METHODOLOGY FOR PREDICTING DEPENDABILITY MEASURES OF SWARM STRUCTURES OF UNMANNED AERIAL VEHICLES OF AGRICULTURAL APPLICATION

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Abstract

This paper presents a methodology for predicting dependability measures of swarm structures of unmanned aerial vehicles used in agriculture. The main attention is paid to the development of mathematical models for assessing the dependability of hardware, software, and communication systems in drone swarms. Two types of UAVs are considered in the paper: DJI Phantom 4 RTK (for crop monitoring) and Tevel Aerobotics (for automated harvesting). The developed methodology improves the accuracy of dependability prediction of UAV swarm structures, which helps to optimize their maintenance and increase the efficiency of their application in agriculture. The developed mathematical model for predicting the dependability of swarm structures of agricultural UAVs includes a combination of hardware and software components and communication systems.

Keywords: dependability, reliability function, failure rate, swarm of unmanned aerial vehicles, agriculture, communication systems, software, availability operational factor

I. Introduction

In the era of digitalization and automation of human activities, unmanned aerial vehicles (UAVs) play a pivotal role. The rapid growth of the Russian civil unmanned aerial systems (UAS) market, as illustrated in figure 1, reflects the increasing demand for these platforms and the corresponding expansion of this sector [1]. Concurrently, the market for swarm (group) applications of UAVs is also gaining momentum.
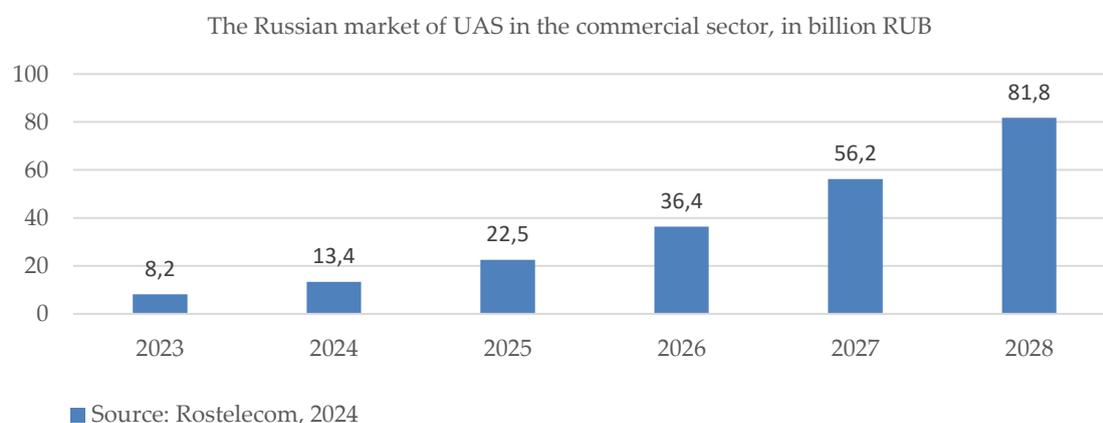
The Russian market of UAS in the commercial sector, in billion RUB

■ Source: Rostelecom, 2024

Figure 1: *UAS market growth chart*

Furthermore, the importance of early dependability prediction in the production of any radio-electronic equipment (REE) at various stages of its lifecycle has become increasingly evident. This approach helps prevent errors in component selection, circuit design, and engineering solutions, thereby avoiding premature REE failures and mitigating associated economic and reputational losses.

Currently, there are numerous known applications for UAV swarms. Key areas include: agriculture, emergency services, mining, construction, geodesy, logistics, insurance, government services, media and journalism, environmental conservation, science and education, telecommunications, photo/videography, and sports/entertainment [2].

The most promising application domain for unmanned aerial vehicle swarm systems is precision agriculture, where these systems integrate multisensory platforms, automated control systems, data analytics, and artificial intelligence across multiple stages of agricultural production [3]. The agricultural workflow typically comprises three key phases: planting, crop cultivation, and harvesting.

This study focuses on UAV groups deployed during the harvest phase. At this stage, UAV swarm systems can provide dual functionality: yield prediction and estimation, and automated harvesting operations.

Currently, there is no comprehensive approach to forecasting the dependability measures of both individual UAVs and their groups: the predictive dependability measures of software (SW), hardware components, and communication systems are evaluated independently, which significantly affects the final outcome and fails to adequately predict the fault tolerance of such systems. Therefore, the primary objective of this work is to increase the accuracy and validity of dependability forecasts for various swarm structures used in agricultural applications. The tasks of this study include the development of a mathematical model for predicting the dependability measures of the software, hardware parts, and communication systems of two different types of UAV groups designed for use during the harvest phase. Additionally, the communication system dependability was calculated both through network topology and signal-to-noise ratio. Moreover, the presence of software on both the ground control station (GCS) and the UAV swarm itself was taken into account.

II. Selection of the object and statement of the research problem

Yield forecasting plays a key role for the producer, as it is at this stage that decisions are made regarding the significance of a range of factors such as insurance, budget formation, resource allocation, and others.

One of the technical solutions for implementing unmanned monitoring of farm surfaces with yield forecasting and assessment functionality is presented in the study [4]. The study is based on the DJI Phantom 3 Professional unmanned aerial vehicle. According to the presented technology, the UAV flies at an altitude of 5 to 6 meters above the plant canopy and takes photographs from two sides, which ensures image quality sufficient for fruit recognition. In this study, 20 trees were involved, which is not a large number for higher-level agricultural plantations. To cover a larger area of agricultural land, the most effective solution would be the use of a swarm of similar drones. This would eliminate additional time costs associated with recharging and surveying the entire area with a single UAV. Figure 2 illustrates the operating principle of the technology using a single UAV and a group of similar drones.

Furthermore, the study [5] conducted research aimed at developing a yield forecasting model for cotton fields. The research was also based on DJI Phantom series unmanned aerial vehicles (4 RTK). The article supports the prevailing view that the use of UAVs in agriculture currently represents an optimal solution, enabling highly accurate detection of crop biomass, quality

forecasting, pest and weed detection, among other applications. The authors provide a detailed description of the drone's hardware components used in their work, including the camera's field of view (84°).
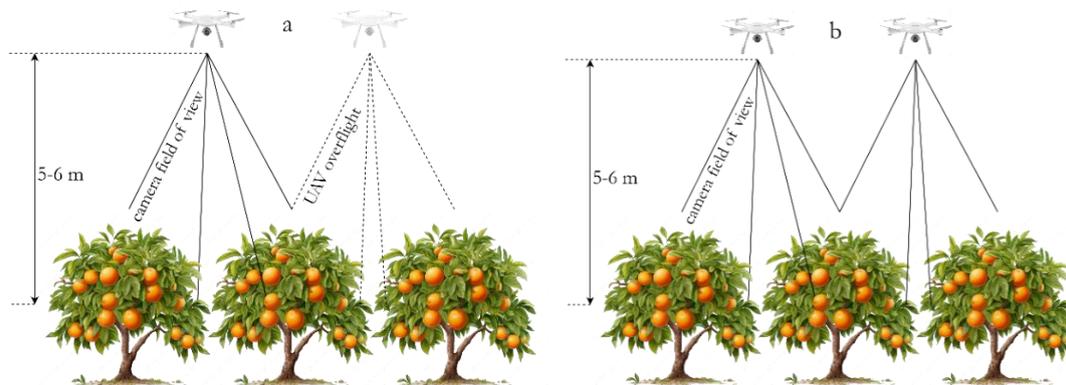

Figure 2: *Information collection process: (a) by a single UAV, (b) by a swarm of UAVs*

Thus, based on the analyzed studies, it is necessary to determine the optimal UAV model and a sufficient number of drones in the group for yield forecasting of an average-sized farm in the Russian Federation. Depending on the region, the sizes of cultivated areas in the Russian Federation can vary significantly; however, as indicated in [6], the average size can be taken as 214.4 hectares.

According to the technical documentation of the DJI Phantom 4 RTK [7] and DJI Phantom 3 Professional [8], the former has superior characteristics, including speed and range. Based on the data regarding the required flight altitude above the plant canopy (5-6 m) and the DJI Phantom 4 RTK's field of view (84°), the camera's surface coverage width was calculated to be approximately 9,9 meters. Using these data, along with the DJI Phantom 4 RTK's maximum speed (50 km/h) and flight duration (30 minutes) from its technical documentation, the necessary number of such UAVs to cover the entire average sowing area in the Russian Federation (214.4 hectares) was calculated: at least 9 such drones are required for a complete analysis of the surveyed area without recharging (i.e., in the minimum possible time). Thus, taking into account adjustments for the imperfections of real operational processes, weather conditions, and other factors affecting the information collection task by a UAV group, this study investigated a swarm of short-range micro UAVs similar to the DJI Phantom 4 RTK in two variations: consisting of 9 and 10 drones.

An equally important part of selecting the necessary unmanned aerial vehicles is considering their classification by design type: fixed-wing (airplane), aerostatic, multirotor, and hybrid [9]. Currently, multirotor UAVs are the most common solution for agricultural monitoring tasks; however, fixed-wing drones may be used for larger areas. Additionally, in agricultural applications, minimizing environmental pollution is essential, so careful consideration must be given to the choice of drone engine type. The following types of engines are distinguished in modern UAVs [10]: electric, fuel-powered, gas-turbine, propeller-driven, and hybrid. The DJI Phantom 4 RTK UAV, like most modern copters, is equipped with an electric motor, making it environmentally safe for crops and fully suitable for the task at hand.

The second and final stage of automating the harvest process using UAV swarm structures in agriculture is the automated harvesting itself.

As shown in [11], a comprehensive automated fruit harvesting system already exists. The operating principle of such a system is based on the use of a group of drones equipped with "tentacles," connected to a central machine with containers. The UAVs themselves are equipped with cameras and can recognize fruits on trees, after which they pick them using their "tentacles" and place them into the machine's container.

The number of UAVs in such a swarm can vary from 2 to 10; however, the baseline should be set at 6 UAVs, with 3 on each side, as shown in [11].

The study was conducted a comprehensive investigation of all components within UAV swarms that affect system dependability to develop a unified dependability forecasting system for such swarm structures operating under normal conditions. By combining all developed models for each component influencing the swarm system's dependability, a single predictive model for the dependability measures of the UAV group will be created. Since the study focuses on normal operating conditions, it assumes the absence of sudden failures, with corresponding approximation of dependability measure values. The operational timeframe considered for the swarm structures in this research pertains to their active mission duration.

III. Development of mathematical models for predicting UAV swarm dependability measures

I. Technical dependability

When developing a mathematical model for forecasting the dependability measures of the technical equipment in UAV swarm structures, it is important to consider not only the components of the drones themselves but also the equipment located at the GCS. According to [12], the GCS consists of the hardware described in table 1. The table contains the analyzed classical mean time between failures (MTBF) for specific types of components and the calculated failure rate using the formula: $\lambda_i = \frac{1}{MTBF_i}$, λ_i is the failure rate of the i-th hardware component, and $MTBF_i$ is its mean time between failures. In addition, there is no redundancy in the system, so the failure of any component will cause the failure of the entire system due to the inability of the UAV swarm to accomplish the mission, hence the failure rates $\lambda_{T_{GCS}1}$ of this GCS can be considered as the total failure rate of all the components $\sum_i \lambda_i$, as shown in the table below. For groups of 9 and 10 drones, the GCSs are identical.

Table 1: *Standard GCS hardware set for DJI Phantom 4 RTK swarm*

Hardware component			MTBF, k hours	Failure rate, 1/h
Name	**Component**	**Abbreviation**		
Control Computer	System unit	SU	150	$\lambda_{SU} = 6,67 * 10^{-6}$
	Monitor	Mon	250	$\lambda_{Mon} = 4 * 10^{-6}$
	Keyboard	K	1100	$\lambda_K = 9,1 * 10^{-7}$
	Mouse	Mou	2000	$\lambda_{Mou} = 5 * 10^{-7}$
Portable personal computer	System unit	SU	150	$\lambda_{SU} = 6,67 * 10^{-6}$
	Monitor	Mon	250	$\lambda_{Mon} = 4 * 10^{-6}$
	Manual remote control	MRC	200	$\lambda_{MRC} = 5 * 10^{-6}$
Network infrastructure	Cable system	CS	100	$\lambda_{CS_1} = 1 * 10^{-5}$
	Modem	Mod	440	$\lambda_{Mod} = 2,27 * 10^{-6}$
	Switch	S	590	$\lambda_S = 1,69 * 10^{-6}$
	Router	R	800	$\lambda_R = 1,25 * 10^{-6}$
Communication system	Receiving and transmitting equipment of the command and telemetry channel	RTECTC	80	$\lambda_{RTECTC} = 1,25 * 10^{-5}$
Flight state change system	Remote display and mode selection	RDMS	150	$\lambda_{RDMS} = 6,67 * 10^{-6}$
Total failure rate				$\lambda_{T_{GCS}1} = 6,09 * 10^{-5}$

To predict the dependability of the above components of the GCS information system, it is necessary to use either the electronic radio items dependability compendium 2006 [13], or reference books and products for foreign products [14], [15], [16], or the MTBF from the technical documentation after selection of specific models, or a combined version, as in the case of UAV components.

Thus, according to the exponential law of dependability, the final formula for predicting the technical dependability indexes (reliability function $P_{T_{GCS1}}$) for the GCS of the DJI Phantom 4 RTK UAV swarm can be summarized as follows:

$$P_{T_{GCS1}} = e^{-\lambda_{T_{GCS1}} * t} \tag{1}$$

The GCS for the Tevel Aerobotics UAV swarm has a different appearance. As a result of the analysis [17], all the obtained data can be summarized in table 2.

In this paper, a variant of the maximum hardware set will be considered, taking into account the possibility of autopiloting the Tevel Aerobotics UAV GCS. When forming an understanding of the type of system from the dependability point of view, several factors should be taken into account, among them: the navigation unit has either a GPS sensor, LPS or ultra-wideband visual positioning system, which directly indicates the presence of redundancy within this unit of the system. The situation is similar in the fruit detection unit, as it is possible to use both a smart camera or laser and a sound sensor, in our case, the presence of all these three components will be considered. Also, it is worth mentioning that in our case the cable system is a power line of 6 cables, as each cable is a connecting element between the platform and the UAV.

Table 2: *Tevel Aerobotics swarm GCS IS hardware set*

Hardware component			MTBF,	Failure rate, 1/h
Name	Component	Abbreviation	k hours	
Fruit detection system	Smart fruit recognition camera	SFRC	200	$\lambda_{SFRC} = 5 * 10^{-6}$
	Laser	L	260	$\lambda_L = 3,85 * 10^{-6}$
	Sound sensor	SS	220	$\lambda_{SS} = 4,55 * 10^{-6}$
Computer system	Processor	P	310	$\lambda_P = 3,23 * 10^{-6}$
	Memory unit	MU	870	$\lambda_{MU} = 1,15 * 10^{-6}$
Transportation conveyor	Motorized belt	MB	150	$\lambda_{MB} = 6,67 * 10^{-6}$
Support frame	Motor	M	230	$\lambda_M = 4,35 * 10^{-6}$
	Fruit sorter	FS	340	$\lambda_{FS} = 2,94 * 10^{-6}$
	Electromotor	E	400	$\lambda_E = 2,5 * 10^{-6}$
	Obstacle Tracking Camera	OTC	400	$\lambda_{OTC} = 2,5 * 10^{-6}$
Navigation unit	GPS	GPS	420	$\lambda_{GPS} = 2,38 * 10^{-6}$
	LPS	LPS	280	$\lambda_{LPS} = 3,57 * 10^{-6}$
	Ultra-wideband visual positioning system	UVPS	420	$\lambda_{UVPS} = 2,38 * 10^{-6}$
Extended platform	Platform height setting mechanism	PHSM	150	$\lambda_{PHSM} = 6,67 * 10^{-6}$
	Platform retrieval mechanism	PRM	150	$\lambda_{PRM} = 6,67 * 10^{-6}$
Network infrastructure	Cable system	CS	100	$\lambda_{CS_2} = 1 * 10^{-5}$

Let us represent the system in terms of dependability as shown in figure 3.
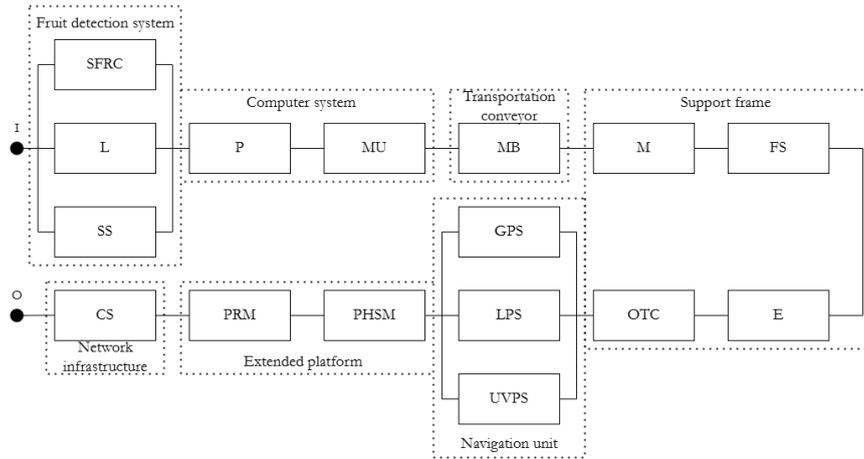

Figure 3: *System view from a dependability perspective*

When connected in series in dependability, the reliability function is considered as follows: $P(t) = \prod_{i=1}^{n} P_i(t)$, where n is the number of elements connected in series. In parallel connection: $P(t) = 1 - \prod_{i=1}^{k}\left(1 - P_i(t)\right)$, where k is the number of elements connected in parallel.

Thus, the final formula for predicting technical dependability performance (reliability function $P_{T_{GCS2}}$) for Tevel Aerobotics UAV swarm GCS can be summarized as follows:

$$P_{T_{GCS2}} = \left\{1 - \left(1 - e^{-\lambda_{SFRC}*t}\right)\left(1 - e^{-\lambda_L*t}\right)\left(1 - e^{-\lambda_{SS}*t}\right)\right\} *$$
$$* \left\{1 - \left(1 - e^{-\lambda_{GPS}*t}\right)\left(1 - e^{-\lambda_{LPS}*t}\right)\left(1 - e^{-\lambda_{UVPS}*t}\right)\right\} *$$
$$* e^{-\left(\lambda_P + \lambda_{MU} + \lambda_{MB} + \lambda_M + \lambda_{FS} + \lambda_E + \lambda_{OTC} + \lambda_{PHSM} + \lambda_{PRM} + 6*\lambda_{CS_2}\right)*t} \quad (2)$$

Let us consider the remaining hardware of the systems under study. For clarity, the hardware parts of DJI Phantom 4 RTK and Tevel Aerobotics drones [18] are summarized in table 3.

Table 3: *Hardware of DJI Phantom 4 RTK and Tevel Aerobotics UAVs*

Component	Abbreviation	MTBF, k hours	Failure rate, 1/h
Total hardware failure rate of DJI Phantom 4 RTK drone equipment			$\lambda_{T_{UAV1}} = 8,84 * 10^{-5}$
Suspension camera	SC	500	$\lambda_{SC} = 2 * 10^{-6}$
Lower vision system	LVS	760	$\lambda_{LVS} = 1,32 * 10^{-6}$
Micro USB port	MUP	630	$\lambda_{MUP} = 1,59 * 10^{-6}$
Camera status indicator	CSI	640	$\lambda_{CSI} = 1,56 * 10^{-6}$
Connection status indicator	ConSI	630	$\lambda_{ConSI} = 1,59 * 10^{-6}$
Communication button	CB	1200	$\lambda_{CB} = 8,33 * 10^{-7}$
Camera microSD card slot	CMCS	750	$\lambda_{CMCS} = 1,33 * 10^{-6}$
Front vision system	FVS	760	$\lambda_{FVS} = 1,32 * 10^{-6}$
Infrared sensor system	ISS	230	$\lambda_{ISS} = 4,35 * 10^{-6}$
Front light-emitting diode	LED	640	$\lambda_{LED} = 1,56 * 10^{-6}$
Motors	Ms	490	$\lambda_{Ms_1} = 2,04 * 10^{-6}$
Propellers	Pr	90	$\lambda_{Pr_1} = 1,11 * 10^{-5}$
Machine status indicators	MSI	510	$\lambda_{MSI} = 1,96 * 10^{-6}$
Antennas OCUSYNCTM	AO	370	$\lambda_{AO} = 2,7 * 10^{-6}$
Integrated antenna D-RTKTM	IAD	310	$\lambda_{IAD} = 3,23 * 10^{-6}$

Component	Abbreviation	MTBF, k hours	Failure rate, 1/h
Rear vision system	RVS	760	$\lambda_{RVS} = 1,32 * 10^{-6}$
Intelligent flight battery	IFB	200	$\lambda_{IFB} = 5 * 10^{-6}$
Power button	PB	1200	$\lambda_{PB} = 8,33 * 10^{-7}$
Battery level indicators	BLI	640	$\lambda_{BLI} = 1,56 * 10^{-6}$
Navigation system	NS	170	$\lambda_{NS} = 5,88 * 10^{-6}$
Total failure rate of the Tevel Aerobotics drone hardware			$\lambda_{T_{UAV2}} = 9,67 * 10^{-5}$
Infrared optical tap	IOT	230	$\lambda_{IOT} = 4,35 * 10^{-6}$
Ultrasonic range meter	URM	200	$\lambda_{URM} = 5 * 10^{-6}$
Stereoscopic camera	StC	230	$\lambda_{StC} = 4,35 * 10^{-6}$
Radar	Rd	420	$\lambda_{Rd} = 2,38 * 10^{-6}$
Night vision camera	NVC	370	$\lambda_{NVC} = 2,7 * 10^{-6}$
Fruit recognition camera	FRC	360	$\lambda_{FRC} = 2,78 * 10^{-6}$
Biaxial robotic arm	BRA	130	$\lambda_{BRA} = 7,69 * 10^{-6}$
Pressure sensor	PS	410	$\lambda_{PS} = 2,44 * 10^{-6}$
Handle	H	100	$\lambda_{H} = 1 * 10^{-5}$
Motors	Ms	490	$\lambda_{Ms_2} = 2,04 * 10^{-6}$
Propellers	Pr	90	$\lambda_{Pr_2} = 1,11 * 10^{-5}$
Battery	B	450	$\lambda_{B} = 2,22 * 10^{-6}$
Processor	P	310	$\lambda_{P} = 3,23 * 10^{-6}$
Memory unit	MU	870	$\lambda_{MU} = 1,15 * 10^{-6}$

Since all drone components have no redundancy (the connection is fully serial), the table presents the total failure rates $\lambda_{T_{UAV1}}$ and $\lambda_{T_{UAV2}}$ for DJI Phantom 4 RTK and Tevel Aerobotics drones, respectively. Each UAV is assumed to have 4 propellers and 2 motors.

According to the original fruit monitoring task, the failure of at least one UAV will actually prevent the task from being accomplished, which can be interpreted as a system failure. Thus, the swarm of DJI Phantom 4 RTK UAVs has a fully sequential connection in terms of dependability, and the final formula for predicting the technical dependability of a swarm of 9 DJI Phantom 4 RTK UAVs, taking into account formula (1) with sequential connection between the swarm and the GCS:

$$P_{T_1^9} = e^{-(9*\lambda_{T_{UAV1}}+\lambda_{T_{GCS1}})*t} \tag{3}$$

Appropriately for a swarm of 10 such UAVs:

$$P_{T_1^{10}} = e^{-(10*\lambda_{T_{UAV1}}+\lambda_{T_{GCS1}})*t} \tag{4}$$

In the case of a group of 6 Tevel Aerobotics drones, a centralized system is used: the failure of one drone will not cause the failure of the entire system. The final formula for predicting the technical dependability of a swarm of 6 Tevel Aerobotics UAVs, taking into account formula (2) and the serial connection between the swarm and the GCS:

$$P_{T_2} = \left\{ 1 - \left(1 - e^{-\lambda_{T_{UAV2}}*t}\right)^6 \right\} * P_{T_{GCS2}} =$$
$$\left\{ 1 - \left(1 - e^{-\lambda_{T_{UAV2}}*t}\right)^6 \right\} * \left\{ 1 - \left(1 - e^{-\lambda_{SFRC}*t}\right)\left(1 - e^{-\lambda_{L}*t}\right)\left(1 - e^{-\lambda_{SS}*t}\right) \right\} *$$
$$* \left\{ 1 - \left(1 - e^{-\lambda_{GPS}*t}\right)\left(1 - e^{-\lambda_{LPS}*t}\right)\left(1 - e^{-\lambda_{UVPS}*t}\right) \right\} *$$
$$* e^{-(\lambda_P+\lambda_{MU}+\lambda_{MB}+\lambda_M+\lambda_{FS}+\lambda_E+\lambda_{OTC}+\lambda_{PHSM}+\lambda_{PRM}+6*\lambda_{CS_2})*t} \tag{5}$$

II. Software dependability

When predicting software dependability measures, it is necessary to take into account the presence of SW not only on the GCS, but also on each UAV. Since software dependability prediction requires years of testing of real code, in this paper, random values of intervals between error occurrence within the acceptable range of values and taking into account the complexity of the software code for swarm structures of the two types of drones under consideration are selected for the example of applying the created model. There are many models for predicting SW dependability performance [19]. The Jelinski-Moranda model should be considered as the optimal method in this case.

Consider a swarm of 9 DJI Phantom 4 RTK UAVs. Similar to the hardware component, a software failure on any drone or GCS will lead to a failure of the entire system due to mission failure. Then the software dependability prediction model itself will be fully consistent. Taking into account the Jelinski-Moranda model, the developed model takes the following form:

$$P_{SW_1^9}(t_i) = P_{SW_{UAV1}}(t_i) * P_{SW_{GCS}}(t_i) = e^{-\left(9*\lambda_{iSW_{UAV1}} + \lambda_{iSW_{GCS1}}\right)*t_i} \tag{6}$$

At the same time, for a swarm structure of 10 DJI Phantom 4 RTK UAVs:

$$P_{SW_1^{10}}(t_i) = P_{SW_{UAV1}}(t_i) * P_{SW_{GCS1}}(t_i) = e^{-\left(10*\lambda_{iSW_{UAV1}} + \lambda_{iSW_{UAV1}}\right)*t_i} \tag{7}$$

For a swarm of 6 Tevel Aerobotics UAVs, the model for predicting the SW dependability performance considering the presence of redundancy in the system due to non-failure in case of failure of any UAV is as follows:

$$P_{SW_2}(t_i) = P_{SW_{UAV2}}(t_i) * P_{SW_{GCS}}2(t_i) = \left\{1 - \left(1 - e^{-\lambda_{iSW_{UAV2}}*t_i}\right)^6\right\} * e^{-\lambda_{iSW_{GCS2}}*t_i} \tag{8}$$

According to the Jelinski-Moranda model, at each testing step the program is checked for errors, and it is important to determine the initial number of errors. For example, let us take the GCS for a swarm of DJI Phantom 4 RTKs. $\rfloor \exists N = 7$, where N – number of errors in the initial flight control program on the standard GCS. Consider a time interval t_i of 3 years (26280 h) and find the failure rate $\lambda_{iSW_{GCS1}}$. For this purpose, we should determine the value of the proportionality factor $C_{SW_{GCS1}}$ from the formula $\lambda_{iSW_{GCS1}} = C_{SW_{GCS1}}(N - i + 1)$ (in our case $i = N \Rightarrow \lambda_{iSW_{GCS1}} = C_{SW_{GCS1}}$), where i s the number of the last error detected at time t_i. For convenience, all data on error numbers and time intervals between the moments of their detection are summarized in table 4, where i is the error numbers and X_i is the time between their detection.

Table 4: *Demonstration table of possible moments of error detection*

i	1	2	3	4	5	6	7
Xi, h	2154,3	4987,6	1876,2	3421,8	1765,4	6210,7	5864

The value of the proportionality coefficient is determined by the formula:

$$C_{SW_{GCS1}} = \frac{k}{\sum_{i=1}^{k} t_i * \left(N + 1 - \frac{\sum_{i=1}^{k} i * t_i}{\sum_{i=1}^{k} t_i}\right)}.$$

According to the data received $C_{SW_{GCS1}} = \lambda_{iSW_{GCS1}} = 7{,}64 * 10^{-5}$. Similarly, $\lambda^9_{iSW_{UAV1}} = 7{,}2 * 10^{-5}$ at $N = 10$, $\lambda^{10}_{iSW_{UAV1}} = 9{,}23 * 10^{-5}$ at $N = 12$, $\lambda_{iSW_{GCS2}} = 7{,}17 * 10^{-5}$ at $N = 11$ and $\lambda_{iSW_{UAV2}} = 7{,}64 * 10^{-5}$ at $N = 8$ were calculated.

To combine the obtained final models for predicting the dependability measures of the technical hardware and software of UAV swarm structures, we present a view of the system from the dependability point of view, taking into account that the failure of a software part or hardware will lead to the failure of the entire system, which indicates a serial connection. The system is depicted in figure 4.
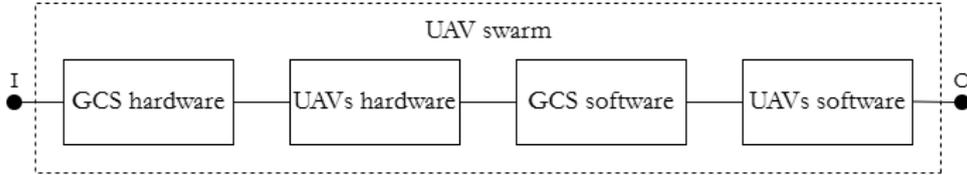
Figure 4: *Relationship between software and hardware in terms of dependability*

Thus, we obtain the final combined mathematical models for predicting the dependability indices of the software and hardware parts of UAV swarm structures. For a swarm of 9 UAVs of DJI Phantom 4 RTK model taking into account sequential connection of software and hardware parts and formulas (3) and (6):

$$P_{SWT_1^9} = e^{-\left(9*\lambda_{T_{UAV1}} + \lambda_{T_{GCS1}} + 9*\lambda^9_{iSW_{UAV1}} + \lambda_{iSW_{GCS1}}\right)*t} \tag{9}$$

Similarly for a swarm of 10 DJI Phantom 4 RTK model UAVs considering (4), (7):

$$P_{SWT_1^{10}} = e^{-\left(10*\lambda_{T_{UAV1}} + \lambda_{T_{GCS1}} + 10*\lambda^{10}_{iSW_{UAV1}} + \lambda_{iSW_{GCS1}}\right)*t} \tag{10}$$

For a swarm of 6 Tevel Aerobotics model UAVs considering (5), (8):

$$P_{SWT_2} = \left\{1 - \left(1 - e^{-\lambda_{iSW_{UAV2}}*t}\right)^6\right\} * \left\{1 - \left(1 - e^{-\lambda_{T_{UAV2}}*t}\right)^6\right\} *$$
$$* \left\{1 - \left(1 - e^{-\lambda_{SFRC}*t}\right)\left(1 - e^{-\lambda_L*t}\right)\left(1 - e^{-\lambda_{SS}*t}\right)\right\} *$$
$$* \left\{1 - \left(1 - e^{-\lambda_{GPS}*t}\right)\left(1 - e^{-\lambda_{LPS}*t}\right)\left(1 - e^{-\lambda_{UVPS}*t}\right)\right\} *$$
$$* e^{-\left(\lambda_{iSW_{GCS2}} + \lambda_P + \lambda_{MU} + \lambda_{MB} + \lambda_M + \lambda_{FS} + \lambda_E + \lambda_{OTC} + \lambda_{PHSM} + \lambda_{PRM} + 6*\lambda_{CS_2}\right)*t} \tag{11}$$

III. Communication system dependability

In addition to hardware components responsible for ensuring their core functionality and software systems, UAVs also include network components that enable information exchange with other UAVs within a swarm configuration and with GCS.

To evaluate the dependability of UAV network elements, mathematical approaches are employed to compute quantitative dependability measures, taking into account the structural configuration of the system under analysis. These measures must reflect the network nodes' ability to maintain communication and connectivity. One of the most commonly used criteria for assessing the dependability of network components is the probability of connectivity between a specific pair of nodes. This parameter indicates the likelihood that there exists at least one data transmission route between the two nodes in question [20]. From the perspective of dependability theory, this measure is equivalent to the operational availability factor K_{OG} of the network, which is calculated using the following formula:

$$K_{OG} = K_G * P(t) = \frac{T_0}{T_0 + T_B} * P(t), \tag{12}$$

where K_G is the availability factor; $P(t)$ is the reliability function; T_0 is MTBF [hours]; T_R is the restoration time [hours].

In the case of a series connection of nodes, the availability factor is calculated as follows:

$$K_G = \prod_{i=1}^{n} K_{G_i}, \tag{13}$$

where K_{G_i} is the availability factor of the i-th node; n is the number of nodes in the system.

In the case of a parallel connection of nodes, the availability factor is calculated as follows:

$$K_G = 1 - \prod_{i=1}^{n} (1 - K_{G_i}), \tag{14}$$

Essentially, the operational availability factor can be interpreted as the system's ability to maintain continuous functionality, provided that the prescribed operational and maintenance requirements are met.

To predict the dependability measures of UAV network components, it is necessary to consider the specific characteristics of their topology, the impact of the signal-to-noise ratio, and also account for the bit error rate, which depends on the type of modulation used.

Network topology refers to the arrangement of nodes and the method of their interconnection via communication links (edges). Figure 5 illustrates a case where the network consists of nine DJI Phantom 4 RTK drones used for crop yield forecasting and one GCS.

As shown in Figure 5(a), this example involves three swarms. Each swarm comprises three UAVs, one of which serves as the leader, while the others act as followers. The UAVs within each swarm are interconnected using a ring topology. A ring topology is a network configuration in which each node is connected via communication links (edges) to two neighboring nodes, forming a closed loop for data transmission.
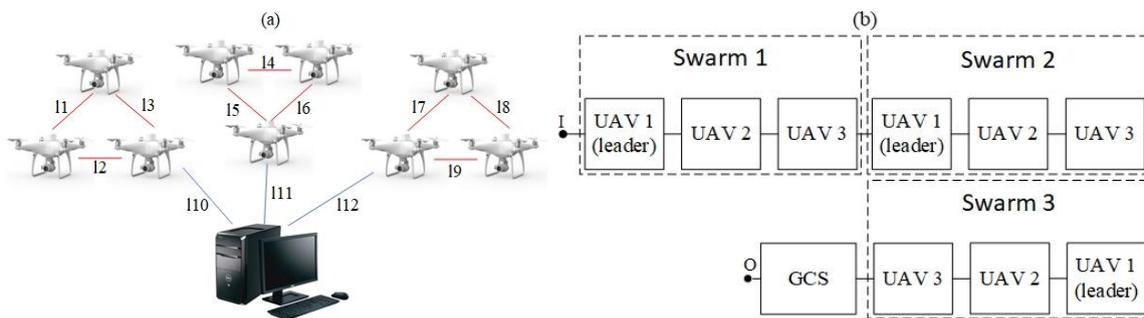

Figure 5: *Nine DJI Phantom 4 RTK drones and one GCS: (a) network configuration, (b) structural diagram for dependability assessment*

However, a disadvantage of the ring topology is that the failure of a single node or a communication link between UAVs can lead to a disruption in the operation of the entire network. The GCS is connected to each swarm through the leader UAV of that swarm. Communication between UAVs and the GCS is established wirelessly using WiMAX technology.

Thus, the structural diagram for dependability assessment of this network configuration represents a series connection of nodes and is illustrated in Figure 5(b).

Based on the analysis of Figures 5(a) and 5(b), it is possible to calculate the operational availability factor of the network with this configuration, denoted as $K_{OG_{ring}}$. In this calculation, both the nodes and the communication links (edges) must be taken into account.

Expression (15) for evaluating this factor is derived based on formulas (12)–(14):

$$K_{OG_{ring}} = \prod_{i=1}^{9} K_{G_{node\_UAV_i}} * K_{G_{node\_GCS}} * \prod_{l=1}^{12} K_{G_{edge_l}} * P_{RTECTC}(t) = \prod_{i=1}^{9} \frac{T_{0\_UAV_i}}{T_{0\_UAV_i} + T_{R\_UAV_i}} *$$

$$* \frac{T_{0\_GCS}}{T_{0\_GCS} + T_{R\_GCS}} * \prod_{l=1}^{12} \frac{T_{0\_edge_l}}{T_{0\_edge_l} + T_{R\_edge_l}} * e^{(-\lambda_{RTECTC}*t)}, \tag{15}$$

where $K_{G_{node\_UAV_i}}$, $K_{G_{node\_GCS}}$, $K_{G_{edge_l}}$ are the availability factors of the i-th UAV, GCS, and the communication links (edges), respectively; $T_{0\_UAV_i}$, T_{0_GCS}, $T_{0\_edge_l}$ denote MTBF of the i-th UAV, GCS, and the WiMAX router, respectively [hours]; $T_{R\_UAV_i}$, T_{R_GCS}, $T_{R\_edge_l}$ denote the restoration time of the i-th UAV, GCS, and the WiMAX network, respectively [hours]; P_{RTECTC}, λ_{RTECTC} are the reliability function and failure rate of the receiving and transmitting equipment of the command and telemetry channel, respectively; t is the operating time [hours].

The next example of a network configuration consists of two UAV swarms, each comprising five DJI Phantom 4 RTK drones used for crop yield forecasting, and one GCS (Figure 6(a)).
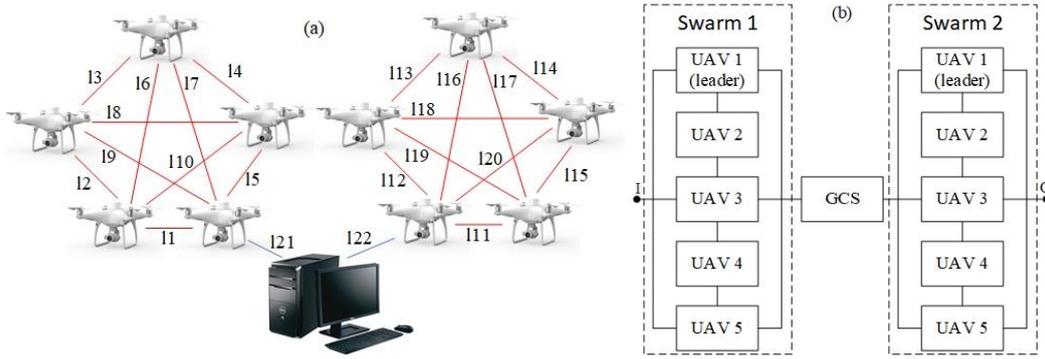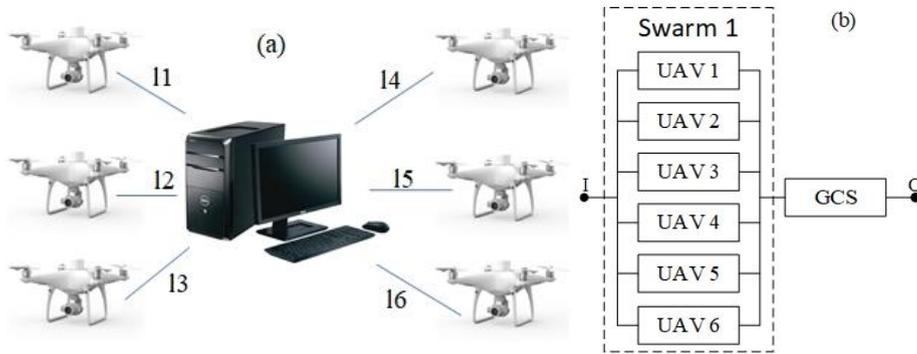

Figure 6: *Ten DJI Phantom 4 RTK drones and one GCS: (a) network configuration, (b) structural diagram for dependability assessment*

As illustrated in Figure 6(a), each UAV swarm employs a mesh network topology. A mesh topology is a network structure in which nodes are interconnected through multiple communication links (edges), thereby providing several alternative paths for data transmission in the event of a node or link failure. From a dependability perspective, this topology is considered more reliable than a ring configuration.

Accordingly, the DJI Phantom 4 RTK drones within each swarm are connected in parallel. The leader drones of the two swarms are connected in series. As in the previous case, the UAVs and the GCS are wirelessly connected via WiMAX technology. The GCS also has a series connection with the leader drones.

Thus, the structural diagram for dependability assessment of this network configuration is shown in Figure 6(b).

Based on the analysis of Figures 6(a) and 6(b), a corresponding expression can be derived for the quantitative evaluation of the operational availability factor of the network in this configuration, denoted as $K_{OG_{mesh}}$, using formulas (12)–(14). This configuration represents a series–parallel arrangement of nodes and communication links (edges).

$$K_{OG_{mesh}} = \prod_{i=1}^{10} K_{G_{node\_UAV_i}} * K_{G_{node\_GCS}} * \prod_{l=1}^{20} K_{G_{edge_l}} * \prod_{l=21}^{22} K_{G_{edge_l}} * P_{RTECTC}(t) =$$

$$= \prod_{i=1}^{10} \frac{T_{0\_UAV_i}}{T_{0\_UAV_i} + T_{R\_UAV_i}} * \frac{T_{0\_GCS}}{T_{0\_GCS} + T_{R\_GCS}} * \left(1 - \prod_{l=1}^{20} \left(1 - \frac{T_{0\_edge_l}}{T_{0\_edge_l} + T_{R\_edge_l}}\right)\right) *$$

$$* \prod_{l=21}^{22} \frac{T_{0\_edge_l}}{T_{0\_edge_l} + T_{R\_edge_l}} * e^{(-\lambda_{RTECTC}*t)}, \tag{16}$$

The final system configuration considered in this study is a UAV swarm for fruit harvesting, consisting of six Tevel Aerobotics drones and one GCS (vehicle-based) (Figure 7(a)).

Figure 7: *Six Tevel Aerobotics drones and one GCS: (a) network configuration, (b) structural diagram for dependability assessment*

Figure 7(a) illustrates that the given network configuration employs a star topology, in which all nodes are connected to a central communication node. In this example, the GCS serves as the central node. All UAVs are connected to it via a wired system (power line communication).

The failure of one or more drones does not compromise the operability of the system as a whole. The system remains functional as long as at least one drone from the swarm and the GCS are operational. The structural diagram for dependability assessment of this network configuration is shown in Figure 7(b).

As shown in Figure 7(b), this network configuration employs a parallel–series arrangement of nodes and communication links (edges). Accordingly, the expression for calculating the operational availability factor is as follows:

$$K_{OG_{star}} = \prod_{i=1}^{6} K_{G_{node\_UAV_i}} * K_{G_{node\_GCS}} * K_{G_{edge_l}} * \prod_{l=2}^{6} K_{G_{edge_l}} * P_{CS_2}(t) =$$

$$= \prod_{i=1}^{6} \frac{T_{0\_UAV_i}}{T_{0\_UAV_i} + T_{R\_UAV_i}} * \frac{T_{0\_GCS}}{T_{0\_GCS} + T_{R\_GCS}} * \frac{T_{0\_pl\_edge_l}}{T_{0\_pl\_edge_l} + T_{R\_pl\_edge_l}} *$$

$$* \left(1 - \prod_{l=2}^{6} \left(1 - \frac{T_{0\_pl\_edge_l}}{T_{0\_pl\_edge_l} + T_{R\_pl\_edge_l}}\right)\right) * e^{(-\lambda_{CS_2}*t)}, \tag{17}$$

where $T_{0\_pl\_edge_l}$, $T_{R\_pl\_edge_l}$ are MTBF and recovery time of the power line communication link, respectively [hours]; $P_{CS_2}(t)$, λ_{CS_2} are reliability function and failure rate of cable system, respectively.

In addition to the type of topology, another parameter that significantly affects the dependability of a communication system is the signal-to-noise ratio (SNR), which characterizes the ratio of the useful signal to the level of background interference and noise. The signal-to-noise ratio is calculated using the following expression:

$$SNR = \frac{E_b}{N_0} = \frac{S * T_b}{N/W} = \frac{S/R_b}{N/W}$$

(18)

where E_b is the bit energy; N_0 is the noise power spectral density; S is the signal power; T_b is the bit duration; N is the noise power; W is the bandwidth; R_b is the bit rate.

A decrease in the SNR significantly degrades data transmission quality and increases the bit error rate [21], thereby reducing the overall dependability level of the entire system.

In turn, the bit error rate is a quantitative measure that characterizes the likelihood of one or more bits being corrupted during data transmission. Its value depends on the modulation scheme used in the communication system. In modern UAVs, the most commonly used modulation types include phase modulation, frequency modulation, and quadrature amplitude modulation (QAM) [22]-[23]. However, the choice of modulation depends on the environmental conditions.

Under conditions of high noise power N, when the SNR is minimal (according to expression (18)), it is advisable to use binary phase shift keying (BPSK). Under low noise conditions, frequency shift keying with a modulation order of M=32 (32-FSK) is preferable. This conclusion is supported by simulation results conducted in Simulink (Figure 8).

All UAV models considered in this study are operated in flat terrain areas with minimal presence of other equipment that could significantly interfere with drone functionality, and under low noise power N conditions. Therefore, frequency modulation with 32 frequency-shift keying (32-FSK) was selected as the modulation scheme.

To calculate the numerical value of the bit error rate for frequency modulation, the following mathematical model is used (19) [24]:

$$P_{BER} = \frac{M}{4} * erfc\left(\sqrt{\frac{log_2 M}{2} * \frac{E_b}{N_0}}\right)$$

(19)

where M is the modulation order; $erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty exp(-y^2)dy$ is the complementary error function.
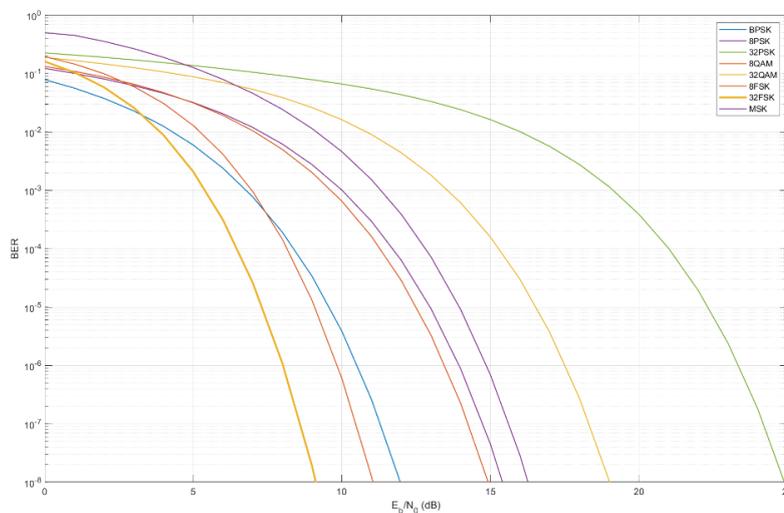

Figure 8: *Dependence of bit error rate on the SNR*

In existing scientific research on network dependability assessment, the bit error rate is not taken into account, which renders current approaches to UAV network dependability forecasting incomplete.

Therefore, this article proposes introducing a bit error factor K_{BER} into the general formula for the network's operational availability factor (12). From a dependability standpoint, as the bit error rate P_{BER} increases, the network's dependability decreases. Consequently, a correction factor K_{BER}, defined as the reciprocal of P_B, is proposed to establish a direct proportionality (20).

$$K_{BER} = 1 - P_{BER} \qquad (20)$$

Thus, the final mathematical models of the network's operational availability factor, according to expressions (15)–(17) and (19)–(20), for each system configuration are presented below.

3 UAV swarms, each consisting of 3 DJI Phantom 4 RTK drones and 1 GCS:

$$K_{OG_{ring}} = \prod_{i=1}^{9} \frac{T_{0\_UAV_i}}{T_{0\_UAV_i} + T_{R\_UAV_i}} * \frac{T_{0\_GCS}}{T_{0\_GCS} + T_{R\_GCS}} * \prod_{l=1}^{12} \frac{T_{0\_edge_l}}{T_{0\_edge_l} + T_{R\_edge_l}} *$$

$$* e^{(-\lambda_{RTECTC}*t)} * \left(1 - \left(\frac{M}{4} * erfc\left(\sqrt{\frac{log_2 M}{2} * \frac{E_b}{N_0}} \right) \right) \right) \qquad (21)$$

2 UAV swarms, each consisting of 5 DJI Phantom 4 RTK drones and 1 GCS:

$$K_{OG_{mesh}} = \prod_{i=1}^{10} \frac{T_{0\_UAV_i}}{T_{0\_UAV_i} + T_{R\_UAV_i}} * \frac{T_{0\_GCS}}{T_{0\_GCS} + T_{R\_GCS}} * \left(1 - \prod_{l=1}^{20} \left(1 - \frac{T_{0\_edge_l}}{T_{0\_edge_l} + T_{R\_edge_l}} \right) \right) *$$

$$* \prod_{l=21}^{22} \frac{T_{0\_edge_l}}{T_{0\_edge_l} + T_{R\_edge_l}} * e^{(-\lambda_{RTECTC}*t)} * \left(1 - \left(\frac{M}{4} * erfc\left(\sqrt{\frac{log_2 M}{2} * \frac{E_b}{N_0}} \right) \right) \right) \qquad (22)$$

1 UAV swarm consisting of 6 Tevel Aerobotics drones and 1 GCS:

$$K_{OG_{star}} = \prod_{i=1}^{6} \frac{T_{0\_UAV_i}}{T_{0\_UAV_i} + T_{R\_UAV_i}} * \frac{T_{0\_GCS}}{T_{0\_GCS} + T_{R\_GCS}} * \frac{T_{0\_pl\_edge_l}}{T_{0\_pl\_edge_l} + T_{R\_pl\_edge_l}} *$$

$$* \left(1 - \prod_{l=2}^{6} \left(1 - \frac{T_{0\_pl\_edge_l}}{T_{0\_pl\_edge_l} + T_{R\_pl\_edge_l}} \right) \right) * e^{(-\lambda_{CS_2}*t)} * \left(1 - \left(\frac{M}{4} * erfc\left(\sqrt{\frac{log_2 M}{2} * \frac{E_b}{N_0}} \right) \right) \right) \qquad (23)$$

IV. Approbation of the developed mathematical model

The developed mathematical models 9-11 were applied to the selected UAV swarms using the data described in tables 3-5. The results of calculating the reliability function are presented in figures 9-11.

It should be noted that the indicators calculated by the model characterize the operational time of the drone swarm, i.e. those periods when the DJI Phantom 4 RTK UAV is in flight and Tevel Aerobotics is in the process of collection. The following fact should be taken into account when

analyzing the obtained dependencies: it takes less than half an hour of operational time for DJI Phantom 4 RTK drones to cover an average agricultural plot.
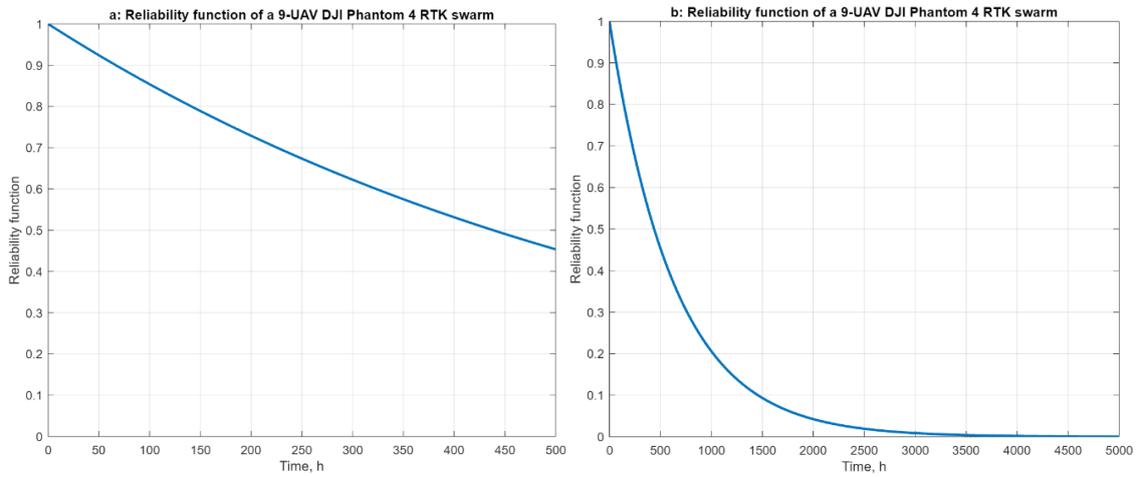

Figure 9: *Time dependence of reliability function for a swarm of 9 DJI Phantom 4 RTK UAVs: (a) - 500 h, (b) - 5000 h*
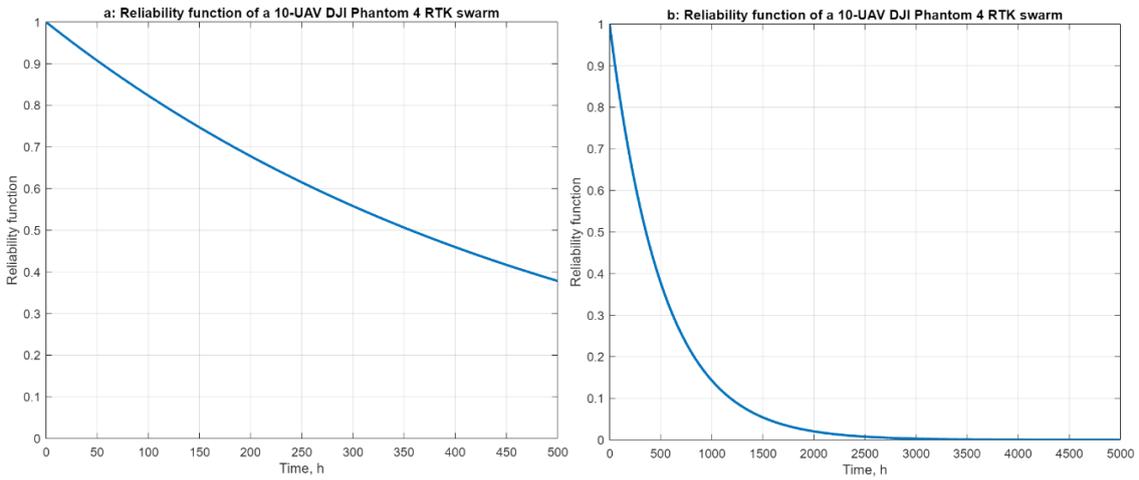

Figure 10: *Time dependence of reliability function for a swarm of 10 DJI Phantom 4 RTK UAVs: (a) - 500 h, (b) – 5000 h*
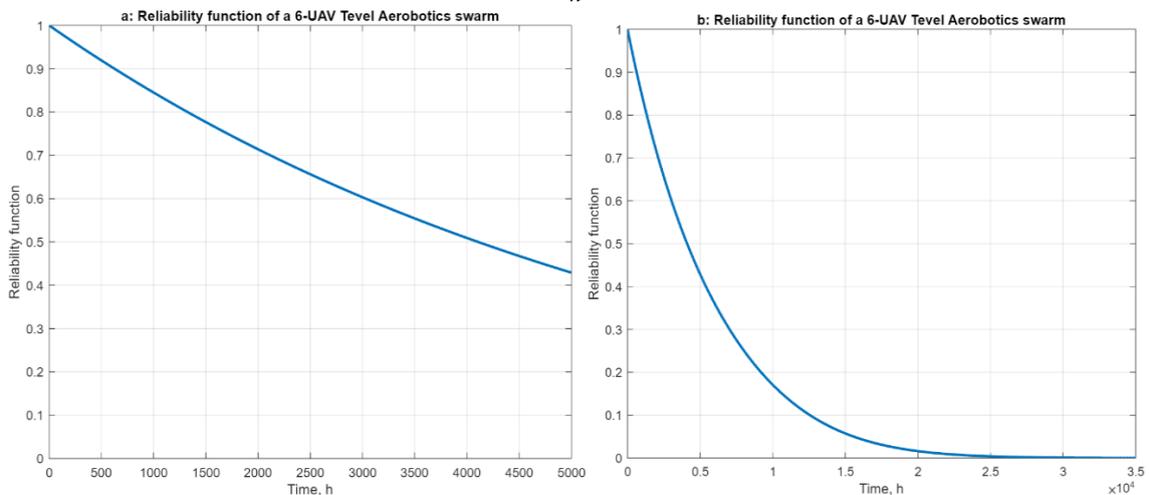

Figure 11: *Time dependence of reliability function for a swarm of 6 Tevel Aerobotics UAVs: (a) - 5000 h, (b) -35000 h*

According to the results of the analysis, for the selected swarm of 9 drones responsible for the analysis of ripe fruits, reliability function at the 440th hour of operational work will decrease by 2 times, and by the 5000th hour of operation reliability function will be close to 0. Based on this, it can be concluded that it is necessary to conduct regular maintenance work with such a group of UAVs.

The results for a swarm of 10 drones of the same model were less reliable: at the 360th hour of operation, the probability of failure drops by half, and by the 5000th hour it approaches 0.

The swarm structure consisting of 6 Tevel Aerobotics drones designed for harvesting has the highest probability of failure, while the process of its operation is longer. In continuous operation of such a system, reliability function without maintenance will reach 0,5 in 4100 hours, and will approach 0 at the 35000th hour.

What is more, based on the derived mathematical models (21)–(23), a plot was constructed to illustrate the dependence of the operational availability factor on time for each swarm configuration (Figure 12).
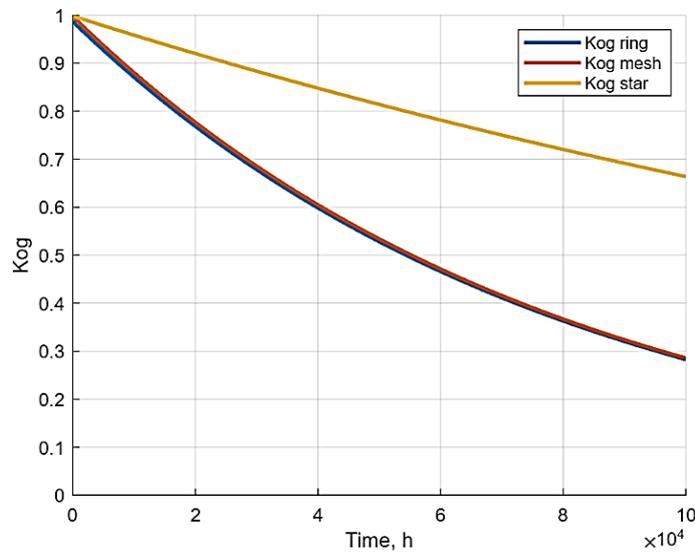

Figure 12: *Time dependence of operational availability factor for various UAV swarm configurations*

An analysis of Figure 12 shows that, from a dependability standpoint, the best performance was demonstrated by the swarm configuration consisting of six Tevel Aerobotics drones and one GCS. The operational availability factor $K_{OG_{star}}$ reaches approximately 0.96 at 10000 hours of operation. In contrast, the system comprising three UAV swarms, each with three DJI Phantom 4 RTK drones and a GCS, exhibited the lowest dependability, with an operational availability factor of approximately 0.88 at the same time mark (10000 hours).

V. Description of the developed methodology

The description of the developed methodology for predicting dependability measures of UAV swarm structures is presented in figures 13-14 in the form of IDEF0-diagram.
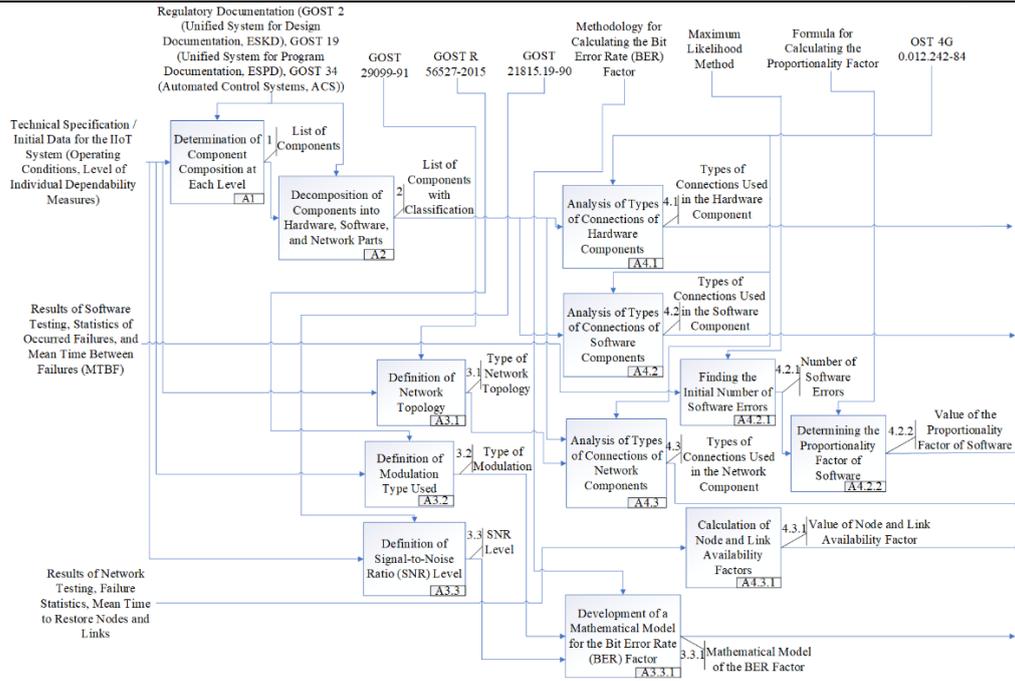
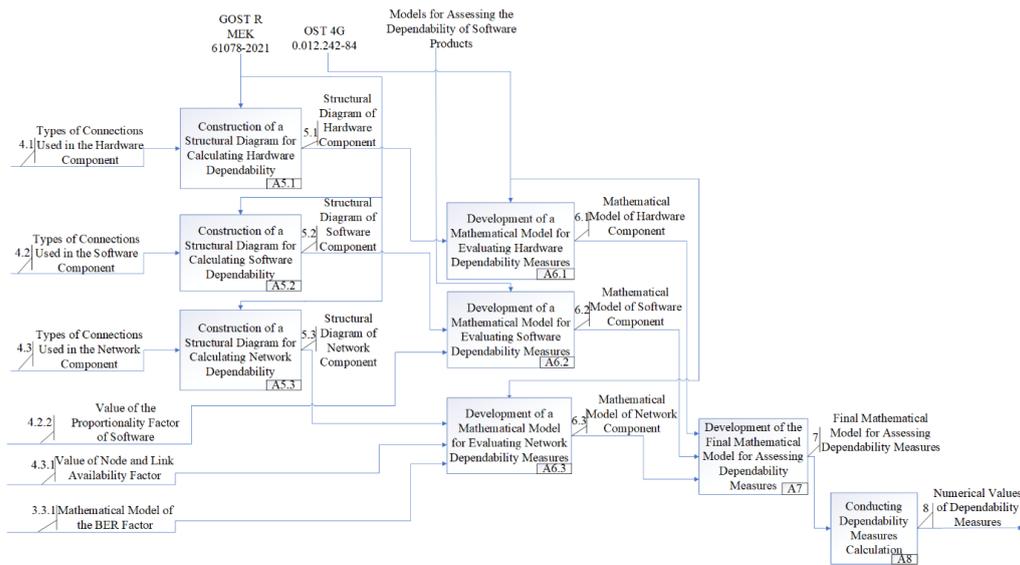**Figure 13:** *Developed methodology for predicting dependability measures. Part 1*

Figure 14: *Developed methodology for predicting dependability measures. Part 2*

As shown in Figures 13–14, the proposed methodology for predicting dependability measures consists of eight stages (blocks A1–A8):

1) Analysis of UAV swarm structures, resulting in the formation of a list of components.

2) Classification of components based on their functional purpose into hardware, software, and network elements.

3) Analysis of connection types between hardware, software, and network components.

4) Development of a structural diagram for dependability calculation of hardware and software components. When assessing the hardware part, it is often sufficient to use initial data such as the mean time to failure (MTTF) and recovery time, which are usually provided in the technical documentation. If these data are not available, it is necessary to calculate the dependability of individual electronic components, including zero-level electronic modules, using specialized

reference manuals, such as [13]. For software dependability assessment, initial data are required, including software testing results—namely, the number of failures and the mean time between failures (MTBF). The initial number of software errors and the proportionality factor are estimated using the Jelinski-Moranda model, as described in Chapter II.

    5) Development of a structural diagram for dependability calculation of network components, considering the applied network topology, modulation type, and bit error probability, which is incorporated into the proposed methodology as a correction factor K_{BER}.

    6) Formulation of a mathematical model for predicting the dependability of hardware, software, and network components.

    7) Formulation of a comprehensive mathematical model for assessing the dependability of UAV swarm structures.

    8) Numerical calculation of dependability measures.

VI. Conclusions

Based on the results of this work, a single combined mathematical model for predicting the dependability performance of swarm structures for agricultural applications was created, consisting of software dependability prediction models for each UAV and GCS and hardware dependability prediction models for the drones and GCS. Software dependability was calculated using the Jelinski-Moranda model, and hardware dependability was calculated using the exponential dependability law via MTBF. Furthermore, the operational readiness of the communication systems involved in the UAV swarm mission was investigated.

    The developed mathematical model allows to refine the predicted dependability measures. The results of the practical calculation were the conclusions that the selected objects of the study require regular maintenance work, and also the communication system for a swarm of 10 UAVs of Phantom DJI 4 RTK model is more reliable than for 9, while the overall hardware and software dependability of a group of 9 similar drones is much higher.

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