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Preliminary statistical identification and prediction of the container gantry crane operation process

Keywords

semi-markov process, system operation process, sojourn time, estimation

Abstract

In the paper a Semi-markov process is used to construct a general model of complex industrial systems' operation processes. Main parameters of this model are defined and its main characteristics are determined as well. In particular case, for a gantry crane, the operation states are defined, the relationships between them are fixed and particular model of its operation process is constructed and finally its main characteristics are determined.

1. Introduction

The complexity of the systems' operation processes and their influence on changing in time the systems' structures and their components' reliability characteristics is often very difficult to fix and to analyse. A convenient tool for solving this problem is semi-markov modelling of the systems operation processes proposed in the paper. This model and statistical methods of its unknown parameters estimation are applied in a gantry crane operation process identification and prediction.

2. Modelling of system operation process

We assume that the system during its operation process has v different operation states. Thus we can define the system operation process $Z(t)$, $t \in <0,+\infty>$, as the process with discrete operation states from the set

$$Z = \{z_1, z_2, \ldots, z_v\}.$$

In practice a convenient assumption is that $Z(t)$ is a semi-Markov process [2] with its conditional sojourn times θ_{bl} at the operation state z_b when its next operation state is z_l, $b, l = 1,2,...,v$, $b \neq l$. In this case the process $Z(t)$ may be described by:

- the vector of probabilities of the system operation process initial states

$$[p_b(0)]_{1 \times v} = [p_1(0), p_2(0), ..., p_v(0)],$$

where

$$p_b(0) = P(Z(0) = z_b) \text{ for } b = 1,2,...,v,$$

- the matrix of probabilities of the system operation process transitions between the operation states

$$[p_{bl}]_{v \times v} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1v} \\ p_{21} & p_{22} & \cdots & p_{2v} \\ \cdots \\ p_{v1} & p_{v2} & \cdots & p_{vv} \end{bmatrix}, \tag{1}$$

where $p_{bb} = 0$ for $b = 1,2,...,v,$

- the matrix of the system operation process conditional sojourn times θ_{bl} distribution functions

$$[H_{bl}(t)]_{v \times v} = \begin{bmatrix} H_{11}(t) & H_{12}(t) & \ldots & H_{1v}(t) \\ H_{21}(t) & H_{22}(t) & \ldots & H_{2v}(t) \\ \cdots \\ H_{v1}(t) & H_{v2}(t) & \ldots & H_{vv}(t) \end{bmatrix}, \tag{2}$$

where

$$H_{bl}(t) = P(\theta_{bl} < t) \text{ for } b, l = 1,2,...,v, \ b \neq l,$$

and

$$H_{bb}(t) = 0 \text{ for } b = 1,2,...,v.$$

Under these assumptions, the mean values of the system operation process conditional sojourn times θ_{bl} are given by

$$M_{bl} = E[\theta_{bl}] = \int_0^{\infty} t dH_{bl}(t), \ b, l = 1,2,...,v, \ b \neq l. \quad (3)$$

By the formula for total probability the unconditional distribution functions of the sojourn times θ_b of the system operation process $Z(t)$ at the operation states z_b, $b = 1,2,...,v,$ are given by

$$H_b(t) = \sum_{l=1}^{v} p_{bl} H_{bl}(t), \ b = 1,2,...,v. \quad (4)$$

Hence, the mean values $E[\theta_b]$ of the system operation process unconditional sojourn times θ_b in the particular operation states are given by

$$M_b = E[\theta_b] = \sum_{l=1}^{v} p_{bl} M_{bl}, \ b = 1,2,...,v, \quad (5)$$

where M_{bl} are defined by (3).
Moreover, it is well known [2], [3] that the limit values of the system operation process transient probabilities at the particular operation states

$$p_b(t) = P(Z(t) = z_b), \ t \in <0,+\infty), \ b = 1,2,...,v,$$

are given by

$$p_b = \lim_{t \to \infty} p_b(t) = \frac{\pi_b M_b}{\sum_{l=1}^{v} \pi_l M_l}, \ b = 1,2,...,v, \quad (6)$$

where $M_b, b = 1,2,...,v,$ are defined by (5), whereas the probabilities π_b of the vector $[\pi_b]_{1xv}$ satisfy the system of equations

$$\begin{cases} [\pi_b] = [\pi_b][p_{bl}] \\ \sum_{l=1}^{v} \pi_l = 1. \end{cases} \quad (7)$$

Other interesting characteristics of the operation process $Z(t)$ possible to obtain are its total sojourn times $\hat{\theta}_b$ in the particular operation states z_b, $b = 1,2,...,v.$ It is well known [3] that the system operation process total sojourn times $\hat{\theta}_b$ in the particular operation states z_b, for sufficiently large operation time θ, have approximately normal distribution with the expected value given by

$$E[\hat{\theta}_b] = p_b \theta, \ b = 1,2,...,v, \quad (8)$$

where p_b are given by (6).

3. The container gantry crane description

The container terminal GCT S.A. is a company which is engaged in trans-shipment of containers. Discharging (loading) of containers is carried out by using of gantry cranes called Ship-To-Shore (STS).
One of them, the most modern, is a container gantry crane STS 03. We assume that this gantry crane is composed of 5 basic subsystems S_1, S_2, S_3, S_4, S_5, having an essential influence on its reliability. Those subsystems are as follows:

S_1 - the crane power supply subsystem,
S_2 - the crane control and monitoring subsystem,
S_3 - the crane arm getting up and getting down subsystem,
S_4 - the crane transferring subsystem,
S_5 - the containers' loading and unloading subsystem.

The gantry crane power supply subsystem S_1 consists of:

- a high voltage cable delivering energy from substation to gantry crane,
- a drum allowing cable unreeling during crane transferring,
- an inner crane power supply cable,
- a device transmitting energy from high voltage cable to inner crane cable,
- main and supporting voltage transformers,
- a low voltage power supply cable,
- relaying and protective electrical components.

The gantry crane control and monitoring subsystem S_2 consists of:

- a crane software controller precisely analyzing the situation and takes suitable actions in order to assure correct work of the crane,

- a measuring and diagnostic device sending signals about the crane state to the software controller,
- a transmitter of signals from controller to elements executing the set commands,
- devices carrying out controller’s orders (a permission to work, a blockade of work, etc.),
- control panels (an engine room, an operator’s cabin, a crane arm cabin),
- control and steering cable connections.

The gantry crane arm getting up and getting down subsystem S_3 consists of:

- a propulsion unit (an engine, a rope drum, a transmission gear, a clutch, breaks, a rope),
- a set of rollers and multi-wheels,
- a crane arm (joints, hooks fastening the arm).

The gantry crane transferring subsystem S_4 consists of:

- a driving unit (an engine, a clutch, breaks, a transmission gear, gantry crane wheels)

The containers’ loading and unloading subsystem S_5 consists of:

- the winch unit:
  - a propulsion unit (an engine, a clutch, breaks, a transmission gear, ropes),
  - a winch head (which a container grab is connected to),
  - a container’s grab,
  - a container’s grab stabilizing unit,
- the cart unit:
  - a propulsion unit (an engine, a clutch, breaks, a transmission gear, cart wheels, ropes),
  - rails which cart is moving on during the operation,
  - a crane cart.

Figure 1. The container gantry crane

4. The gantry crane operation process and its preliminary statistical identification

Taking into account the expert opinion and the varying in time operation process of the considered gantry crane we distinguish the following as its six operation states:

- an operation state $z_1 -$ the crane standby with the power supply on and the control system off,
- an operation state $z_2 -$ the crane prepared either to starting or finishing the work with the crane arm angle position of 90^o,
- an operation state $z_3 -$ the crane prepared either to starting or finishing the work with the crane arm angle position of 0^o,
- an operation state $z_4 -$ the crane transferring either to or from the loading and unloading area with the crane arm angle position of 90^o,
- an operation state $z_5 -$ the crane transferring either to or from the loading and unloading area with the crane arm angle position of 0^o,
- an operation state $z_6 -$ the containers’ loading and unloading with the crane arm angle position of 0^o.

To identify all parameters of the gantry crane operation process the statistical data about this process is needed. The statistical data that has been collected up to now is given in [6] in Tables 1-17. In the *Table 1* there are given exemplary realizations of the conditional sojourn times in particular operation states of the gantry crane operation process. All realizations are given in Tables 1-17 in [6].

Table 1. Realization of the gantry crane conditional sojourn times in operation states during one day (24 hours).

Conditional sojourn times θ_{bl} in operation state	Realization of conditional sojourn times θ_{bl} in operation state (in minutes)					
θ_{23}	1	2				
θ_{36}	4	2	6	8	2	
θ_{63}	32	19	6	2	3	6
θ_{36}	8	2				

θ_{65}	27	21					
θ_{56}	4						
θ_{53}	3						
θ_{32}	3	3					
θ_{21}	5	5	1				
θ_{12}	127	64	978				
θ_{31}	34						
θ_{13}	11						
θ_{24}	1						
θ_{42}	3						

It is assumed that one day (24 hours) of working of the system is a single realization of its operation process. The conditional sojourn times θ_{bl} at the operation states z_b when its next operation state is z_l, $b,l = 1,2,3,4,5,6,$ $b \neq l,$ of each single realization of the gantry crane operation process are given in separate rows. In [6] there are collected realizations of the conditional sojourn times in particular operation states of considered system on the basis of a sample composed of $n = 17$ realizations.
From data given in [6], on the basis of methods and procedures given in [4], the following operation process statistical data are fixed:
- the number of the gantry crane operation process states

$$\nu = 6;$$

- the gantry crane operation process observation/experiment time

$$\Theta = 19 \text{ days};$$

- the number of the gantry crane operation process realizations

$$n(0) = 17;$$

- the realization $n_b(0)$ of the number of the gantry crane operation process transients in the particular operation states z_b at the initial moment $t = 0$

$$n_1(0) = 1,\ n_2(0) = 11,\ n_3(0) = 1,\ n_4(0) = 0,$$

$$n_5(0) = 2,\ n_6(0) = 2,$$

where

$$n_1(0) + n_2(0) + n_3(0) + n_4(0) + n_5(0) + n_6(0) = 17;$$

- the vector of realizations of the numbers of the gantry crane operation process transitions in the particular operation states z_b at the initial moment $t = 0$

$$[n_b(0)] = [n_1(0), n_2(0), n_3(0), n_4(0), n_5(0), n_6(0)]$$

$$= [1, 11, 1, 0, 2, 2];$$

- the realization n_{bl} of the numbers of the gantry crane operation process transitions from the state z_b into the state z_l during the experiment time $\Theta = 19$ days

$$n_{11} = 0,\ n_{12} = 62,\ n_{13} = 26,\ n_{14} = 1,$$
$$n_{15} = 0,\ n_{16} = 1,$$
$$n_{21} = 49,\ n_{22} = 0,\ n_{23} = 31,\ n_{24} = 9,$$
$$n_{25} = 0,\ n_{26} = 0,$$
$$n_{31} = 26,\ n_{32} = 30,\ n_{33} = 0,\ n_{34} = 0,$$
$$n_{35} = 33,\ n_{36} = 156,$$
$$n_{41} = 5,\ n_{42} = 5,\ n_{43} = 0,\ n_{44} = 0,$$
$$n_{45} = 0,\ n_{46} = 0,$$
$$n_{51} = 1,\ n_{52} = 0,\ n_{53} = 25,\ n_{54} = 0,$$
$$n_{55} = 0,\ n_{56} = 115,$$
$$n_{61} = 4,\ n_{62} = 0,\ n_{63} = 163,\ n_{64} = 0,$$
$$n_{65} = 107,\ n_{66} = 0;$$

- the matrix of realizations n_{bl} of the numbers of the gantry crane operation process transitions from the state z_b into the state z_l during the experiment time $\Theta = 19$ days

$$[n_{bl}]$$

$$= \begin{bmatrix} n_{11} & n_{12} & n_{13} & n_{14} & n_{15} & n_{16} \\ n_{21} & n_{22} & n_{23} & n_{24} & n_{25} & n_{26} \\ n_{31} & n_{32} & n_{33} & n_{34} & n_{35} & n_{36} \\ n_{41} & n_{42} & n_{43} & n_{44} & n_{45} & n_{46} \\ n_{51} & n_{52} & n_{53} & n_{54} & n_{55} & n_{56} \\ n_{61} & n_{62} & n_{63} & n_{64} & n_{65} & n_{66} \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 62 & 26 & 1 & 0 & 1 \\ 49 & 0 & 31 & 9 & 0 & 0 \\ 26 & 30 & 0 & 0 & 33 & 156 \\ 5 & 5 & 0 & 0 & 0 & 0 \\ 1 & 0 & 25 & 0 & 0 & 115 \\ 4 & 0 & 163 & 0 & 107 & 0 \end{bmatrix};$$

- the realization n_b of the total numbers of the gantry crane operation process transitions from the operation state z_b during the experiment time $\Theta = 19$ days (the sums of the numbers of the matrix $[n_{bl}]$)

$$n_1 = n_{11} + n_{12} + n_{13} + n_{14} + n_{15} + n_{16} = 90,$$
$$n_2 = n_{21} + n_{22} + n_{23} + n_{24} + n_{25} + n_{26} = 89,$$
$$n_3 = n_{31} + n_{32} + n_{33} + n_{34} + n_{35} + n_{36} = 245,$$
$$n_4 = n_{41} + n_{42} + n_{43} + n_{44} + n_{45} + n_{46} = 10,$$
$$n_5 = n_{51} + n_{52} + n_{53} + n_{54} + n_{55} + n_{56} = 141,$$
$$n_6 = n_{61} + n_{62} + n_{63} + n_{64} + n_{65} + n_{66} = 274;$$

- the matrix of realizations of the total numbers of the gantry crane operation process transitions from the operation state z_b during the experiment time $\Theta = 19$ days

$$[n_b] = [n_1, n_2, n_3, n_4, n_5, n_6]$$

$$= [90, 89, 245, 10, 141, 274].$$

On the basis of the above statistical data it is possible to estimate

- the vector

$$[p(0)] = [0.059, 0.647, 0.059, 0, 0.117, 0.117]$$

of the initial probabilities $p_b(0)$, $b = 1,2,3,4,5,6,$ (1) [3] of the gantry crane operation process transients in the particular states z_b at the moment $t = 0$

- the matrix

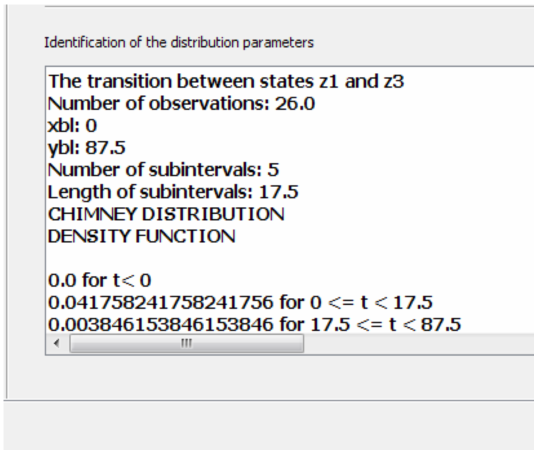
$$[p_{bl}]$$

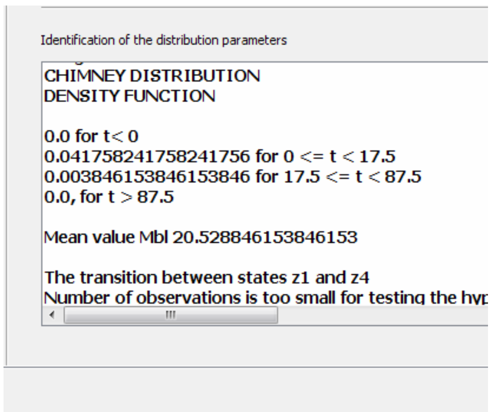
$$= \begin{bmatrix} 0 & 0.689 & 0.289 & 0.011 & 0 & 0.011 \\ 0.551 & 0 & 0.349 & 0.1 & 0 & 0 \\ 0.106 & 0.122 & 0 & 0 & 0.135 & 0.637 \\ 0.5 & 0.5 & 0 & 0 & 0 & 0 \\ 0.007 & 0 & 0.177 & 0 & 0 & 0.816 \\ 0.015 & 0 & 0.595 & 0 & 0.390 & 0 \end{bmatrix},$$

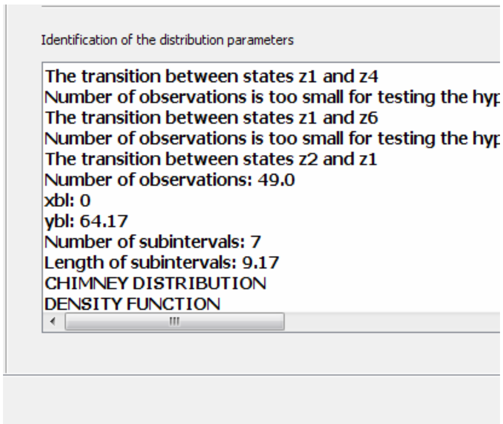
of the transition probabilities p_{bl}, $b, l = 1,2,3,4,5,6,$ (2) [3] of the gantry crane operation process from the operation state z_b into the operation state z_l.

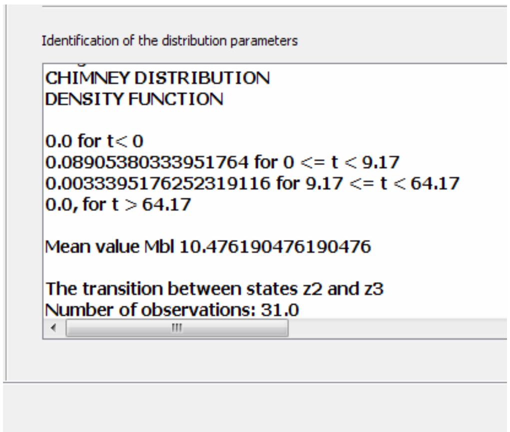
5. The gantry crane operation process characteristics evaluation

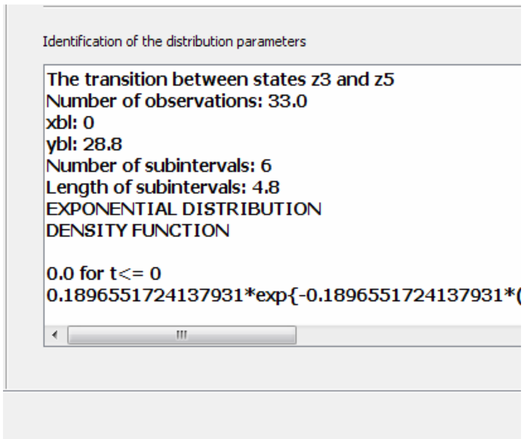
On the basis of statistical data coming from experiment it is possible to verify hypotheses on the distributions of the conditional sojourn times θ_{bl}, $b, l = 1,2,...,6,$ $b \neq l,$ in the particular operation states. At the moment, because of the lack of statistical data it is not possible to verify all hypotheses on the distributions of the sojourn times. The hypotheses which have been verified by the chi-square goodness of fit test are given in [6]. Selected examples of these results of hypotheses testing are presented below [1]:

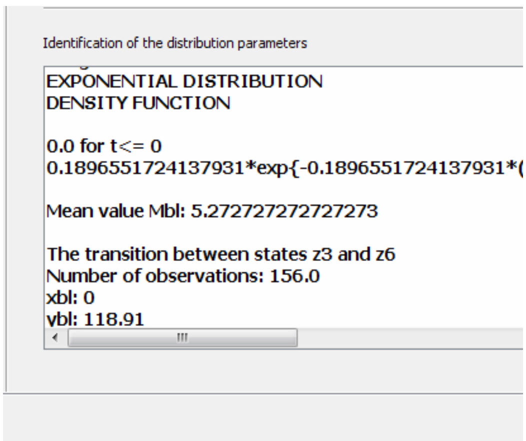


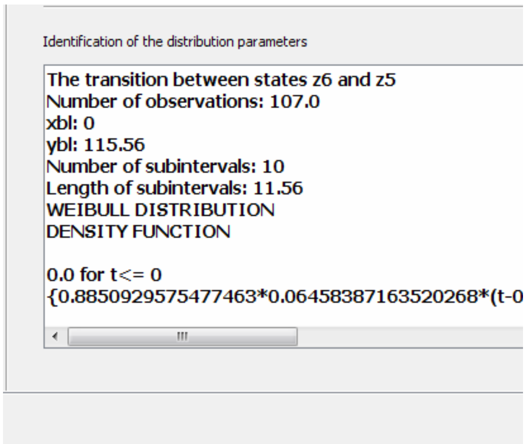


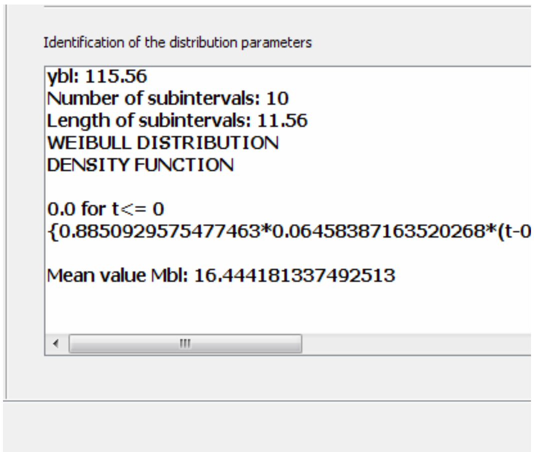












For the verified in [6] distributions, we can find the following mean values $M_{bl} = E[\theta_{bl}]$, $b,l = 1,2,...,6$, $b \neq l$, (3) of the conditional sojourn times in the particular operation states:

$$M_{13} = 20.529,$$

$$M_{21} = 10.476, \; M_{23} = 9.758,$$

$$M_{31} = 8.885, \; M_{32} = 4.357, \; M_{35} = 5.273,$$

$$M_{53} = 2.650, \; M_{56} = 28.343,$$

$$M_{63} = 17.261, \; M_{65} = 16.444.$$

In the remaining cases it is possible to find only the empirical values of the mean values $M_{bl} = E[\theta_{bl}]$ of the conditional sojourn times in the particular operation states that are as follow:

$$M_{12} = 312.629, \; M_{14} = 50, \;\; M_{16} = 3,$$

$$M_{24} = 1.111,$$

$$M_{36} = 7.295,$$

$M_{41} = 2, \;\; M_{42} = 2,$

$M_{51} = 10,$

$M_{61} = 25.250.$

Hence, by (5), the unconditional mean sojourn times in the particular operation states are given by:

$$M_1 = E[\theta_1] = p_{12}M_{12} + p_{13}M_{13} + p_{14}M_{14} + p_{16}M_{16}$$

$$= 0.689 \cdot 312.629 + 0.289 \cdot 20.529$$

$$+ 0.011 \cdot 50 + 0.011 \cdot 3 \cong 221.918,$$

$$M_2 = E[\theta_2] = p_{21}M_{21} + p_{23}M_{23} + p_{24}M_{24}$$

$$= 0.551 \cdot 10.476 + 0.349 \cdot 9.758$$

$$+ 0.1 \cdot 1.111 + \cong 9.289,$$

$$M_3 = E[\theta_3] = p_{31}M_{31} + p_{32}M_{32} + p_{35}M_{35} + p_{36}M_{36}$$

$$= 0.106 \cdot 8.885 + 0.122 \cdot 4.357 +$$

$$+ 0.135 \cdot 5.273 + 0.637 \cdot 7.295 + \cong 6.832,$$

$$M_4 = E[\theta_4] = p_{41}M_{41} + p_{42}M_{42}$$

$$= 0.5 \cdot 2 + 0.5 \cdot 2 = 2,$$

$$M_5 = E[\theta_5] = p_{51}M_{51} + p_{53}M_{53} + p_{56}M_{56}$$

$$= 0.007 \cdot 10 + 0.177 \cdot 2.650$$

$$+ 0.816 \cdot 28.343 \cong 23.667,$$

$$M_6 = E[\theta_6] = p_{61}M_{61} + p_{63}M_{63} + p_{65}M_{65}$$

$$= 0.015 \cdot 25.250 + 0.595 \cdot 17.261$$

$$+ 0.390 \cdot 16.444 \cong 17.062.$$

Since from the system of equations below (7)

$$\begin{cases} [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6] \\ = [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6][p_{bl}]_{6x6} \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 + \pi_6 = 1, \end{cases}$$

we get

$$\pi_1 = 0.1056, \;\; \pi_2 = 0.1142, \;\; \pi_3 = 0.2879,$$

$$\pi_4 = 0.0126, \;\; \pi_5 = 0.1625, \;\; \pi_6 = 0.3172.$$

Then the limit values of the transient probabilities $p_b(t)$ at the operational states z_b, according to (6), are given by

$$p_1 = 0.6556, \;\; p_2 = 0.0297, \;\; p_3 = 0.0550,$$

$$p_4 = 0.0007, \;\; p_5 = 0.1076, \;\; p_6 = 0.1514.$$

5. Conclusion

In the paper the model of the operation process of the complex technical system with the distinguished their operation states is proposed. The semi-markov process is used to construct a general probabilistic model of the considered system operation process. To construct this model there are defined the vector of the probabilities of the system initial operation states, the matrix of the probabilities of transitions between the operation states. To describe the system operation process conditional sojourn times in the particular operation states the uniform distribution, the triangular distribution, the double trapezium distribution, the quasi-trapezium distribution, the exponential distribution, the Weibull’s distribution, the normal distribution and the chimney distribution suggested in [4] are considered. Moreover these tools are applied to unknown parameters estimation and characteristics prediction of the gantry crane operation process.
The input data concerned with the operation process are coming from experts and are concerned with the conditional sojourn times of the system in the operation states. To improve the achieved results it is supposed that the statistical data given in [6] will be collected in future and more precise full identification of the gantry crane operation process will be performed and this process main characteristics will be determined and used in gantry crane reliability, risk and availability analysis and evaluation.

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