On one Construction of a Finite Automation

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Abstract: - An algorithm of the behavior of a finite automation in a stationary random medium with binary reactions is proposed. The problem of expedient behavior of the considered automation is studied by the methods of the random walk theory and the conditions are obtained under which its behavior in a stationary random medium is expedient.

Key-Words: - Finite automata, Behavior of automata, Stationary random medium, State of automata, Actions of automata, Behavior of infinite automata, Gain of automata, Expedient behavior.

1 Introduction

Finite automata of both determinate and probabilistic structure are widely used in the mathematical models of a complex system. The idea that finite automata are quite a convenient object for the construction of complex mathematical models, including biological systems, was originally proposed by J. von Neumann |1|. However, the construction of automata behavior models was formulated and developed by M.L. Tsetlin |2|. who supposed that an elementary behavioral act can be singled out from the complex behavior and an elementary behavior problem can be formulated. If, after that, a device (finite automation) that solve well an elementary problem, i.e., an automation having expedient behavior in an elementary situation, then the complex behavior of a complex object can be regarded as a result of the joint behavior of a large number of elementary objects, each of them solving an elementary problem.

As an elementary behavior problem M.L. Tsetlin considered the problem of a choice of one or several actions in the conditions of uncertainty, i.e., the problem of automation behavior in a random medium. The choice of this problem as an elementary one is not casual. Indeed, the above-mentioned statement of the problem can be reduced to absurdity in the following way: any complex behavior based on a finite storage space can be represented as being generated by a realization algorithm with a finite memory, i.e., by a finite automation. Then the problem of investigation of the complex behavior automatically reduces to the problem of decomposition of the original automation or to the problem of construction of a complex automation of elementary (base) automata, i.e. to the classical problem of finite automata synthesis.

An automation is understood as some device functioning at a discrete time moment t=1,2,… and having a finite or countable set of internal sets. At any moment of time t the automation can be in one of these states. An automation can receive some finite input signals and, depending on a signal received, can change its internal state. An automation can perform some number of actions, this number being determined by its internal state.

The functioning of an automation A_k in an external medium C implies that the input signals (actions) f of the automation A_k are the input signals for some device C. To the actions of the f automation the A_k medium C produces responses S, which in their turn are the input signals for the automation A_k The automation uses them, so to say, to take decisions on further actions.

The role of the medium consists in establishing relationship between the actions of the automation and signals delivered to its input.

It is of special interest to investigate automata which have expedient behavior and do not have, so to say, “a priori expediency” of behavior: for a sequence of equal input signals delivered when various actions are used, the automation must behave equally.

Thus it is important to construct such a symmetric automation that would possess maximal expediency in elementary cases and after that to study the automata behavior in more complicated media.

2 Automata Functioning in Random Media

Let the automation A_k function in a random medium $C(a_1, a_2, ..., a_k)$.Like in |2| it is assumed that all possible responses S=$\{s_1, s_2, ..., s_g\}$ of the medium *C*, are understood by the automation as belonging to one of the following two classes – the class of favorable responses (gain, *S* = +1) and the class of unfavorable responses (loss, *S* = - 1). The information received by the automata from the medium *C* is only the information which response (gain, loss) entailed its last action. So the automation does not know a priori the character of the medium.

Definition 1. We say |2| that the automaton A_k functions in a stationary random medium $C(a_1, a_2, ..., a_k)$ if the actions of the automat and the values of its input signal are connected as follows: the action f_α performed by the automation at the moment of time t implies that at the moment of time $t+1$ we have the value of the signal $S = +1$ (gain) with probability $q_\alpha = \frac{1+a_\alpha}{2}$ and the value of the signal $S = -1$ (loss) with probability. $p_\alpha = \frac{1-a_\alpha}{2}$ ($\alpha = \overline{1,k}$). Here the value $a_\alpha = q_\alpha - p_\alpha (|a_\alpha| < 1)$ is used in the sense of mathematical expectation of a gain for the action f_α.

Since the automation A_k and the random medium $C(a_1, a_2, ..., a_k)$ in which the automation is immersed are independent of each other, it is a priori unknown what action of the automation is optimal in the sense that an average gain for this action is maximal. By varying the numeration of actions of automata we can always succeed in obtaining $a_1 > a_2 \geq ... \geq a_k$, certainly assuming that at least two values of a_α are different. Then the actions of the automation with an average gain a_1 in the medium C will be optimal.

A question naturally arises by means of what set of characteristics the behavior of the automation in a random medium can be described. Such characteristics are |3|: probabilities $\sigma_{x,\alpha}$ of a change (at some time) of the action f_α at the start from a state $x \in L_\alpha$; mathematical expectations for a random time $\tau_{x,\alpha}$ before the change of the action f_α at the start from a state $x \in L_\alpha$, where L_α - is a subset of states in which the action f_α ($\alpha = \overline{1,k}$) is performed.

If $u^{(n)}_{x,d}$ is a probability that at the moment of time d the finite automation $A^{(n)}_k$ (here n is its storage capacity) will for the first time change the action f_α starting from a state $x \in L^{(n)}_\alpha$, then

$$\sigma^{(n)}_{x,\alpha} = \sum_{d=0}^{\infty} u^{(n)}_{x,d},$$

$$\tau^{(n)}_{x,\alpha} = \sum_{d=0}^{\infty} d u^{(n)}_{x,d}, \; x \in L^{(n)}_\alpha .$$

Then the limit average gain of the one-input and one-output automation $A^{(n)}_k$ in a stationary random medium $C(a_1, a_2, ..., a_k)$ is defined by the formula |4|

$$M(A^{(n)}_k; C) = \frac{\sum_{\alpha=1}^{k} a_\alpha \tau^{(n)}_{x,\alpha}}{\sum_{\alpha=1}^{k} \tau^{(n)}_{x,\alpha}} .$$

Note that analogous relations hold also for one-input and many-output automata. Since the proof of this statement completely coincides with that of an analogous statement given in |4| for one-input and one-output automata, we omit it here.

It is natural to compare the gain of such an automation with the gain of an automation that chooses its actions independently of responses of the medium and with equal possibility. The mathematical expectation of a gain of such an automation is

$$M_0 = \frac{1}{k} \sum_{\alpha=1}^{k} a_\alpha .$$

Definition 2. We will say that the automation A_k has expedient behavior in the medium $C(a_1, a_2, ..., a_k)$ if $M(A^{(n)}_k; C) > M_0$; if however $M(A^{(n)}_k; C) = M_0$, then the behavior of the automation A_k in the medium C is indifferent, and if $M(A^{(n)}_k; C) < M_0$, then it is inexpedient.

It is obvious that

$$\min_\alpha a_\alpha < M(A^{(n)}_k; C) < \max_\alpha a_\alpha .$$

It is natural to compare an average gain of such an automation with an average gain which the man, who (as different from the automation) was informed in advance of the parameters $a_1, a_2, ..., a_k$, could surely get for himself. This man would evidently perform the action which ensures a maximal gain, and the average gain for him would be equal to a maximal number among the numbers $a_1, a_2, ..., a_k$.

For a finite automation

$$M(A_k^{(n)}; C) < \max_{\alpha} a_\alpha ,$$

but we can construct sequences of finite automata $A_k^{(1)}, A_k^{(2)}, ... A_k^{(n)}, ...,$ such that

$$\lim_{n\to\infty}(M(A_k^{(n)}; C) = \max_{\alpha} \alpha_\alpha \quad (\alpha = \overline{1,k}).$$

These sequences are called asymptotically optimal.

Some constructions of finite automata having expedient behavior in the random medium $C(a_1, a_2, ..., a_k)$ are given in |2|. However asymptotic (relative to the storage capacity *n*) analysis of the behavior of these automata was based on the study of final (as $t \to \infty$) probabilities of Markovian chains describing the behavior of finite automata in random media, and the behavior of individual automata was studied with insufficient completeness and strictness. This kind of analysis became possible thanks to the investigation of the behavior of infinite (with a countable number of states) automata |3|.

It is important to prove the convergence (as $n \to \infty$) of statistical characteristics of the behavior of finite automata $A_k^{(n)}$ to the corresponding statistical characteristics of an automation A_k of the same structure.

Definition 3. Following |3|, we say that a sequence of finite automata $\left\{A_k^{(n)}\right\}_{n=1}^{\infty}$, functions in a stationary random medium *C* and has an infinite automation A_k ($A_k = \lim_{n\to\infty} A_k^{(n)}$) as its limit if

$$\lim_{n\to\infty} u_{x,d}^{(n)} = u_{x,d} \, , \ \forall x, d \, . \qquad (1)$$

We immediately note that in the case of the continuity theorem |5| the existence of limit (1) can be proved if we establish that the generating function $n \to \infty$ of probabilities of a change of the action for a finite automation $A_k^{(n)}$ converges to the corresponding generating function $U_x^{(n)}(z)$ for an infinite automation A_k converges to the corresponding generating function $U_x(z)$, where $U_x^{(n)}(z)$ and $U_x(z)$ are generating functions of the form

$$U_x^{(n)}(z) = \sum_{d=0}^{\infty} u_{x,d}^{(n)} z^d, \qquad U_x(z) = \sum_{d=0}^{\infty} u_{x,d} z^d.$$

Note that

$$\sigma_{x,\alpha}^{(n)} = U_x^{(n)}(1), \quad \tau_{x,\alpha}^{(n)} = \frac{dU_{x,d}^{(n)}(z)}{dz} \Big|_{z=1}.$$

Analogous formulas hold for $\sigma_{x,\alpha}, \tau_{x,\alpha}$ (certainly, if the corresponding conditions are fulfilled).

In terms of the above set of characteristics the behavior of an infinite (with a countable number of states) automation in a random medium is classified as follows (recall that by virtue of the condition $a_1 > a_2 \geq ... \geq a_k$, the action f_1 is optimal).

Definition 4. Following |3|, we say that then an automation A_k functioning in the random medium $C(a_1, a_2, ..., a_k)$ is

optimal for $\sigma_{x,1} < 1$, $\sigma_{x,\alpha} = 1$ $(\alpha = \overline{2,k})$ $\forall x$;

strictly optimal for $\sigma_{x,1} < 1$, $\sigma_{x,\alpha} = 1$, $\tau_{x,\alpha} < \infty$ $(\alpha = \overline{2,k}) \forall x$;

quasioptimal for $\sigma_{x,\alpha} = 1$, $\alpha = \overline{1,k}$, $\tau_{x,1} = \infty$, $\tau_{x,\alpha} < \infty$ $(\alpha = \overline{2,k})$;

drawn in for $\sigma_{x,\alpha} < 1$, $\forall x, \alpha$;

drawn out for $\sigma_{x,\alpha} = 1$, $\tau_{x,\alpha} < \infty$ $\forall x, \alpha$;

anti-optimalfor $\sigma_{x,k} < 1$, $\sigma_{x,\alpha} = 1$, $(\alpha = \overline{1,k-1}) \forall x$;

antiquasioptimal for $\sigma_{x,\alpha} = 1$ $(\alpha = \overline{1,k})$, $\tau_{x,k} = \infty$ $\forall x$.

The notion of expedient behavior of an automation in a stationary random medium is introduced in a natural manner |3|.

Definition 5. In the stationary random medium $C(a_1, a_2, ..., a_k)$, an automation A_k has statistically expedient behavior if $\sigma_{x,1} < \sigma_{x,\alpha}$, and for $\sigma_{x,1} = \sigma_{x,\alpha}$, $\tau_{x,1} > \tau_{x,\alpha}$, $\alpha = \overline{2,k}$. If however $\sigma_{x,1} = \sigma_{x,\alpha}$, $\tau_{x,1} = \tau_{x,\alpha}$, $\forall x$, $\alpha = \overline{2,k}$, then the automation is called indifferent, while if $\sigma_{x,1} > \sigma_{x,\alpha}$, then the behavior of the automation is inexpedient.

Note that Definition 5 is equivalent to Definition 2.

A corollary of the existence of limit (1) is a full classification of the asymptotic (as $n \to \infty$) behavior of a sequence of finite automata $A_k^{(n)}$.

Definition 6. A sequence of finite automata $\left\{A_k^{(n)}\right\}_{n=1}^{\infty}$ is called asymptotically optimal (strictly optimal) if a limit infinite automation A_k is optimal (strictly optimal).

Other sequences of finite automata $\left\{A_k^{(n)}\right\}_{n=1}^{\infty}$ are defined analogously if the limit infinite automation A_k possesses the corresponding property.

3 The Finite Automation Behavior Algorithm

Let the finite automation $T_{2n,2}$ which has $2n$ $(n=e+m-1)$ internal states $L^{(n)}=L_1^{(n)}\cup L_2^{(n)}=\{-(e+m-1),...,-2,-1,\ 1,2,...,e+m-1\}$ and can perform two different actions f_1 and f_2 function in the random medium $C(a_1,a_2)$. It is assumed that the first action is performed in the states of the region $L_1^{(n)}=\{-(e+m-1),-(e+m-2),...,-2,-1\}$, while the second action in the states of the region $L_2^{(n)}=\{1,2,...,e+m-2,e+m-1)$. The tactic of behavior of the automation $T_{2n,2}$ in the medium $C(a_1,a_2)$ is given as follows: the automation changes the action if a penalty of length e and an award of length m are successively delivered to its input. In this case the automation may change its action only from the extreme states $|x|=1$ and $|x|=e+m-1$. Therefore the automation $T_{2n,2}$ has one input and two outputs (Fig. 1).

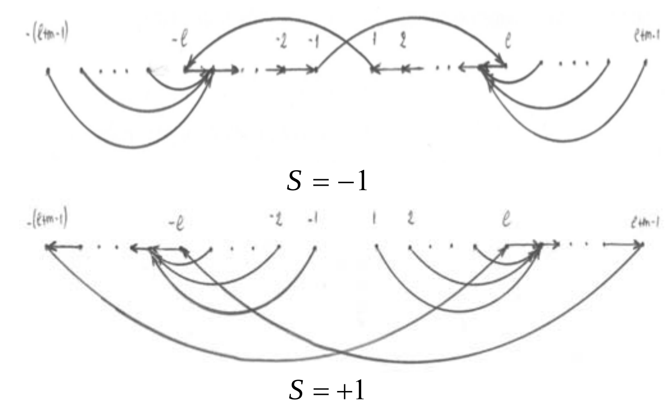

Fig. 1. Graphs of states for the automation $T_{2n,2}$

In the sequel we will consider mainly the automation behavior in the region marked by some action before the change of this action, and omit the index *a* for the sake of abbreviation.

Taking into account the behavior of the automation $T_{2n,2}$ in the medium $C(a_1,a_2)$ relative to probabilities $u_{x,d}^{(n)}$, we obtain the equations

$$\begin{aligned}
&u_{x,d+1}^{(n)}=p\,u_{x-1,d}^{(n)}+q\,u_{e+1,d}^{(n)}, \quad x=\overline{1,e-1},\\
&u_{e,d+1}^{(n)}=p\,u_{e-1,d}^{(n)}+q\,u_{e+1,d}^{(n)}, \qquad (2)\\
&u_{x,d+1}^{(n)}=p\,u_{e-1,d}^{(n)}+q\,u_{x+1,d}^{(n)}, \quad x=\overline{e+1,e+m-1}
\end{aligned}$$

and, due to the probabilistic meaning of $u_{x,d}^{(n)}$, the boundary conditions

$$u_{0,0}^{(n)}=1,\ u_{e+m,0}^{(n)}=1, u_{x,0}^{(n)}=0, \forall\ x\neq 0,\ e+m. \quad (3)$$

Mltiplying (2) and (3) by z^d and performing summation over all $d=0,1,2,...$ we see that the generating function $U_x^{(n)}(z)$ of an action change probability is a solution of the following boundary value problem:

$$\begin{aligned}
&U_x^{(n)}(z)=p\,zU_{x-1}^{(n)}(z)+q\,zU_{e+1}^{(n)}(z)\\
&x=\overline{1,e-1},\\
&U_e^{(n)}(z)=p\,zU_{e-1}^{(n)}(z)+q\,zU_{e+1}^{(n)}(z), \qquad (4)\\
&U_x^{(n)}(z)=p\,zU_{e-1}^{(n)}(z)+q\,zU_{x+1}^{(n)}(z),\\
&x=\overline{e+1,e+m-1},
\end{aligned}$$

$$U_0^{(n)}(z)=U_{e+m}^{(n)}(z)=1. \qquad (5)$$

From (4) with (5) taken into account we obtain

$$U_x^{(n)}(z)=(pz)^x+qz\frac{1-(pz)^x}{1-pz}U_{e+1}^{(n)}(z),\ x=\overline{1,e-1}, \qquad (6)$$

$$U_x^{(n)}(z)=(qz)^{e+m-x}+pz\frac{1-(qz)^{e+m-x}}{1-qz}U_{e-1}^{(n)}(z),\quad x=\overline{e+1,e+m-1} \qquad (7)$$

From (6) and (7) we have

$$U_{e-1}^{(n)}(z)=\frac{(p\,z)^{e-1}(1-p\,z)+(q\,z)^m[1-(p\,z)^{e-1}]}{1-z+q\,p^e z^{e+1}+p\,q^m z^{m+1}-q^m p^e z^{e+m}}(1-q\,z)$$

$$U_{e+1}^{(n)}(z)=\frac{(q\,z)^{m-1}(1-q\,z)+(p\,z)^e[1-(q\,z)^{m-1}]}{1-z+q\,p^e z^{e+1}+p\,q^m z^{m+1}-q^m p^e z^{e+m}}(1-p\,z).$$

Substituting these expressions into (4) we obtain a formula for the generating function $U_e^{(n)}(z)$ of an action change probability in the form

$$U_e^{(n)}(z)=\frac{(1-pz)p^e z^e(1-q^m z^m)+(1-qz)q^m z^m(1-p^e z^e)}{1-z+q\,p^e z^{e+1}+pq^m z^{m+1}-p^e q^m z^{m+e}}. \qquad (8)$$

It is not difficult to verify that the functioning of the automation $T_{2n,2}$ in the medium $C(a_1,a_2)$ is described by a uniform finite Markovian chain which is ergodic. For such automata, probabilities of the change $\sigma_a^{(n)}$ of the action f_α are equal to one, while average times $\tau_\alpha^{(n)}$ before the change of the action f_α are finite in any nondegenerate $(|a_\alpha| \neq 1)$ medium $C(a_1, a_2)$. Therefore, according to 4, the finite automata $T_{2n,2}$ are of the drawn-out type in each stationary random medium.

Thus the optimality of the behavior of such automata is excluded and the quality of their behavior is defined by a degree of their functioning expediency.

For the automation $T_{2n,2}$

$$\sigma_{\ell,\alpha}^{(n)} = U_e^{(n)}(1) = 1,$$

$$\tau_{\ell,\alpha}^{(n)} = \frac{dU_e^{(n)}(z)}{dz}\Big|_{z=1} = \frac{(1-p_\alpha^e)(1-q_\alpha^m)}{q_\alpha p_a^e + p_\alpha q_a^m - q_\alpha^m p_\alpha^e} < \infty$$

and therefore $T_{2n,2}$ is a drawn-out automation.

Let us now investigate the behavior of the automation $T_{2n,2}$ in the medium $C(a_1, a_2)$. For this we will consider the following cases.

1. Let $e = 1$, $m \geq 2$. Then $\tau_\alpha^{(n)} = \dfrac{1-q_\alpha^m}{p_\alpha}$ and it is not difficult to verify that $\tau_{\ell,1}^{(n)} > \tau_{\ell,2}^{(n)}$. Therefore in this case the behavior of the automation $T_{2n,2}$ in the medium $C(a_1, a_2)$ is expedient.

2. If $e = m = 1$, then $\tau_{\ell,1}^{(n)} = \tau_{\ell,2}^{(n)} = 1$ and the behavior of the automation $T_{2n,2}$ is indifferent.

3. For $m = 1$, $e \geq 2$ $\tau_{\ell,\alpha}^{(n)} = \dfrac{1-p_a^e}{q_\alpha}$ and $\tau_{\ell,1}^{(n)} < \tau_{\ell,2}^{(n)}$, and the behavior of the automation $T_{2n,2}$ is inexpedient.

4. Let us now assume that $e = m \neq 1$. Then it can be easily shown that

a) for $p_1 + p_2 > 1$, $\tau_{\ell,1}^{(n)} > \tau_{\ell,2}^{(n)}$ and therefore the behavior of the automation $T_{2n,2}$ is expedient;

b) for $p_1 + p_2 = 1$, $\tau_{\ell,1}^{(n)} = \tau_{\ell,2}^{(n)}$ and the behavior of the automation $T_{2n,2}$ is indifferent;

c) for $p_1 + p_2 < 1$, $\tau_{\ell,1}^{(n)} < \tau_{\ell,2}^{(n)}$ and the behavior of the automation $T_{2n,2}$ is inexpedient.

Now we will consider the behavior of infinite (with a countable number of states) analogues of the automa tion $T_{2n,2}$ in the stationary random medium $C(a_1, a_2)$, subsets $L_\alpha (\alpha = 1,2)$, the states of which are equivalent.

Assume that $m \to \infty$ $(n = e + m - 1 \to \infty)$. Then, taking into account the probabilistic meaning of the value $u_{x,d}$ and the structure of the infinite automation T_2, for $u_{x,d}$ we obtain

$$u_{x,d+1} = pu_{x-1,d} + qu_{e,d}, \quad x = \overline{1,e}, \; d = 0,1,2,\dots \quad (9)$$

$$u_{0,0} = 1, \; u_{x,0} = 0 \;\; \forall x > 0. \quad (10)$$

Multiplying (9) and (10) by Z^d and performing summation over all $d = 0,1,2,\dots$, for $U_x(z)$ we obtain the difference equation

$$U_x(z) = pzU_{x-1}(z) + qzU_e(z), \quad x = \overline{1,e} \quad (11)$$

with the boundary condition

$$U_0(z) = 1. \quad (12)$$

From (11) with (12) taken into account we obtain

$$U_x(z) = (pz)^x + qz\frac{1-(pz)^x}{1-pz}U_e(z), \quad x = \overline{1,e} \quad (13)$$

From this we finally get

$$U_e(z) = \frac{(1-pz)p^e z^e}{1 - z + q\; p^e z^{e+1}}. \quad (14)$$

From (14) we find

$$\sigma_{e,\alpha} = U_e(1) = 1,$$

$$\tau_{e,\alpha} = \frac{1-p_\alpha^e}{q_\alpha p_\alpha^e} < \infty, \; \alpha = 1,2.$$

Therefore the infinite automation T_2 is of the drawn-out type and by Definition 5 its behavior in the medium $C(a_1, a_2)$ is expedient since for $a_1 > a_2$, $\sigma_{e,1} = \sigma_{e,2}$ and $\tau_{e,1} > \tau_{e,2}$.

Passing to the limit in (8) as $m \to \infty$, we obtain

$$\lim_{m\to\infty} U_e^{(n)}(z) = U_e(z).$$

Thus we find, Thus the sequence of finite automata $\{T_{2n,2}\}_{m=1}^{\infty}$ converges to the infinite automation T_2 and therefore the asymptotic behavior of the finite automation $T_{2n,2}$ is defined as in |3|, by the behavior of the corresponding infinite automation T_2. Thus the sequence of finite automata is of the drawn-out type.

Now let us assume that $e \to \infty$ $(n = e + m - 1 \to \infty)$ Then, numerating the automation states in reverse order, it is not difficult to verify that the generating function of an action change probability is a solution of the boundary value problem (11),(12) if we replace in it e by m, p by q and q by p. The resulting solution has the form

$$U_m(z) = \frac{(1-q\;z)q^m z^m}{1 - z + p\; q^m z^{m+1}}.$$

Whence we find

$$\sigma_{m,\alpha} = 1,$$

$$\tau_{m,\alpha} = \frac{dU_m(z)}{dz}\bigg|_{z=1} = \frac{1-q_\alpha^m}{p_\alpha q_\alpha^m} < \infty, \ \alpha = 1,2 \text{ and}$$

$$\lim_{e\to\infty} U_e^{(n)}(z) = U_m(z),$$

i.e., the sequence of finite automata $\{T_{2n,2}\}_{m=1}^{\infty}$ converges to the corresponding infinite automation T_2, the behavior of which in the medium $C(a_1, a_2)$ is inexpedient.

If $e \to \infty$ and $m \to \infty$, then the infinite automation will forever remain in the subset of states where it was at the initial moment of time. In that case, the infinite automation T_2 is of the drawn-in type and

$$\lim_{\substack{e\to\infty \\ m\to\infty}} U_e^{(n)}(z) = U_e(z) = 0, \ \forall x > 0 .$$

This equality proves that the sequence of finite automata $\{T_{2n,2}\}_{e,m=1}^{\infty}$ also converges to the corresponding infinite automation T_2 for which $\sigma_{x,\alpha} = 0$, $\tau_{x,\alpha} = \infty$, α =1,2 and, according to Definition 5, its behavior in the medium $C(a_1, a_2)$ is indifferent.

The obtained results can be easily extended to the case of *k* actions of the automation.

4 Conclusion

The proposed structure of a finite automation is the finitely automated realization of the well-known statistical rule from the recurrent event theory: "either a series of successes of length m or a series of failures of length ℓ".

The formula obtained for the generating function of an action change probability of the considered finite automation completely coincides with the well-known formula for a generating function of the event recurrence time obtained by the recurrent method.

The expedient behavior of a finite automation depends both on the parameters of the automation and on those of the medium, while the sequence of finite automata of the proposed structure does not possess asymptotically optimal behavior.

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