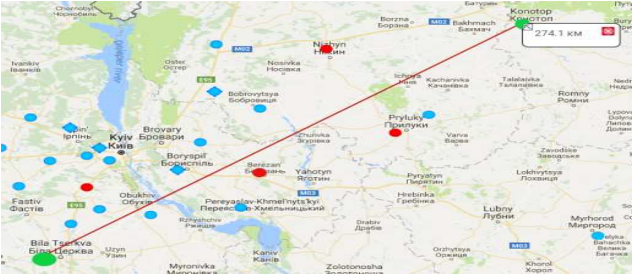


Fig. 2. Scheme of the route of flight Bila Tserkva (D_1) – Konotop (D_2).

For the optimum CDM, operators have analyzed the present situation. Three operators are involved in CDM process: remote pilot (O_1), ATCO (O_2), pilot of the manned aircraft (O_3). Factors affecting decision-making for each operator: $\{x\}$ – factors taken into account by operator O_1 (remote pilot); $\{y\}$ – factors taken into account by operator O_2 (ATCO); $\{z\}$ – factors taken into account by operator O_3 (pilot of the manned aircraft).

Each operator has constructed an individual decision-making matrix, where alternative decisions are the usable airfields along the route Bila Tserkva (D_1) – Konotop (D_2), and operators have considered the identical factors in the actual situation, but with various priorities. While selecting an optimum alternative, operators are guided by the common factors (x_j, y_j, z_j):

- x_1, y_1, z_1 is the meteorological conditions at the airfields;
- x_2, y_2, z_2 is the distance between UAV and the airfields;
- x_3, y_3, z_3 is the technical characteristics of the airfields;
- x_4, y_4, z_4 is the existence of fuel/energy onboard of UAV;
- x_5, y_5, z_5 is the sureness of C2 lines for interconnection with UAV;
- x_6, y_6, z_6 is the capability of interaction with ATCO units;
- x_7, y_7, z_7 are other factors (logistics, aeronautical fees, the priority of UAV, etc.).

These factors are objective. The matrices of decision-making for operators during FE "Engine failure on the UAV" are in Tables III–V. The optimum decisions are marked in the matrices by red color. Expected results appreciated by the remote pilot (operator O_1) are presented in Table III.

The optimum landing airfield while the flight along the route Bila Tserkva (D_1) – Konotop (D_2) following the remote pilot's decision is: Nizhyn (D_{c3}) or Pryluky (D_{c4}) – based on Wald criterion; Berezan (D_{c1}), Nizhyn (D_{c3}) or Pryluky (D_{c4}) – based on Laplace criterion; Pryluky (D_{c4}) – based on Hurwitz criterion.

TABLE III. THE MATRIX OF DECISION-MAKING IN UNCERTAINTY FOR OPERATOR O_1 (REMOTE PILOT)

The matrix 1	$\{D\}$	Factors affecting decision-making for operator O_1 – remote pilot							Decisions		
		x_1	x_2	x_3	x_4	x_5	x_6	x_7	W	L	$H, \alpha=0.5$
Usable airfields	Bila Tserkva (D_1)	9	2	5	8	0	3	9	0	0.7	4.5
	Konotop (D_2)	3	5	7	9	2	4	9	2	0.8	5.5
	Berezan (D_{c1})	2	8	8	9	2	4	10	2	0.9	6.0
	Vasylkiv (D_{c2})	7	1	8	7	1	7	7	1	0.8	4.5
	Nizhyn (D_{c3})	6	4	8	6	6	5	8	4	0.9	6.0
	Pryluky (D_{c4})	4	8	9	8	4	6	6	4	0.9	6.5

Expected results appreciated by the ATCO (operator O_2) are presented in Table IV.

TABLE IV. THE MATRIX OF DECISION-MAKING IN UNCERTAINTY FOR OPERATOR O_2 (ATCO)

The matrix 2	$\{A\}$	Factors affecting decision-making for operator O_2 – ATCO							Decisions		
		y_1	y_2	y_3	y_4	y_5	y_6	y_7	W	L	$H, \alpha=0.5$
Usable airfields	Bila Tserkva (D_1)	9	5	5	8	2	7	9	2	0.9	5.5
	Konotop (D_2)	5	5	7	9	2	7	9	2	0.9	5.5
	Berezan (D_{c1})	5	8	8	9	2	5	10	2	1.0	6.0
	Vasylkiv (D_{c2})	7	5	8	7	1	7	7	1	0.9	4.5
	Nizhyn (D_{c3})	6	4	8	6	6	5	8	4	0.9	6.0
	Pryluky (D_{c4})	5	8	9	8	4	4	6	4	0.9	6.5

The optimum landing airfield while the flight along the route Bila Tserkva (D_1) – Konotop (D_2) following the ATCO's decision is: Nizhyn (D_{c3}) or Pryluky (D_{c4}) – based on Wald criterion; Berezan (D_{c1}) – based on Laplace criterion; Pryluky (D_{c4}) – based on Hurwitz criterion.

Expected results appreciated by the pilot of manned aircraft (operator O_3) are presented in Table V.

TABLE V. THE MATRIX OF DECISION-MAKING IN UNCERTAINTY FOR OPERATOR O_3 (PILOT OF THE MANNED AIRCRAFT)

The matrix 3	$\{D\}$	Factors affecting decision-making for operator O_3 – pilot of the manned aircraft							Decisions		
		z_1	z_2	z_3	z_4	z_5	z_6	z_7	W	L	$H, \alpha=0.5$
Usable airfields	Bila Tserkva (D_1)	9	2	5	8	0	3	3	0	0.6	4.5
	Konotop (D_2)	3	5	7	9	2	4	3	2	0.7	5.5
	Berezan (D_{c1})	2	8	8	9	2	4	1	1	0.7	5.0
	Vasylkiv (D_{c2})	7	1	8	7	1	7	1	1	0.7	4.5
	Nizhyn (D_{c3})	6	4	8	6	6	5	3	3	0.8	5.5
	Pryluky (D_{c4})	4	4	9	8	4	6	5	4	0.8	6.5

The optimum landing airfield while the flight along the route Bila Tserkva (D_1) – Konotop (D_2) following the pilot's of the manned aircraft decision is: Nizhyn (D_{c3}) or Pryluky (D_{c4}) – based on Wald criterion; Nizhyn (D_{c3}) – based on Laplace criterion; Pryluky (D_{c4}) – based on Hurwitz criterion.

To identify the consistency of operators, the collective decision-making matrix was built, in which the factors for all operators (remote pilot (O_1), ATCO (O_2), pilot of the manned aircraft (O_3)) are similar; the decisions of the operators are taken from individual matrices in Tables III–V.

In the CDM matrix, are using the subjective factors – reviews of operators. All operators' optimum CDM is presented in Table VI. Thus, the optimum landing airfield is defined based on both objective and subjective factors. The optimum CDM while the flight along the route Bila Tserkva (D_1) – Konotop (D_2) following the decision of all operators is: Nizhyn (D_{c3}) or Pryluky (D_{c4}) – based on Wald criterion; Nizhyn (D_{c3}) – based on Laplace criterion; Pryluky (D_{c4}) – based on Hurwitz criterion.

TABLE VI. THE COLLABORATIVE DECISION-MAKING MATRIX IN UNCERTAINTY

The collaborative matrix	$\{A\}$	Operators/decisions											
		O_1	O_2	O_3	W	O_1	O_2	O_3	L	O_1	O_2	O_3	$H, \beta=0.5$
Usable airfields	Bila Tserkva (D_1)	0	2	0	0	0.7	0.9	0.6	0.6	4.5	5.5	4.5	4.5
	Konotop (D_2)	2	2	2	2	0.8	0.9	0.7	0.7	5.5	5.5	5.5	5.5
	Berezan (D_{c1})	2	2	1	1	0.9	1.0	0.7	0.7	6.0	6.0	5.0	5.0
	Vasylkiv (D_{c2})	1	1	1	1	0.8	0.9	0.7	0.7	4.5	4.5	4.5	4.5
	Nizhyn (D_{c3})	4	4	3	3	0.9	0.9	0.8	0.8	6.0	6.0	5.5	5.5
	Pryluky (D_{c4})	4	4	4	4	0.9	0.9	0.8	0.8	6.5	6.5	6.5	6.5

The study was performed within the research work "Methodology of the situational shared management of manned and unmanned aerial vehicles in single airspace" [16].

IV. CONCLUSION

The technics of CDM by the various aviation staff for selecting the optimum decision in uncertain conditions during the performance of UAV flight in non-segregated airspace are developed. The example of the synthesis of the CDM models for choosing the optimum landing airfield by the remote pilot, ATCO, and the pilot of manned aircraft in the case of engine failure on the UAV is submitted.

The optimum landing airfield while the monitoring flight along the route Bila Tserkva (D_1) – Konotop (D_2) during FE "Engine failure on the UAV" is defined based on both the objective factors (meteorological conditions, distance between UAV and the usable airfields, technical characteristics of the usable airfields, the existence of fuel/energy onboard of UAV, the sureness of C2 lines for interconnection with UAV, the capability of interaction with ATCO units, other factors) and subjective factors (reviews of the remote pilot, ATCO, pilot of the manned aircraft).

The efficient application of CDM models ensures synchronization of the operators' decision-making, the

operative information exchange among them, the optimum balance between the flight safety and the costs in collective decisions.

The direction of further research is working out decision-making models for all CDM participants within the Airport CDM (A-CDM) concept that can unite the interests of partners (airport operators, manned aircraft operators, unmanned aircraft operators, ground handling agents, and air traffic services) in joint work within non-segregated airspace, to create the basis for effective decision-making through more accurate and timely information that provides all partners at the airport a single operational picture of air traffic.

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