The 12th IEEE International Conference on Dependable Systems, Services and Technologies, DESSERT'2022
9-11 Dec, 2022, Athens, Greece

Swarm of Unmanned Aerial Vehicles as a Multi-State Queueing System with Non-Controlled and Controlled Degradation

Ihor Kliushnikov
Department of Computer Systems, Networks and Cybersecurity of National Aerospace University "KhAI"
Kharkiv, Ukraine
i.kliushnikov@csn.khai.edu

Herman Fesenko
Department of Computer Systems, Networks and Cybersecurity of National Aerospace University "KhAI"
Kharkiv, Ukraine
h.fesenko@csn.khai.edu

Gennadiy Fedorenro
Department of Computer Systems, Networks and Cybersecurity of National Aerospace University "KhAI"
Kharkiv, Ukraine
g.fedorenko@csn.khai.edu

Serhii Rudakov
Department of Fire Prevention in Settlements of National University of Civil Defence of Ukraine
Kharkiv, Ukraine
serg_73@i.ua

Vitalii Mikhalevskyi
Department of Computer Science of Khmelnytskyi National University
Khmelnytskyi, Ukraine
cezar61mv@gmail.com

***Abstract* — The paper is devoted to unmanned aerial vehicle (UAV) swarm-based multi-state queueing systems (UAVSw-MQSs). A set of Markov models of the UAVSw-MQSs are developed and explored. The states of these models are described in detail. The main features of utilizing strategies without resource allocation (non-controlled degradation) and with resource allocation (non-controlled degradation) when the UAVSw-MQS operating are described and discussed. An example of a model of the UAVSw-MQS, servicing the requests for food and medicine delivery, in the failures of UAVs and when using controlled degradation are given and analyzed. The possibility of strategies with controlled degradation on increasing efficiency of the UAVSw-MQS servicing requests with various weighting coefficients is demonstrated and discussed.**

Keywords* — *unmanned aerial vehicle, swarm, queueing system, multi-state system, degradation

I. Introduction

The utilization of unmanned aerial vehicles (UAVs) for servicing various requests allows for the creation of flexible systems able to adapt to changing conditions of their usage environment, as well as to the expansion of the range of requests. At present, UAVs can provide a wide range of services:

- A drone-based IoT as a service (IoTaaS) framework to enable the dynamic provisioning or deployment of IoT devices utilizing drones [1].
- An intelligent, autonomous UAV-enabled solution for a traffic monitoring and emergency response handling system utilized in the smart city [2].
- The 5G IoT network formed by a fleet of UAVs for future smart cities [3].
- The development of a UAV–assisted vehicular ad hoc network (VANET) communication architecture [4].
- Medicine delivery [5].

Being remotely piloted, the UAVs are ideal for performing risk-related tasks: assessing the consequences of destruction, monitoring objects in potentially dangerous areas, and searching for explosive objects. At the same time, the utilization of adequately formed UAV swarms increases the efficiency and reliability of mission performance.

A UAV is a complex technical system, therefore, like all technical systems, it can fail. Failures of the UAV while servicing a request can result in the loss of the request. But there are situations when the failure of individual UAVs of the swarm does not lead to the termination of the mission. For example, if the mission of the swarm is to search for an object in a specified area within a specified time, the occurrence of UAV failures during the execution of such a mission does not lead to its termination, but will only increase the search time. The mission itself will continue as long as at least one UAV is operable. In this case, we have UAV swarm-based multi-state queueing system (UAVSw-MQS)

The rest of the paper is structured as follows.

In the next section considers the existing studies regarding to multi-state systems and features of the operation of UAV-based queueing systems in various domains.

Section III presents and explores Markov models of UAVSw-MQSs with non-controlled and controlled degradation.

Section IV gives and analyses an example of a model of the UAVSw-MQS, servicing the requests for food and medicine delivery, in the failures of UAVs and when using controlled degradation.

Section V briefly summarizes the main results obtained and highlights the next research steps.

II. STATE-OF-THE-ART

The approaches of reliability assessment of UAV are considered in many studies.

In order to increase the amount of parcels delivered to customers safely, the study [6] presented the concept of including the reliability issues in the drone delivery scheduling. The concept allows for minimization of expected loss of demand by increasing the reliability of the delivery network.

Li et al. [7] investigate the novel Reliability-Aware Multi-Agent Coverage Path Planning (RA-MCPP) problem and propose a Genetic Algorithm optimisation approach for finding RA-MCPP path plans. The approach utilization allows for maximisation of the probability of mission completion.

Considering UAV's communication network, the authors of [8] present expected transmission account metric via a new algorithm for reliability. The authors show that the increase of the fluctuations in links between UAVs can be detected by taking into account the relative speed between UAVs.

The work [9] reveals the features of utilizing the fault tree analysis method for UAVs reliability assessment. An absorbing Markov chain approach, developed in the paper, allows finding the most risky scenarios and considerations for improving reliability.

The paper [10] suggests the possible use of the Birnbaum importance-based genetic algorithm to solve the reliability optimization problem for the circular-consecutive k-out-of-n: (G) system.

The study [11] describes the concept of probability, failures, series and parallel systems, k-out-of-n systems and reveals the features of evaluating the reliability and risk of systems with load-sharing effects.

Considering a UAV as a multi-state system (MSS), the authors of [12] address the reliability models of UAV taking into account of the decomposition of the UAV into degradable and non-degradable components.

In the context of developing a novel multi-channel load awareness-based MAC protocol for the flying ad hoc network, the paper [13] proposes the multi-priority queueing and service mechanism aimed at efficiently utilizing the network bandwidth resource.

The authors of [14] suggest the queueing theory based enhanced collaborative computing model aimed at supporting the computation-intensive and latency-critical services for UAV swarm and achieving the closed-form solution of the decision threshold.

The work [15] addresses the multiclass M/D/1 queueing system-based optimization model considering the waiting times of drones served at automated battery maintenance system.

The paper [16] considered UAVs utilized to build flying ubiquitous sensor networks as a queuing system and their swarm—as a queuing network. Modelling results showed that a relatively small number of UAVs to estimate the time of the data delivery for a relatively small number of UAV familiar approximate estimates for systems G/G/1 could be applied.

The study [17] suggested a model of a UAV-based system for monitoring NPP accidents by use of queueing theory and reliability models considering routings covered by drones during monitoring activities. At the same time, aspects of a more detailed assessment of UAV fleet efficiency considering failures and recovery procedures were also addressed.

Hence, most of the considered works propose approaches of assessment of reliability UAVs and UAV-based monitoring systems taking into account the fatal failures of UAVs but do not consider different strategies of state control for UAVSw-MQS.

III. MODELS OF UAV SWARM-BASED MULTISTATE QUEUING SYSTEMS WITH NON-CONTROLLED AND CONTROLLED DEGRADATION

A. Model of the UAVSw-MQS with non-controlled degradation

Let us consider a model of UAVSw-MQS as a Markov model of the UAVSw-MQS of M/M/n(u):(F) type. M/M/n(u):(F) means that UAVSw-MQS is a queuing system where the requests arrive according to a Poisson process with rate λ (the first letter M), that is the interarrival times are independent, exponentially distributed random variables with parameter λ. The service times are also assumed to be independent and exponentially distributed (the second letter M). The requests are served by n UAV swarms (the letter n) comprising u UAV (the letter u). When servicing the requests, UAVs can fail and recover (the letter F) [5].

The Markov model of UAVSw-MQS of M/M/n(u):(F) type is shown in Fig.1 where λ is the arrival rate, μ_f is the failure rate, μ_0 is the service rate when all UAVs are operable, μ_1 is the service rate when one UAV is non-operable, $\mu_{(u-1)}$ is the service rate when *(u-1)* UAVs are non-operable.

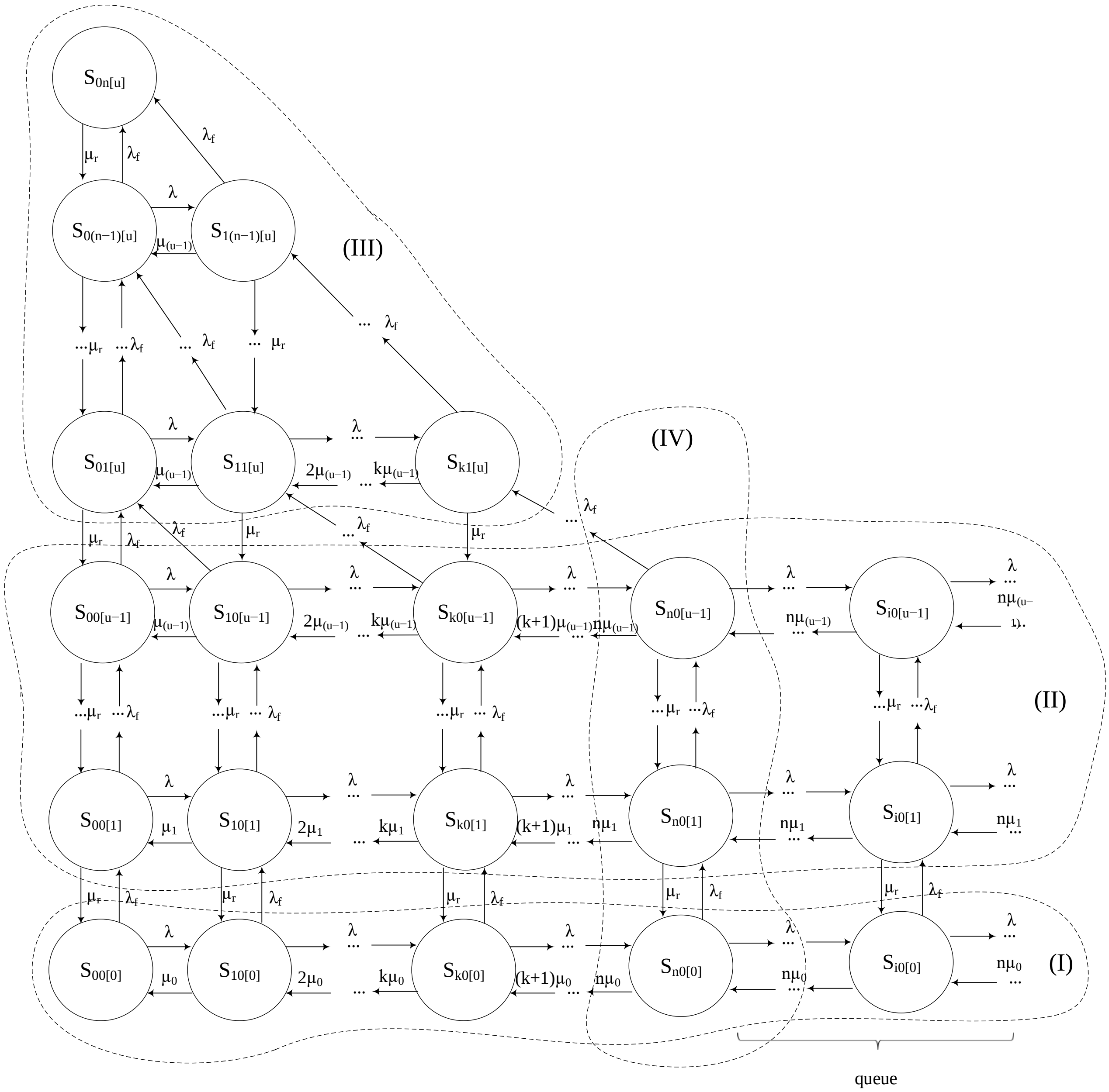

Fig. 1. Markov model of the UAVSw-MQS of M/M/n(u):(F) type.

The set of states (I) comprises the states where all UAVs are operable. The set of states (II) comprises the states where one or more UAVs are non-operable but part of the requests are served by the rest of operable UAVs (in this case, UAVSw-MQS is in degraded state). The set of states (III) comprises the states where all UAVs are non-operable (the existing requests are lost). The set of states (IV) comprises the states where all UAVs are involved in servicing the requests.

B. *Model of a UAVSw-MQS with controlled degradation*

In the operation of a UAVSw-MQS, there may be situations when requests have a different degree of importance depending on their weighting coefficients. Assume that the sum of the weighting coefficients is 1. In this case, when all UAVs are involved in servicing the requests and can fail, the various strategies for servicing requests can be considered:

- Strategies without the reallocation of resources ($Str_{alloc(-)}$).
- Strategies with the reallocation of resources ($Str_{alloc(+)}$).

A strategy without the reallocation of resources is utilized in case of failures of UAVs that are part of the swarm servicing the request with less weighting coefficient. A strategy with the reallocation of resources is utilized in case of failure of UAVs that are part of the swarm servicing the request with a large weighting coefficient. The reallocation of resources lies in the fact that this swarm involves operable UAVs of the swarm servicing the request with less weighting coefficient to change its own failed UAVs. This strategy allows for higher efficiency of utilizing UAVs of both swarms which is illustrated in Fig. 2 where g_1 and g_2 are the weighting coefficients for less and a large of degrees of request importance, respectively.

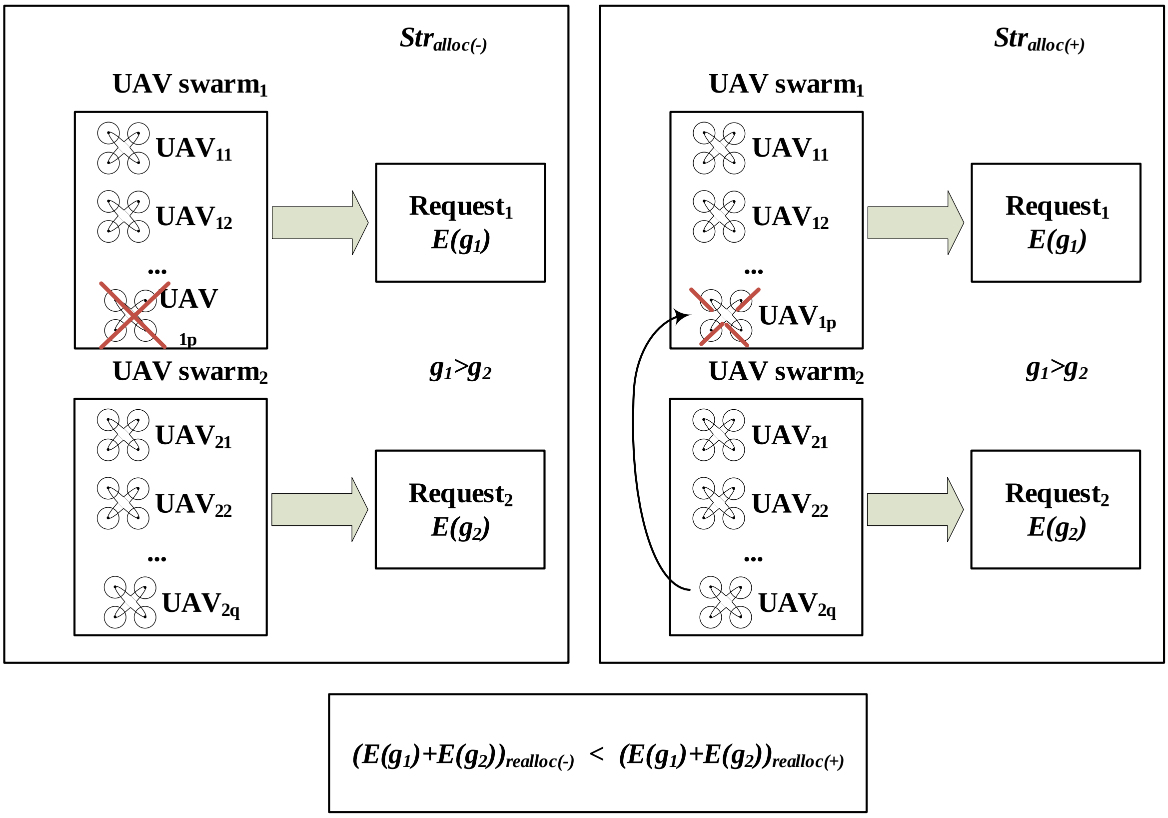

Fig. 2. Example of utilizing the strategies $Str_{alloc(-)}$ and $Str_{alloc(+)}$.

Modelling of the UAVSw-MQS can be difficult due to significant increasing the number of states and the uncertainty regarding to transitions between states.

Consider a fragment of a Markov model of the UAVSw-MQS where two UAVs service one request with a large weighting coefficient (g_1), two UAVs service one request with less weighting coefficient (g_2), and two UAVs are in operational reserve (Fig. 3).

When developing the model presented in Fig. 3, the following assumptions were accepted:

- UAVs can fail and recover.
- When a UAV, servicing the request with a large weighting coefficient, fails, it is replaced with a reserve UAV (if available).
- When a UAV, servicing the request with a large weighting coefficient, fails and there are no reserve UAVs, it is replaced with one of the UAVs, servicing the request with less weighting coefficient but only one such a UAV can be used.
- When a UAV, servicing the request with less weighting coefficient, fails, it is not replaced.

The description of states for the fragment of the Markov model shown in Fig 3 is presented in Table 1.

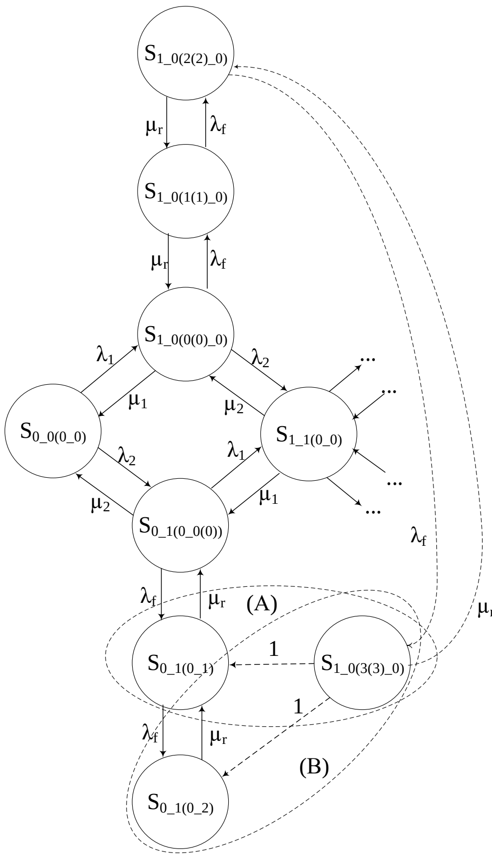

Fig. 3. Fragment of a Markov model of UAVSw-MQS with controlled degradation.

TABLE I. DESCRIPTION OF STATES FOR THE FRAGMENT OF THE MARKOV MODEL OF UAVSW-MQS WITH CONTROLLED DEGRADATION

State	Description of the state	Опис стану системи
$S_{0\_0(0(0)\_0)}$	There are no requests. All UAVs are operable.	в системі відсутні замовлення, всі БПЛА справні
$S_{1\_0(0(0)\_0)}$	The request with a large weighting coefficient is served by two UAVs. All UAVs are operable.	в системі обробляється одне замовлення з більшою вагою, всі БПЛА справні
$S_{1\_0(1(1)\_0)}$	The request with a large weighting coefficient is served by two UAVs. One of the UAVs has failed and has been replaced with the first reserve UAV	в системі обробляється одне замовлення з більшою вагою, БПЛА, що його обслуговує відмовив, для поновлення обслуговування залучено один БПЛА
$S_{1\_0(2(2)\_0)}$	After changing the failed UAV by the first reserve UAV, the request with a large weighting coefficient is served by two UAVs. One of the UAVs has failed and has been replaced with the second reserve UAV. Thus, two UAVs are non-operable and all reserve UAVs have been used.	в системі обробляється одне замовлення з більшою вагою, 2 БПЛА, що його обслуговують відмовили, для поновлення обслуговування залучено два БПЛА
$S_{1\_0(3(3)\_0)}$	After using all reserve UAVs to change failed UAVs, the request with a large weighting coefficient is served by two UAVs. One of the UAVs has failed and has been replaced with the UAV servicing the request with less weighting coefficient. Thus, three UAVs are non-operable, all reserve UAVs and one UAV servicing the request with less weighting coefficient have been used.	в системі обробляється одне замовлення з більшою вагою, 3 БПЛА, що його обслуговує відмовили, для поновлення обслуговування залучено три БПЛА (два вільних та один, що обслуговував замовлення з меншою вагою)
$S_{0\_1(0\_0)}$	The request with less weighting coefficient is served by two UAVs. All UAVs are operable.	в системі обробляється одне замовлення з меншою вагою, всі БПЛА справні
$S_{0\_1(0(0)\_1)}$	The request with less weighting coefficient is served by two UAVs. One of the UAVs has failed.	в системі обробляється одне замовлення з меншою вагою, один БПЛА, що його обслуговує відмовив
$S_{0\_2(0(0)\_2)}$	The request with less weighting coefficient is served by two UAVs. Two UAVs have failed.	в системі обробляється одне замовлення з меншою вагою, два БПЛА, що його обслуговують відмовили

There are two set of states in the fragment of the model presented in Fig. 3:

The set (A) which can be considered as one state in the case when the strategy $Str_{alloc(+)}$ is used and all UAVs of the swarm, servicing the request with less weighting coefficient, are operable.

The set (B) which can be considered as one state in the case when the strategy $Str_{alloc(+)}$ is used and one UAV of the swarm, servicing the request with less weighting coefficient, is non-operable.

Thus, there is the uncertainty regarding to transitions between states. To cope with this problem, the following assumption can be introduced: the swarm, servicing the request with less weighting coefficient, can allocate a UAV only when its own UAVs are operable.

IV. EXAMPLE OF A MODEL OF THE UAVSW-MQS, SERVICING THE REQUESTS FOR FOOD AND MEDICINE DELIVERY, IN THE FAILURES OF UAVS AND WHEN USING CONTROLLED DEGRADATION

Let us analyze a UAVSw-MQS with controlled degradation when two UAVs serve the requests for medicine delivery and two UAVs serve the requests for food delivery. The weighting coefficients for medicine and food delivery are 0.7 and 0.3, respectively.

The following assumptions are accepted:

- One request is served by one UAV.
- UAVs can fail (except in cases of waiting for requests) and recover.
- Only one UAVs can be non-operable.
- When a UAV, servicing the request for medicine delivery, fails, it is replaced with the reserve UAV or UAV servicing the request for food delivery.
- When a UAV, servicing the request for food delivery, fails, it is not replaced.

The Markov model of the described UAVSw-MQS is presented in Fig. 4 where λ_m is the arrival rate of request for medicine delivery, λ_g is the arrival rate of request for food delivery, μ_m is the service rate of request for medicine delivery, μ_g is the service rate of request for food delivery, λ_f is the failure rate of a UAV, μ_f is the recovery rate of a UAV, λ_{ch} is service resumption rate of request for medicine delivery by involving additional UAVs.

The description of states for the Markov model shown in Fig. 4 is presented in Table II.

TABLE II. DESCRIPTION OF STATES FOR THE MARKOV MODEL OF THE UAVSW-MQS SERVICING THE REQUESTS FOR FOOD AND MEDICINE DELIVERY

State	Description of the state
$S_{0\_0(0\_0)}$	There are no requests. All UAVs are operable.
$S_{1\_0(0\_0)}$	One request for medicine delivery is served by one UAV. All UAVs are operable.
$S_{1\_0(1\_0)}$	One request for medicine delivery is served by one UAV. The UAV is non-operable.
$S_{1\_0(1(1)\_0)}$	One request for medicine delivery is served by one UAV. The UAV is non-operable. To continue servicing the request, another UAV has been involved.
$S_{2\_0(0\_0)}$	Two requests for medicine delivery are served by two UAVs. All UAVs are operable.
$S_{2\_0(1\_0)}$	Two requests for medicine delivery are served by two UAVs. One of the UAVs is non-operable.
$S_{0\_1(0\_0)}$	One request for food delivery is served by one UAV. All UAVs are operable.
$S_{0\_1(0\_1)}$	One request for food delivery is served by one UAV. The UAV is non-operable.
$S_{0\_2(0\_0)}$	Two requests for food delivery are served by two UAVs. All UAVs are operable.
$S_{0\_2(0\_1)}$	Two requests for food delivery are served by two UAVs. One of the UAVs is non-operable.
$S_{1\_1(0\_0)}$	One request for medicine delivery is served by one UAV and one request for food delivery is served by one UAV. All UAVs are operable.
$S_{1\_1(1\_0)}$	One request for medicine delivery is served by one UAV and one request for food delivery is served by one UAV. The UAV, servicing the request for medicine delivery, is non-operable.
$S_{1\_1(0\_1)}$	One request for medicine delivery is served by one UAV and one request for food delivery is served by one UAV. The UAV, servicing the request for food delivery, is non-operable.
$S_{0\_0(1\_0)}$	There are no requests. One of the UAVs is non-operable.

The states $S_{1\_0(1\_0)}$ and $S_{1\_1(1\_0)}$ are the states where the additional UAVs need involving to continue servicing request for medicine delivery. The state $S_{1\_0(1\_0)}$ is characterized by involving the reserve UAV, and $S_{1\_1(1\_0)}$ is characterized by involving the UAV servicing the request for food delivery.

Probabilities of the UAVSw-MQS being in the states can be obtained by solving the system of equations (1).

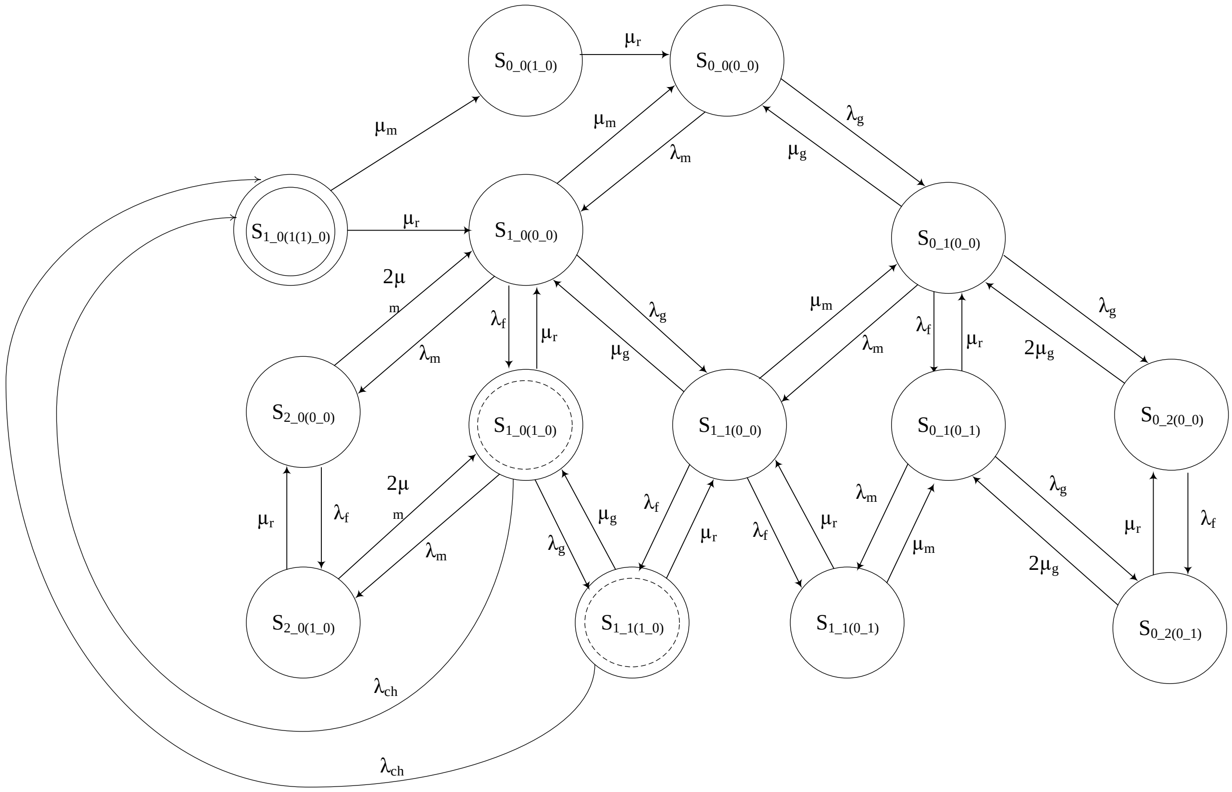

Fig. 4. Markov model of the UAVSw-MQS servicing the requests for food and medicine delivery.

$$\begin{cases}
-\left(\lambda_m+\lambda_g\right)P_{0_0(0_0)}+\mu_m P_{1_0(0_0)}+\mu_g P_{0_1(0_0)}+\\
+\mu_r P_{0_0(1_0)}=0;\\
-\mu_r P_{0_0(1_0)}+\mu_m P_{1_0(1(1)_0)}=0;\\
-\left(\mu_m+\mu_r\right)P_{1_0(1(1)_0)}+\lambda_{ch}P_{1_0(1_0)}+\lambda_{ch}P_{1_1(1_0)}=0;\\
-\left(\lambda_m+\lambda_g+\lambda_f+\mu_m\right)P_{1_0(0_0)}+\lambda_m P_{0_0(0_0)}+\mu_g P_{1_1(0_0)}+\\
\mu_r P_{1_0(1_0)}+2\mu_m P_{2_0(0_0)}+\mu_r P_{1_0(1(1)_0)}=0;\\
-\left(\lambda_m+\lambda_g+\lambda_f+\mu_g\right)P_{0_1(0_0)}+\lambda_m P_{0_0(0_0)}+\mu_m P_{1_1(0_0)}+\\
\mu_r P_{0_1(0_1)}+2\mu_g P_{0_2(0_0)}=0;\\
-\left(\lambda_f+2\mu_m\right)P_{2_0(0_0)}+\lambda_m P_{1_0(0_0)}+\mu_r P_{2_0(1_0)}=0;\\
-\left(\lambda_m+\lambda_{ch}+\lambda_g+\mu_r\right)P_{1_0(1_0)}+\lambda_f P_{1_0(0_0)}+2\mu_m P_{2_0(1_0)}+\\
+\mu_g P_{1_1(1_0)}=0;\\
-\left(2\lambda_f+\mu_g+\mu_m\right)P_{1_1(0_0)}+\lambda_g P_{1_0(0_0)}+\lambda_m P_{0_1(0_0)}+\\
\mu_r P_{1_1(1_0)}+\mu_r P_{1_1(0_1)}=0;\\
-\left(\lambda_m+\lambda_g+\mu_r\right)P_{0_1(0_1)}+\lambda_f P_{0_1(0_0)}+\mu_m P_{1_1(0_1)}+\\
+2\mu_g P_{0_2(0_1)}=0;\\
-\left(\lambda_f+2\mu_g\right)P_{0_2(0_0)}+\lambda_g P_{0_1(0_0)}+\mu_r P_{0_2(0_1)}=0;\\
-\left(2\mu_m+\mu_r\right)P_{2_0(1_0)}+\lambda_f P_{2_0(0_0)}+\lambda_m P_{1_0(1_0)}=0;\\
-\left(\lambda_{ch}+\mu_g+\mu_r\right)P_{1_1(1_0)}+\lambda_g P_{1_0(1_0)}+\lambda_f P_{1_1(0_0)}=0;\\
-\left(\mu_m+\mu_r\right)P_{1_1(0_1)}+\lambda_m P_{0_1(0_1)}+\lambda_f P_{1_1(0_0)}=0;\\
-\left(\mu_r+2\mu_g\right)P_{0_2(0_1)}+\lambda_g P_{0_1(0_1)}+\lambda_f P_{0_2(0_0)}=0;\\
P_{0_0(0_0)}+P_{1_0(0_0)}+P_{1_0(1_0)}+P_{2_0(0_0)}+P_{2_0(1_0)}+\\
+P_{1_1(0_0)}+P_{1_1(1_0)}+P_{1_1(0_1)}+P_{0_1(0_0)}+P_{0_1(0_1)}+\\
P_{0_2(0_0)}+P_{0_2(0_1)}+P_{0_0(1_0)}+P_{1_0(1(1)_0)}=0.
\end{cases} \tag{1}$$

For λ_m = 0.6, λ_g = 0.7, μ_m = 2, μ_g = 3, λ_f = 0.001, μ_f = 1, and λ_{ch} = 4, these probabilities are as follows:

$$P_{0\_0(0\_0)}=0.5488;\ P_{1\_0(0\_0)}=0.1624;$$
$$P_{1\_0(1\_0)}=0.0185;\ P_{2\_0(0\_0)}=0.0249;$$
$$P_{2\_0(1\_0)}=0.0022;\ P_{1\_1(0\_0)}=0.0365;$$
$$P_{1\_1(1\_0)}=0.0016;\ P_{1\_1(0\_1)}=0.00003;$$
$$P_{0\_1(0\_0)}=0.1117;\ P_{0\_1(0\_1)}=0.0001;$$
$$P_{0\_2(0\_0)}=0.013;\ P_{0\_2(0\_1)}=0.00001;$$
$$P_{0\_0(1\_0)}=0.0535;\ P_{1\_0(1(1)\_0)}=0.0267.$$

The probability of the UAVSw-MQS servicing all requests without losses is 0.996. When utilizing the strategy $Str_{alloc(-)}$ (non-controlled degradation), the probabilities of the UAVSw-MQS losing the requests for medicine and food delivery are 0.00384 and 0.00016, respectively. When utilizing the strategy $Str_{alloc(+)}$ (controlled degradation), these probabilities are 0.00222 and 0.00178, respectively. In other words, if 10000 requests are served (5000 requests for medicine delivery and 5000 requests for food delivery), 38 out of every 5000 requests for medicine delivery and 2 out of every 5000 requests for food delivery are lost when utilizing the strategy $Str_{alloc(-)}$ (non-controlled degradation). When utilizing the strategy $Str_{alloc(+)}$ (controlled degradation), these losses are 22 and 18, respectively. For g_1 = 0.7 and g_2 = 0.3, the overall losses in the UAVSw-MQS are 38·0.7 + 2·0.3 = 27.2 conventional units when utilizing the strategy $Str_{alloc(-)}$ and 22·0.7+18·0.3=20.8 conventional units when utilizing the strategy $Str_{alloc(+)}$. In that way, utilization of the strategy $Str_{alloc(+)}$ provides decreasing the overall losses of the requests by 24 percent.

Based on the obtained results, we can make the following conclusions.

- The total number of lost requests when applying different strategies remains unchanged.
- The benefit of applying the strategy with the reallocation of resources (controlled degradation) becomes significant in cases where the weighting coefficients of served requests differ significantly.
- The utilization of strategy with the reallocation of resources increases the time and complexity of the UAVSw-MQS operation due to the need to change routes of UAVs and spend time on additional servicing of more important requests.

V. CONCLUSION AND FUTURE WORK

Various Markov models of the UAVSw-MQS are developed and explored.

An example of a model of the UAVSw-MQS, servicing the requests for food and medicine delivery, in the failures of UAVs and when using controlled and non-controlled degradation was given and analysed.

It was demonstrated that for the given data, utilization of controlled degradation (strategy with the reallocation of resources) provides decreasing the overall losses of the requests by 24 percent.

It was found that the total number of lost requests when applying different strategies remains unchanged.

The next research steps can cover the development of models of UAVSw-MQSs taking into account strategies of utilizing the ground components of UAV maintenance.

REFERENCES

[1] M. A. Hoque, M.Hossain, S. Noor, S.M.R. Islam, R. Hasan. “IoTaaS: Drone Based Intrenet of Things as a Service Framework For Smart Cities”. *IEEE IoT* Journal, 2021, no. 9, 12425-12439. https://doi.org/10.1109/JIOT.2021.3137362.

[2] A. Beg, A.R.Qureshi, T.Sheltami, A.Yasar. “UAV-enabled intelligent traffic policing and emergency response handling system for the smart city”. *Pers. Ubiquit. Computing*, no. 25, 2021, pp. 33–50. https://doi.org/10.1007/s00779-019-01297-y.

[3] F. Qi, X. Zhu, G. Mang, M.Kadoch; W. Li. “UAV Network and IoT in the Sky for Future Smart Cities”. *IEEE Network*, no. 33, 2019, pp. 96–101. https://doi.org/10.1109/MNET.2019.1800250.

[4] A. Raza, S.H.R. Bukhari, F. Aadil, Z. Iqbal. “An UAV-assisted VANET architecture for intelligent transportation system in smart cities”. *International Journal of Distributed Sensor Networks*, no. 17, 2021. https://doi.org/10.1177/15501477211031750.

[5] V.Kharchenko, I. Kliushnikov, A. Rucinsky, H. Fesenko, O. Illiashenko. “UAV Fleet as a Dependable Service for Smart Cities: Model-based Assessment and Application”. *Smart Cities*, no. 5 (3), 2022, pp. 1151-1178. https://doi.org/10.3390/smartcities5030058.

[6] M. Torabbeigi, G.J. Lim, S.J. Kim, “UAV delivery schedule optimization considering the reliability of UAVs”. *In Proc. of the International Conference on Unmanned Aircraft Systems* (ICUAS), Dallas, TX, USA, 2018, pp. 1048-1053.

[7] M.H.L. Li, A.G. Richards, M.Sooriyabandara,“Reliability-Aware Multi-UAV Coverage Path Planning using a Genetic Algorithm”. *In Proc. of the 20th International Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, online, 2021, pp. 1584-1586.

[8] J. Musaab, H. Al-Qaysi, Y. Allbadi, M. Musaab, M. Jasim, “Reliability-based routing metric for UAVs networks”. *Indonesian Journal of Electrical Engineering and Computer Science*, no. 21, 2021, pp. 1771-1783. https://doi.org/10.11591/ijeecs.v21.i3. pp1771-1783.

[9] R. Abdallah, “Reliability approaches in networked systems: Application on Unmanned Aerial Vehicles“. PhD these. *Université Bourgogne Franche-Comté*, 2019, 140 p. Available online: https://tel.archives-ouvertes.fr/tel-02192738/document (accessed on 23 Desember 2021).

[10] H. Dui, L. Chen, J. Li, “Importance analysis in two kinds of redundant systems: k-out-of-n and consecutive k-out-of-n: F systems”. *Advances in Mechanical Engineering*, 2019. https://doi.org/10.1177/1687814018819248.

[11] A. Blokus. “Multistate System Reliability with Dependencies”. Academic Press, 2020, 298 p. https://doi.org/10.1016/C2019-0-02187-5.

[12] I. Kliushnikov, V. Kharchenko, H. Fesenko, Herman. “An Unmanned Aerial Vehicle as a Multi-State System”. *In Proc. of the 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET’2022)*, lviv, Ukraine, February 22-26, 2022, pp. 291-296. 10.1109/TCSET55632.2022.9766951.

[13] B. Zheng, Y. Li, W. Cheng, H. Wu, W. Liu. “A multi-channel load awareness-based MAC protocol for flying ad hoc networks”. *Journal of Wireless Comminication Network*. no. 181, 2020. https://doi.org/10.1186/s13638-020-01797-z.

[14] J. Chen, Q. Zhang, Z. Feng. “Timeliness analysis of service-driven collaborative mobile edge computing in UAV swarm”. *In Proc. of the 2019 IEEE Globecom Workshops (GC Wkshps)*, Waikoloa, HI, USA, December 09-13, 2019, pp. 1–6. https://doi.org/10.1109/GCWkshps45667.2019.9024534.

[15] T. Cokyasar, W. Dong, M. Jin. “Network optimization for hybrid last-mile delivery with trucks and drones”. *In Proceedings of the 2019 IISE Annual Conference*, Orlando, Florida, USA, May 18–21, 2019, pp. 19–24.

[16] R. Kirichek, A. Paramonov, A Koucheryavy. “Swarm of Public Unmanned Aerial Vehicles as a Queuing Network”. In *Distributed Computer and Communication Networks. DCCN 2015. Communications in Computer and Information Science*: *monograph* / Ed by V. Vishnevsky, D.Kozyrev, Eds. Springer International Publishing: Cham, Switzerland, 2016. Vol. 601, pp. 111–120. https://doi.org/10.1007/978-3-319-30843-2_12.

[17] I. Kliushnikov, V. Kharchenko, H. Fesenko, K. Leontiiev, O. Illiashenko. “UAV Fleet with Battery Recharging for NPP Monitoring: Queuing System and Routing Based Reliability Models”. *New Advances in Dependability of Networks and Systems. DepCoS-RELCOMEX 2022. Lecture Notes in Networks and Systems: collective monograph* / Ed. by W. Zamojski, J.Mazurkiewicz, , Sugier, J., Walkowiak, T., Kacprzyk, J. eds. Springer International Publishing: Cham. 2022, vol. 484, pp. 109-119. https://doi.org/10.1007/978-3-031-06746-4_11.