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Analytical Approach in Solving Specific Queuing Theory Problem

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Problems from the area of queuing theory can be solved by different methods. If the problem is so simple, that it is possible to find the corresponding classic model of queuing theory, we can simply use the existing expressions defining the main parameters of classic model. More complicated problems, which are not classic and look like real practical problems, need deeper analysis. There are two ways of solving them. One is simulation, which means statistical analysis of the results of a few times repeating simulation. If the real system we are trying to describe is so complex that it has a lot of possible states, simulation method can be used. Otherwise, if we are able, while solving a queuing problem, to make some presumptions not destroying the real picture of the problem, analytical method is recommended. In this work we present such analytical solution.

1. Introduction

The maintenance system is, generally, a complicated system. Its analysis needs deep approach with numerous random elements. An essential part of maintenance system is the repair shop, to repair and maintain specific technical equipment. In this work an analysis is given of repair and maintain processes in a technical repair shop. The devices which need to be repaired and maintained in this shop are different kinds of radio devices. Trying to mathematically describe this kind of problem, we can choose between two methods — analytic and by simulation. Both methods use queuing theory for the repair shop description. The simulation method is based on a statistical analysis of the results of several times repeating simulation. On the other side, analytic method is based on the mathematical model generated by analytic description of the problem. The analytic solution is presented in this work. What we want to achieve is to determine the probabilities of states, in which the repair shop can be. Those probabilities can be used to determine the probability of complex events (one or more mechanics are not available for service, the device demanding service or repair cannot be serviced because all mechanics are engaged etc.), which can be used to analyse important parameters like the minimum cost needed for normal functioning of the repair shop. Functional and organizational description of the radio devices repair shop is given in the second chapter and it is used as the basis for analytic description (by the terms of the queuing theory) which is discussed in the third and fourth chapters. The fifth chapter verifies the results we got using the proposed repair shop mathematical model. This verification is made comparing our results we got with the results of some classic queuing systems.

2. Organizational and functional structure of the radio devices repair shop

The purpose of the radio devices repair shop is to maintain different kinds of radio equipment and therefore there are four kinds of radio mechanics working there. These four kinds of radio mechanics are enough to support all radio devices that are maintained in the repair shop. They will be denoted as RMi, $i = 1, 2, 3, 4$. Each radio device can be maintained or repaired by one of the four mentioned mechanics. The mechanics do not work independently. The second mechanic (RM2) is qualified to help the first mechanic (RM1) by servicing radio devices that is the first mechanic is trained for. Equallu so, the fourth mechanic (RM4) can help the third

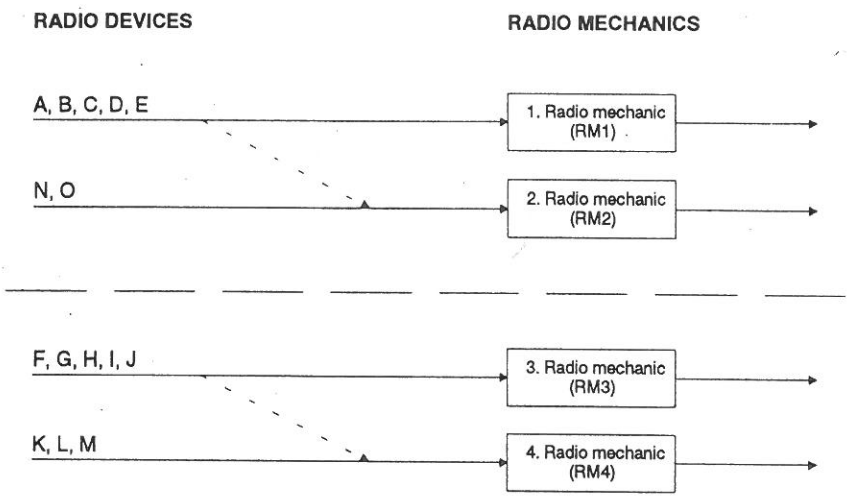

Fig. 1. The repair shop schema

mechanic. If we assume that RM1 is trained for servicing radio devices A, B, C, D and E, RM2 for servicing devices N and O, RM3 for servicing devices F, G, H, I and J, RM4 for servicing devices K, L and M, the repair shop organizational and functional scheme looks like the one presented in figure 1. Broken arrows

depict the direction of help given by RM2 and RM4 to RM1 and RM3, respectively. The services done by RM1 and RM2 are functionally independent from the services doned by RM3 and RM4, which is depicted by the broken line.

3. Input process

The term "input process" means the radio devices that originate over time demanding service and join the queue of a system (repair shop) providing such service. Due to the complexity of the matter analytic description of the queuing theory problem demands certain presumptions. As we mentioned, the first pair of mechanics (RM1 and RM2) are functionally independent from the second pair (RM3 and RM4) and therefore we can analyse the service of RM1 and RM2 first and use the results for description of RM3 and RM4 service. RM1 services A, B, C, D and E types of radio devices, RM2 services N and O types and A, B, C, D and E types if helps the RM1. The streams of customers (radio devices) coming to the queuing system (repair shop) are, in fact the streams of types of devices mentioned above (A, B, C, D, E, N, O), and they form the input processes. Each type of the radio device generates its own input stream, so we have seven input streams for seven types of devices. We assume that four technological maintenance programs [1] are performed in the repair shop: two preventive programs — PP–3 (periodical service) and PP–5 (technical service) and two corrective programs — CP–3 (easy repair) and CP–4 (module removing repair). Each radio device input stream can be considered as the sum of four independent input streams:

1) radio device input stream that demands service PP–3;

2) radio device input stream that demands service PP–5;

3) radio device input stream that demands service CP–3;

4) radio device input stream that demands service CP–4.

Preventive programs (PP–3, PP–5) and corrective programs (CP–3, CP–4) mentioned above, are taken from the set of eleven preventive and eleven corrective programs which contain all necessary services that radio devices can demand in the maintenance system [1]. So there are seven types of radio devices (A, B, C, D, E, N, O) and each type generates four input streams (PP–3, PP–5, CP–3, CP–4). Therefore we have 28 radio devices input streams coming to RM1 and RM2. We assume input streams of one type of radio device to be mutually independent. In the next step we should consider the characteristics of four input streams generated by each type of the radio device. There are two input streams for preventive servicing (PP–3, PP–5) and two input streams for corrective servicing (CP–3, CP–4). We can consider corrective service streams to be ordinary, because assume the probability that two or more radio devices arrive at the same time demanding corrective service is practically very small. The situation with preventive service streams is more complicated. If the interarrival time between successive appearances of the same type of radio device coming for preventive service is the multiple of interarrival time between successive appearance of another type of radio device coming for preventive service, two or more radio devices demanding service can appear at the same time and thus make the preventive service streams inordinary. The service system organization has solved this problem by planning a few days arrival delay for such radio devices, allowing us to consider preventive service streams to be ordinary, too. We can assume that interarrival times between successive appearances of radio devices are mutually independent for all services. Radio devices input streams are Poisson streams considering the mentioned assumptions.

Let λ_{xk} be the rate of radio device X arrival demanding corrective service and λ_{xp} be the rate of radio device X arrival demanding preventive service. Because of the stability characteristic, the total rate λ_x of radio device X arrival (intensity of radio device X input stream), can be expressed as:

$$\lambda_x = \lambda_{xk} + \lambda_{xp}. \qquad (1)$$

In determining λ_{xk} and λ_{xp} we must consider the following parameters: failure intensities of the radio device X, both when it works and when it does not work, number of radio devices of type X, time period between two successive preventive services (PP–3, PP–5) and the working factor (usability factor) for radio device X. Let us explain this. Every professional radio device has two parameters given by the manufacturer — failure intensity when the device works and failure intensity when it does not work. The radio device working factor is a rate of radio device operational time (when it works) and the whole passed time during one time interval.

So, the value of λ_{xk} (formula 1) can be expressed as $k_e * \lambda_1 + (1 - k_e) * \lambda_2$, where k_e is a working factor and λ_1, λ_2 are failure intensities when the device works/does not work, respectively. As mentioned before, RM1 (radio mechanic 1 or server 1 or channel 1) serves radio devices A, B, C, D, E and RM2 services radio devices N, O. Each radio device type generates its own input stream which, because of the stability characteristic, can be added to the input streams of other radio devices. So, the intensity of radio device input streams sum (coming to RM1 demanding service) equals the sum of intensities of all types of radio device input streams:

$$\lambda_l = \sum_{i \in S1} \lambda_i, \quad S1 = \{A, B, C, D, E\}. \qquad (2)$$

According to formula (2), for RM2 we have:

$$\lambda_2 = \sum_{j \in S2} \lambda_j, \quad S2 = \{N, O\}. \qquad (3)$$

We can get the values of λ_1 and λ_2 using formulas 2 and 3 just in case that help factor k_i equals zero, and which happens when RM2 does not help RM1 servicing a certain number of "his" radio devices A, B, C, D or E (see fig. 2, l stands for λ).

The intensities (λ_1' and λ_2') of real radio device input streams that come to RM1 and RM2 de-

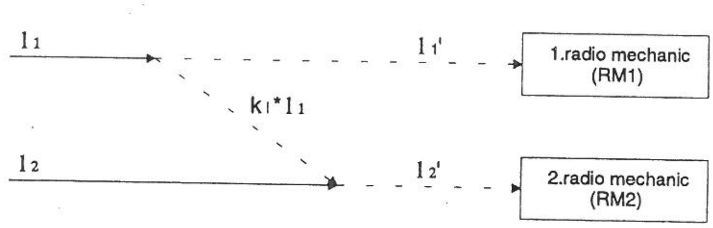

Fig. 2. The repair shop functional scheme

manding service, can be expressed as:

$$\begin{aligned} \lambda_1' &= (1 - k_i) * \lambda_1 \\ \lambda_2' &= \lambda_2 + k_i * \lambda_1 \end{aligned} \tag{4}$$

If RM2 does not help RM1 at all ($k_i = 0$), we have:

$$\begin{aligned} \lambda_1' &= \lambda_1 \\ \lambda_2' &= \lambda_2 \end{aligned} \tag{5}$$

On the contrary, if, for some reason, RM2 services all radio devices that RM1 is supposed to service ($k_i = 1$), we have:

$$\begin{aligned} \lambda_1' &= 0 \\ \lambda_2' &= \lambda_1 + \lambda_2. \end{aligned} \tag{6}$$

4. Formal description of the radio device repair shop as a queuing system

After we described radio device input streams, the next step is the formal description of radio device repair shop. First of all, we have to make some presumptions:

– the activities in radio device repair shop are preventive (PP–3, PP–5) and corrective (CP–3, CP–4) technological programs (services);

– there are four radio mechanics (servers, channels — queuing theory expressions) RM1, RM2, RM3, RM4 working in the repair shop, RM1 and RM2 are organizationally and technologically connected in the same way as RM3 and RM4 (fig. 1);

– the duration of radio device service is random variable having exponential distribution and so is the time interval between two successive radio device arrivals;

– there is one waiting place in the queue, which means that each radio device arriving in the moment when both mechanics (RM1 and RM2) and waiting places are engaged, leaves the queuing system;

– two channels (RM1, RM2 or RM3, RM4) forming one technological and organizational unit have such characteristics that one of them (RM2 or RM4) can help the other (RM1 or RM3) by servicing a certain number of its radio devices. This number of radio devices depends on help factor (k_i) whose possible value may vary between 0 (no help) and 1 (full help) as in fig. 2;

– there are two technological and organizational units each having two channels (RM1, RM2 and RM3, RM4) and they can be described independently;

– each radio mechanic represents one channel or server and adding another mechanic of the same kind means increasing the rate of service or service intensity (μ);

– the process in radio device repair shop is discrete Markov stochastic process with continuous parameter (time).

Figure 3 shows the whole process in a radio device repair shop (l stands for λ). According to the presumption mentioned before, the process in our queuing system is a discrete stochastic process with continuous parameters. Therefore we can determine the states in which the system can be. All states are showed in Table 1. For example, state Y5(1,0,0) describes the situation when channel 1 (RM1) is engaged, channel 2 (RM2) is free and there is no radio device waiting for service. Two states are specially marked: Y2 and Y6. Our queuing system can never be in these states. Table 1 describes just the first (RM1, RM2) of the two technological and organizational parts of the repair shop because those parts are mutually independent.

States	channel 1	channel 2	waiting place
Y1	0	0	0
Y2*	0	0	1
Y3	0	1	0
Y4	0	1	1
Y5	1	0	0
Y6*	1	0	1
Y7	1	1	0
Y8	1	1	1

Tab. 1. The queuing system description (all states)

Eliminating states Y2 and Y6 we get the queuing system description showed in Table 2. One of the important tasks in queuing theory is to find out the probabilities of the states in which

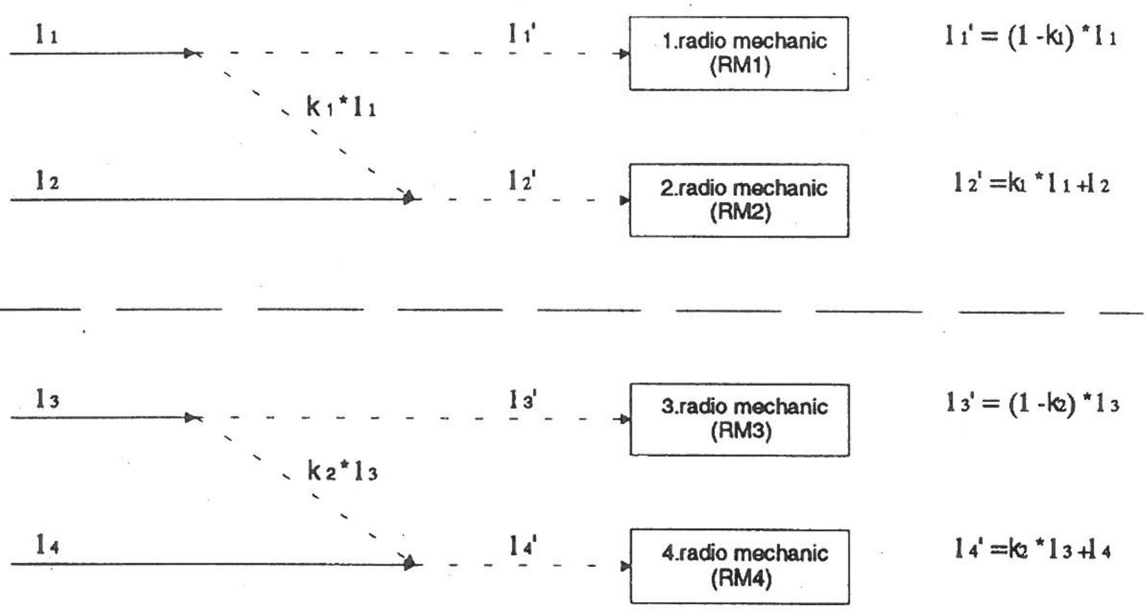

Fig. 3. The radio device repair shop process

the system can be. If we knew those probabilities, we could determine the probabilities of more

States	channel 1	channel 2	waiting place
Y1	0	0	0
Y2	0	1	0
Y3	0	1	1
Y4	1	0	0
Y5	1	1	1

Tab. 2. The queuing system description (possible states)

events like:

a) Probability that the service demanding radio device will be cancelled. This occurs if such a radio device appears in the moment when the system is either in state Y3 or in state Y6. If the system is in state Y3, the radio device that can be serviced only by the second channel (N, O), will be cancelled. If we assume that the events "system is in Y3 state" and "radio device N or radio device O demand service" are mutually independent, the probability of their simultaneous appearance can be expressed as the product of their probabilities. On the other hand, if the system is in Y6 state, any radio device that appears demanding service will be cancelled. The Y3 and Y6 states mutually exclude each other. So, the probability that a service demanding radio device will be cancelled can be expressed by the formula:

$$P_c = \frac{NN+NO}{NA+NA+NC+ND+NE+NN+NO} * P(Y3) + P(Y6) \quad (7)$$

where NI is the number of the radio devices I.

b) Probability that the first channel is engaged can be determined by the sum of probabilities of states Y4, Y5 and Y6. Those states mutually exclude each other and we have:

$$P_{1e} = P(Y4) + P(Y5) + P(Y6) \quad (8)$$

c) Probability that the second channel is engaged:

$$P_{2e} = P(Y2) + P(Y3) + P(Y5) + P(Y6) \quad (9)$$

d) Probability that the queuing system is empty (both channels are free and there are no radio devices waiting):

$$P_0 = P(Y1) \quad (10)$$

Using the queuing system states (Y1 through Y6) we can generate $2^6 = 64$ events (merging different states), but majority of those events have no particular importance to us. After we have found all the states of a queuing system, the following step to determine the probabilities is to define possible transitions between the states. Let λ_1' and λ_2' be the intensities of the radio device input streams demanding service from the first and the second channels. Let μ_1 and μ_2 be the service intensities of the first and the second channels. We can explain the transitions using Y1 and Y2 states as examples (the graph in figure 4 provides the necessary informaton on other states transitions).

From the Y1 state the system can transit to:

– Y2 state with λ_2' intensity

– Y4 state with λ_1' intensity.

From the Y2 state the system can transit to:

– Y1 state with μ_2 intensity

– Y3 state with λ_2' intensity

– Y5 state with λ_1' intensity.

The following graph illustrate the states and transitions (fig. 4, l stands for λ, m stands for μ).

If we assume radio device input streams switching the system from one state to the other to be stationary Poisson streams, the queuing system can be described by means of a linear differential equation system. From figure 4 we can see that all states have input and output streams and therefore there is astationary system state (after some time the values of probabilities of states will be constant). Using the Chapman–Kolmogorov method it is possible to form the system of six linear differential equations (six states of system) with constant coefficients λ and μ.

$$\begin{aligned}
Y1' &= -(\lambda_1' + \lambda_2') * Y1 + \mu_1 * Y4 + \mu_2 * Y2 \\
Y2' &= -(\lambda_1' + \lambda_2' + \mu_2) * Y2 \\
&\quad + \lambda_2' * Y1 + \mu_2 * Y3 + \mu_1 * Y5 \\
Y3' &= -(\lambda_1' + \mu_2) * Y3 + \lambda_2' * Y2 + \mu_1 * Y6 \\
Y4' &= -(\mu_1 + \lambda_2') * Y4 + \mu_2 * Y5 + \lambda_1' * Y1 \\
Y5' &= -(\lambda_1' + \lambda_2' + \mu_1 + \mu_2) * Y5 \\
&\quad + \lambda_1' * Y2 + \lambda_2' * Y4 + (\mu_1 + \mu_2) * Y6 \\
Y6' &= -(2 * \mu_1 + \mu_2) * Y6 \\
&\quad + (1' + 2') * Y5 + 1' * Y3
\end{aligned} \tag{11}$$

$Y1', \ldots, Y6'$ are functions with the parameter t (time) and the depict the probabilities of states $Y1, \ldots, Y6$. If we want to solve this system of equations by some of the numerical methods, initial conditions must be determined. These

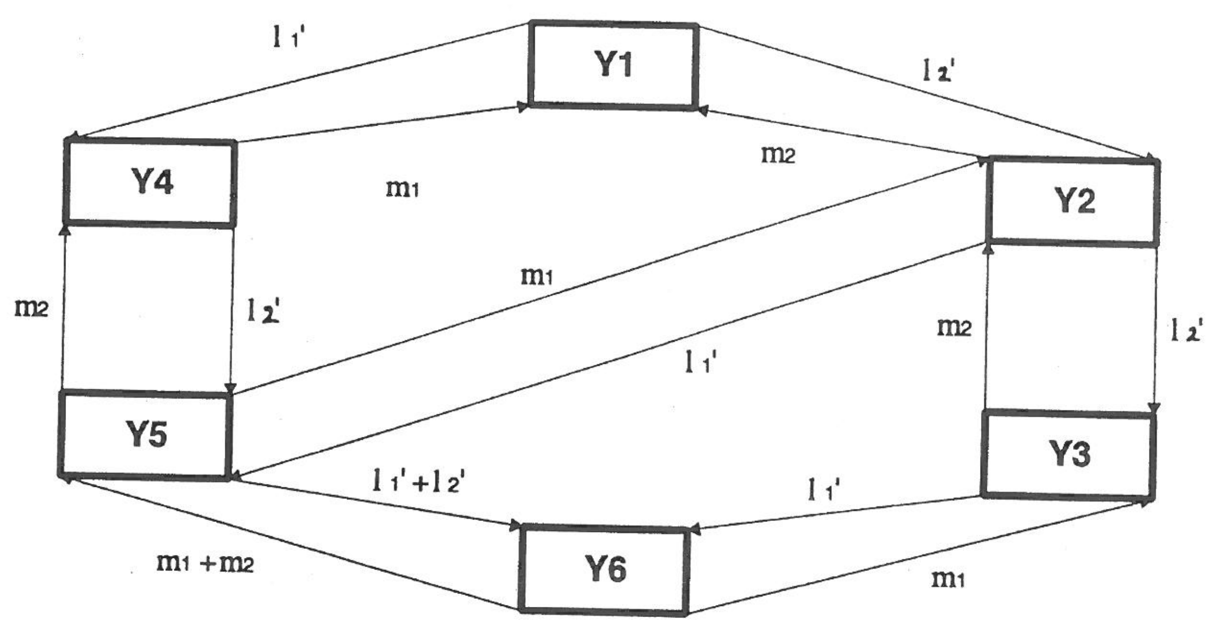

Fig. 4. States and transitions

conditions are the probabilities of states in the moment $t = 0$. It is logical to accept the assumption that the system in moment $t = 0$ is in the state Y1, so we have

$$P_{t=0}(Y1) = 1, \quad P_{t=0}(Yi) = 0, \; i = 2, 3, 4, 5, 6.$$

On the other hand, the set of all states completely describes the queuing system. So we have

$$\sum_{i=1}^{6} P_i(Yi) = 1. \qquad (12)$$

Solution of the system of equations (11) is given in figures 5 and 6 and in tables 3 and 4. It is achieved by using Adams predictor–corrector method. Let us explain tables 3 and 4. Those tables are interactive computer printouts. Input parameters to our computer program are:

– initial values of probabilities of states (P(Y1) to P(Y6));

– failure intensities for all radio devices both when they work and when they do not work;

– the number of all types of maintained radio devices;

– the radio device working factor (usability factor);

– the frequency of radio device preventive service;

– the probability of radio device corrective service;

– the time needed for certain preventive and corrective programs;

– the channel help factor;

– number of radio mechanics per service channel.

Using these input parameters the computer calculates $\lambda 1, \lambda 2, \mu 1, \mu 2$ and the probabilities of states during one time interval (58 time units – hours). Probabilities of states are givenas columns at the end of the tables. Headers of columns are marked as Yi-xxx, for example Y3-011 means the third state (Y3), the first channel is free (0), the second is engaged (1) and the waiting place is occupied(1).

58 hours is enough for the system to reach the stationary state. After 19 hours (table 3) and 16

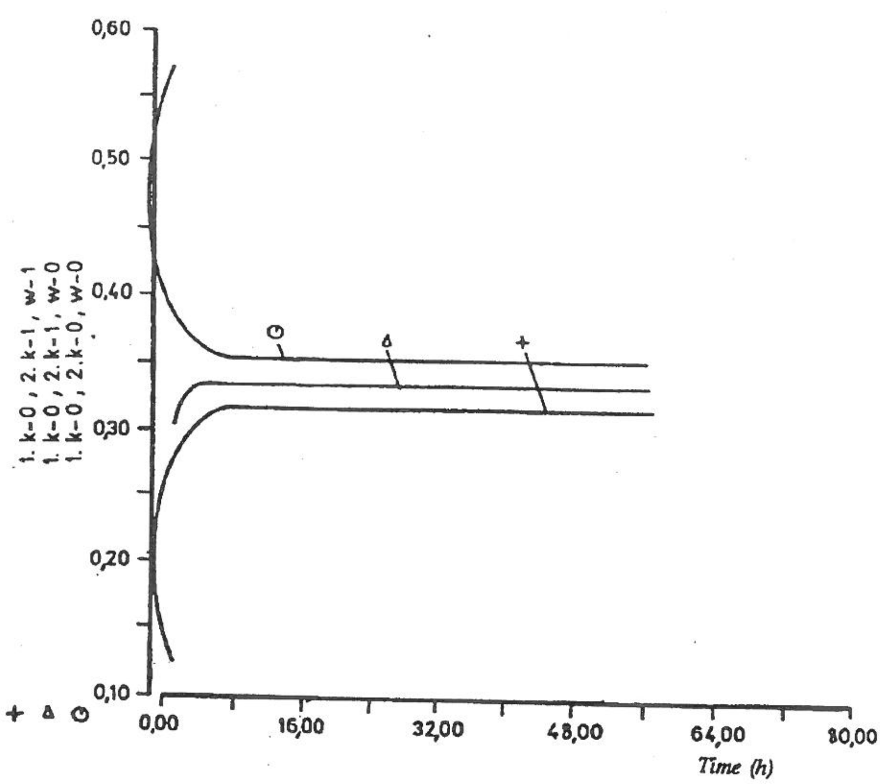

Fig. 5. The probabilities of states (1)

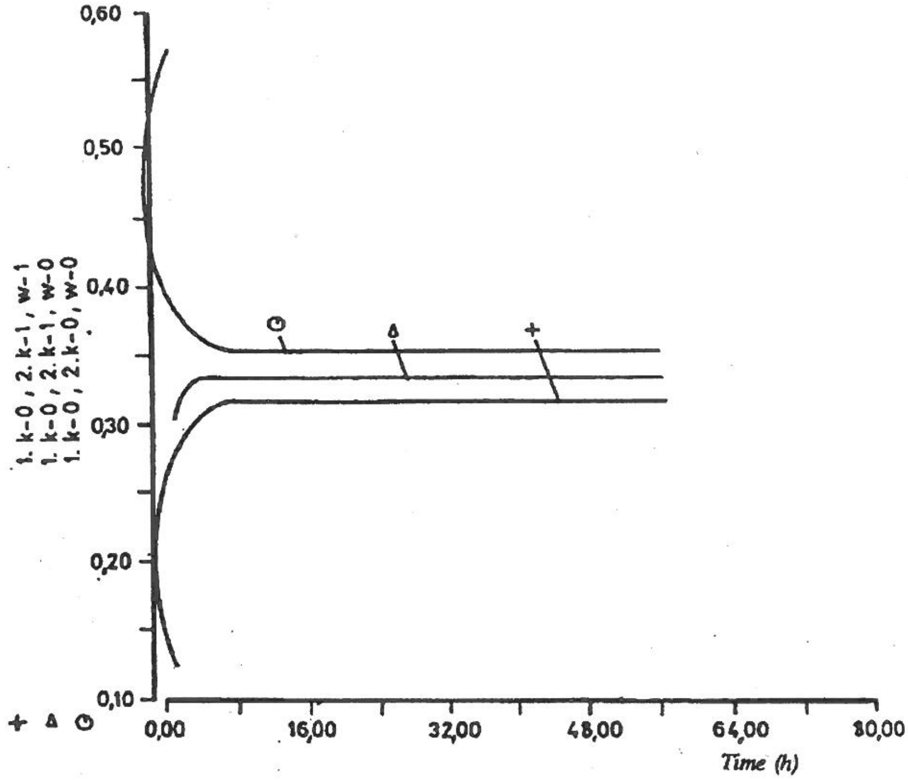

Fig. 6. The probabilities of states (2)

hours (table 4) the system reaches the stationary state and the probabilities of states become constant.

We assumed that the constant value of five numbers after the decimal point is enough to consider the probabilities of states to be constant too. Figures 5 and 6 are graphs of tables 3 and 4, (in that order). Table 3 with figure 5 and table 4 with figure 6 depict the probabilities of the same queuing system states, but with different input parameters. Table 4 and figure 6 describe the situation when there is no radio mechanic in the first channel and one radio mechanic works in the second channel. Therefore the probabilities of states in which the first channel is engaged equal zero (Y4, Y5, Y6). Using the data from tables 3 and 4 we can analyse the exploitation of channels in our system. The first channel is engaged in states Y4, Y5 and Y6.

Therefore the sum of probabilities of those states represents the exploitation of that channel or the probability that the first channel is engaged. The exploitation factor of the second channel equals the sum of probabilities of states Y2, Y3, Y5, Y6. So, using the data from table 3 we can calculate the exploitation of the first channel in the stationary state: $0.37532 + 0.04936 + 0.01983 = 0.4423$ (working 44% of time). In the same way, the exploitation of the second channel equals 0.15 (working 15% of time). Reading the table 4 we can notice an increased exploitation of the second channel (help factor equals 1, there is no mechanic in the first channel). There is one interesting parameter concerning each channel-traffic intensity $\rho = \lambda/\mu$.

From the table 3 we have $\rho_1 = \lambda_1/\mu_1 = 0.8$ and $\rho_2 = \lambda_2/\mu_2 = 0.138$. From the table 4, $\rho_1 = \lambda_1/\mu_1 = 0$ and $\rho_2 = \lambda_2/\mu_2 = 0.951$. As we can see from the table 4, the second channel is almost out of use, because the input stream intensity (λ_2) is almost equal to the service intensity (μ_2). Our queuing system (radio device repair shop) is described with six states, so we can observe $2^6 - 1 = 63$ events and find out the probabilities of their appearance. But not all of them are interesting to us. On the contrary, just a small subset of that set of events is of practical interest.

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Number of radio devices A(75):

?

Number of radio devices B(85) :

?

Number of radio devices C(15) :

?

Number of radio devices D(25) :

?

Number of radio devices E(45) :

?

Number of radio devices N(25) :

?

Number of radio devices O(7) :

?

Write the help factor RM2 to RM1(0.) :

? 0.05

Write the radio device usability factor(0.1) :

?

Number of radio mechanics in the first channel(1) :

?

Number of radio mechanics in the first channel(1) :

?

STABILIZATION OF QUEUING SYSTEM STATES PROBABILITIES FOR THE FOLLOWING PARAMETER VALUES:

$\lambda 1 = 0.709$ $\mu 1 = 0.887$ usability factor $= 0.1$

$\lambda 2 = 0.120$ $\mu 2 = 0.873$ help factor $= 0.05$

X	Y1-000	Y2-010	Y3-011	Y4-100	Y5-110	Y6-111
1.0000	0.59537	0.04685	0.00330	0.32631	0.02311	0.00506
4.0000	0.47858	0.06380	0.01385	0.37956	0.04645	0.01775
7.0000	0.47278	0.06682	0.01588	0.37604	0.04894	0.01954
10.0000	0.47202	0.06728	0.01618	0.37543	0.04930	0.01979
13.0000	0.47191	0.06734	0.01623	0.37534	0.04935	0.01983
16.0000	0.47190	0.06735	0.01623	0.37533	0.04936	0.01983
19.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
22.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
25.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
28.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
31.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
34.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
37.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
40.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
43.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
46.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
49.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
52.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
55.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983
58.0000	0.47189	0.06735	0.01623	0.37532	0.04936	0.01983

Tab. 3. The probabilities of states (1)

```
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        Number of radio devices A( 75) :
?
        Number of radio devices B( 85) :
?
        Number of radio devices C( 15) :
?
        Number of radio devices D( 25) :
?
        Number of radio devices E( 45) :
?
        Number of radio devices N( 25) :
?
        Number of radio devices O( 7) :
?
        Write the help factor RM2 to RM1(0. ) :
?       1.0
        Write the radio device usability factor(0.1) :
?
        Number of radio mechanics in the first channel(1) :
?       0
        Number of radio mechanics in the first channel(1) :
?
```

STABILIZATION OF QUEUING SYSTEM STATES PROBABILITIES FOR THE FOLLOWING PARAMETER VALUES:

$\lambda 1 = 0.$ $\mu 1 = 0.$ usability factor = 0.1

$\lambda 2 = 0.830$ $\mu 2 = 0.873$ help factor = 1.0

X	Y1-000	Y2-010	Y3-011	Y4-100	Y5-110	Y6-111
1.0000	0.57078	0.30294	0.12628	0.00000	0.00000	0.00000
4.0000	0.36642	0.33264	0.30094	0.00000	0.00000	0.00000
7.0000	0.35151	0.33301	0.31548	0.00000	0.00000	0.00000
10.0000	0.35035	0.33305	0.31660	0.00000	0.00000	0.00000
13.0000	0.35026	0.33304	0.31670	0.00000	0.00000	0.00000
16.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
19.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
22.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
25.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
28.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
31.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
34.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
37.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
40.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
43.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
46.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
49.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
52.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
55.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000
58.0000	0.35025	0.33305	0.31670	0.00000	0.00000	0.00000

Tab. 4 The probabilities of states (2)

5. Conclusions

In this work using a queuing system theory, we gave analytic description of the radio device repair shop. The method we used is mathematical modelling based on analytic description of the real system. This model is realised on a computer and can be applied for different analysis (determination of number of workers needed for successful service of given number and types of devices). With a certain appendix we can use this model for calculation of different costs in the system. To be able to apply our model, we must solve a concrete system of linear differential equations. The only practical way of solving this system is to use a computer. Our system (11) is solved by the use of mathematical routines library on the CYBER 170/825 computer. In our repair shop analysis we restricted ourselves to one waiting place in the system. If there is a need for more than one waiting place (with the same input data), the new system of linear differential equations must be defined, because each new waiting place increases the number of states in the system. We do not need to be concerned with the increase of the number of states because there are more impossible states which can be ejected. Finally, the types of devices noted as A, B, C, D, N, O can be any devices and all we need to know is their fault intensity and the average service time.

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