J. Appl. Environ. Biol. Sci., 4(8)160-168, 2014

© 2014, TextRoad Publication

ISSN: 2090-4274
Journal of Applied Environmental and Biological Sciences
www.textroad.com

A Safety Analysis Model for Industrial Robots (Markov Chain Approach) (Case Study: Haierplast Company)

Farzad Gerami, Fatemeh Ebrahimi, Mohammad-Reza Naderi, Mir Emad Aghaei

Faculty Member of Industrial Engineering Department, Naghshe Jahan Institute of Higher Education, Baharestan, Isfahan, Iran

Received: April 26, 2014
Accepted: June 26, 2014

ABSTRACT

The growing application of industrial robots in some of the industries and the nature of their activities (vast work environment, unpredictable movements, and the nature of controlling its computer program) will create a unique challenge in occupational safety. An industrial robot must be safe and reliable so that it does not lead to unsafe situations and high maintenance expenses. Consecutive failures of a robot will cause an industry to suffer from great expenses. This study seeks to develop a safety analysis model for industrial robots. The main aims of the research are, identifying potential risks for industrial robots and the definition of hazard rate at different states for a robot system. Due to the importance of this issue and the dearth of studies done in this regard, this study intended to develop a safety analysis model for industrial robots based on Markov chain. Then, this model was applied to the robots in Haierplast Company; and finally, the results were analyzed. The findings of this study include the computation of danger rate, probabilities, reliability, the average of failure time, and the repair rate of the safety system of robots.

KEYWORDS: robot safety, reliability, severity-frequency index of an event

INTRODUCTION

Researchers contend that thinking about robots dates back to ancient era; however, the word robot was first used in 1920 by Carl Kapk. This word means a worker in Czech language. Today, across industries throughout the world we see the activities of millions of robots. These robots have been used to perform a variety of missions, including welding, painting, material handling, assembly, drilling, and photography.

Using robots takes account of the development priorities of all industries. Reasons to invest in the field of industrial robots include:

- Quality improvement and product consistency
- Reduction in product waste and increase in efficiency
- Increase in production flexibility
- Reduction in the administrative costs
- Increase in production rate
- Saving space in industrial zones
- Reduction in the demand for workers and the difficulty of hiring workers
- Compliance with safety rules and improvement to the health and safety of the workplace
- Reduction in the investment costs

These benefits gained by virtue of using robots in the industry turn out to be attractive and feasible in case it allows for keeping the costs of repairs and maintenance of robots within reasonable limits and to a record low. In this respect, discussing the need for the safety of industrial robots as well as addressing the domain by principle is clearly evident. Because lack of paying enough attention to this topic paves the way for the loss of investment made in the purchase and installation of industrial robots, preventing reaping all the benefits listed above.

Over the years many techniques have been developed for implementation of different types of safety analysis and some of them can be used in conducting safety analysis of industrial robots; however, the number of published articles and studies in this regard are limited.

Hu et al. (2013) examined the design and implementation of the robot-human interaction. They based their research on the five strategies proposed in the safety design. Then, they provided a good model for the risk assessment [1]. Vicentini et al. (2014) introduced a methodology called SafeNet for helping in extending the safety rate of Human Robot Interaction (HRI) systems using unsafe components, including sensors and controllers [2]. Vick & Kruger (2013) presented the safe limitation of contact forces between an industrial robot and its human

*** Corresponding Author:** Farzad Gerami, Faculty Member of Industrial Engineering Department, Naghshe Jahan Institute of Higher Education, Baharestan, Isfahan, Iran, +98-3116826055, Gerami@naghshejahan.ac.ir

operator during physical collaboration [3]. Also, in one study, Oberer & Schraft (2007) embarked on minimizing the potential risks incorporating robot's control system. They having contended that current standards for safety do not fulfill the demands of situations where there is a close relationship between robots and humans, examined the existing methods in the automotive industry. In this study, a type of simulation was used [4]. Haddadin et al. (2007) assessed the safety standards on interaction of robot and human (risks posed by robot to human). They assessed several mechanisms of harm as well as an index of severity of injury [5]. Althoff et al. (2012), presents a probabilistic framework for reasoning about the safety of robot trajectories in dynamic and uncertain environments with imperfect information about the future motion of surrounding objects [6]. On the one hand, Tan et al. (2009) addressed the design of robot-human safety associated with cell production. They suggested and assessed five safety designs of hardware as well as robot control [7]. Fryman & Matthias (2012) surveyed the developments of industrial robots and of the robot safety standards [8]. In the other study, Matthias et al. (2011) discussed a viable approaches to risk assessment for collaborative robots and a more detailed future methodology that will be better able to resolve the relevant low-level injury risks [9]. Also, in one study, Augustsson (2013) tackled the issue of mechanical and physical interactions of robots and humans, investigating the risks posed by robot to human [10].

Also Lacevic et al. (2013) investigated on a synergistic approach to danger assessment and safety-oriented control of articulated robots that are based on a quantity called danger field. This quantity is captured the state of the robot as a whole and indicates how dangerous the current posture and velocity of the robot are to the objects in the environment [11]. Kimura et al. (2013), in their research, investigated on safety standards on special environment robots in Japan. They analyzed the state of art and problems of standardization and safety standards of Special Environment Robots [12].

In this research, we follow some aims, consist of:

- Identify potential risks for industrial robots
- Development a mathematical model to safety analysis for Industrial robots
- The definition of hazard rate at different states for a robot system
- Calculation of reliability and failure rate for industrial robots in different states.

Further, the present study will first deal with the safety analysis model, then the designed model will be implemented and the results will be studied. Finally, the conclusion will be presented.

Methodology (development of safety analysis model)

In this study, the safety analysis model is developed based on the principles of Markov chain (transition from one state to another).

Based on Meyn & Tweedie (2009), Markov chain is a series of random variables having the same sample space. However, their probability distribution can vary. In addition, each random variable in a Markov chain depends only on the variable before it. The sequence of random variables is represented as follows:

$$X^{(0)}, X^{(1)}, X^{(2)}, \ldots$$

Sample space of random variables of Markov chain can be continuous or discrete as well as finite or infinite. Given a finite discrete sample space, each random variable can be shown with its probability distribution. We show this distribution with a vector incorporating the probability (P) of each value of the sample space. Thus, another representation of the Markov chain consists in:

$$\mathbf{P}_0, \mathbf{P}_1, \mathbf{P}_2, \ldots$$

$$\mathbf{P}_\mathbf{i} = [\, p(\mathbf{X}^\mathbf{i} = x_1) \quad , \ldots, \quad p(\mathbf{X}^\mathbf{i} = x_n) \,]$$

According to the definition of the Markov chain, knowing the first component of the chain along with the reaction producing the component i from the component i-1 is sufficient to make a chain [13]. We call this relation the Transfer function (T). How to obtain probability vector components through this function consist in:

The graph of different states of the robot

Based on Gerami & Rocky (2010), we can define states of the robot as follow [14]:

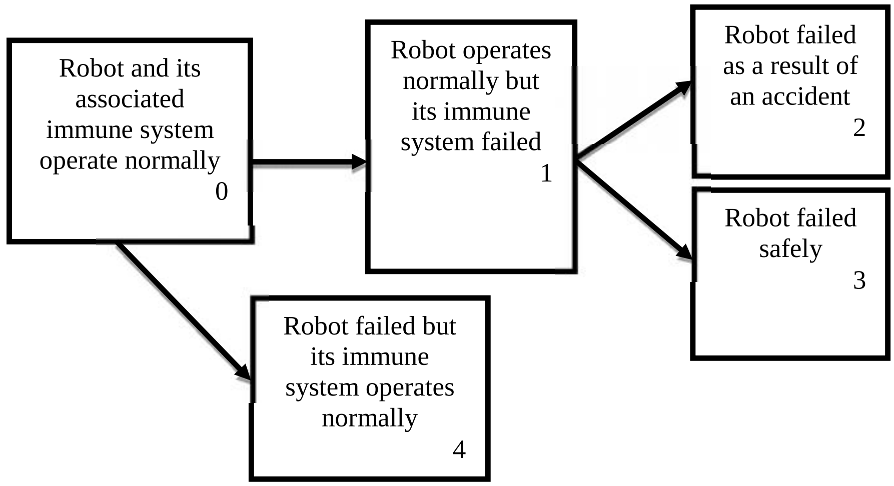


Figure 1. Transition of the system of the robot from one state to another

Model Assumptions

For the graph above, the following assumptions are considered:

- The robot system is composed of a robot and the immune system
- The system of the robot fails when the robot fails
- All failures are constantly independent
- All failure rates are constant

The model variables and components

There are several variables in the design of the model of safety analysis. These variables are defined as follows:

Table 1 - The Model Variable

Description	Variable
i consists in the i-th system mode: $i = 0$: Robot and its associated immune system operate normally $i = 1$: Robot operates normally, but its immune system failed $i = 2$: Robot failed as a result of an accident $i = 3$: Robot failed safely $i = 4$: Robot failed, but its immune system operates normally	i
$P_i(t)$: consists in a probability that robot system remains in state i at time t	$P_i(t)$
a_i : consists in the the i-th rate of constant failure: $i = s$: The transition from state 0 to state 1 $i = ri$: The transition from state 1 to state 2 $i = rs$: The transition from state 2 to state 3 $i = r$: The transition from state 3 to state 4	a_i

In this model, several components hold significance. The components of this model consist in:

Reliability: the reliability of a system is a probability of normal function without fault for a definite period of time under the existing and predetermined conditions.

$$R(t) = 1 - \sum_{0}^{t} f(t)$$

Here f (t) is the probability density function obtained through the Poisson distribution.

$$f(t) = e^{-\alpha}\frac{\alpha^t}{t!}$$

α = the number of failures occurred during the time t

Failure rate: To obtain the failure rate in the case of rather large number of equipment during the operation until disability or failure of devices, survey is done. Equipment failure rate at time t is the density of failure probability in the next time interval, provided that at the beginning of this interval the equipment is safe.

$$a(t) = \frac{f(t)}{R(t)}$$

Maintenance rate: To Modify device failure mode in a given time period, while observing certain techniques

$$\mu\ (t) = \int_0^t \frac{1}{\theta} e^{\frac{t}{\theta}} dt$$

In this formula θ equals the average length of service.

The mean time to failure of the robot: this is a good measure for estimating the average useful working time before the error, which is different in each of the cases described in the graph above.

Safety analysis model equations

Based on the concept of Markov chain as well as the different transitions of a robot along with considering the variables and parameters defined, the following calculation is performed, using the techniques of differential equations:

$$\frac{dp_{0(t)}}{dt} + (\lambda_s + \lambda_r)p_0(t) = 0 \quad (1)$$

$$\frac{dp_{1(t)}}{dt} + (\lambda_{ri} + \lambda_{rs})p_1(t) = p_0(t)\lambda_s \quad (2)$$

$$\frac{dp_2(t)}{dt} = p_1(t)\lambda_{ri} \quad (3)$$

$$\frac{dp_{3(t)}}{dt} = p_1(t)\lambda_{rs} \quad (4)$$

$$\frac{dp_{4(t)}}{dt} = p_0(t)\lambda_r \quad (5)$$

At time t=0، $P_0(0)=1$ و $P_1(0)=P_2(0)=P_3(0)=P_4(0)$

Through solving the equations (1) to (5) we take the equations of probability for all modes:

$$p_0(t) = e^{-At} \quad (6)$$

$$p_1(t) = \frac{\lambda_s}{B}(e^{-Ct} - e^{-At}) \quad (7)$$

$$A = \lambda_s + \lambda_r$$

$$B = \lambda_s + \lambda_r - \lambda_{rs} - \lambda_{ri}$$

$$C = \lambda_{ri} + \lambda_{rs}$$

$$p_2(t) = \frac{\lambda_{ri}\lambda_s}{AC}\left[1 - \frac{(Ae^{-Ct} - Ce^{-At})}{B}\right] \quad (8)$$

$$p_3(t) = \frac{\lambda_{rs}\lambda_s}{AC}\left[1 - \frac{(Ae^{-Ct} - Ce^{-At})}{B}\right] \quad (9)$$

$$p_4(t) = \frac{\lambda_r}{A}(1 - e^{-At}) \quad (10)$$

The equations (7) to (10), respectively point to the possibilities of robot operation, as operating normal, its immune system failed, robot failed as a result of an accident, robot failed safely, and Robot failed but its immune system operates normally.
As explained earlier, in these formulae λ (t) is calculated by the following relation:

$$\text{a}(t) = \frac{f(t)}{R(t)} \qquad \text{Hazard rate}$$

Here f (t) is the probability density function obtained through the Poisson distribution.

$$f(t) = e^{-\alpha}\frac{\alpha^t}{t!}$$

α = the number of failures occurred during the time t and R (t) is calculated from the following relation:

$$1 - \sum_0^t e^{-\sim}\frac{\sim^t}{t!} = \text{R (t)} \qquad \text{Reliability}$$

α = the number of failures occurred during the time t

The reliability of robot and its associated immune system operating normally consist in:

$$R_{rsu}(t) = p_0(t) = e^{-At} \qquad (11)$$

The reliability of robot working normally with or without successful functioning of the immune system is:

$$R_{ss}(t) = p_0(t) + p_1(t) = e^{-At} + \frac{\lambda_s}{B}\left(e^{-Ct} - e^{-At}\right) \qquad (12)$$

The mean time to failure of the immune system along with the immune system working will consist in:

$$MTTF_{rsu} = \int_0^\infty R_{rsu}(t)dt = \frac{1}{A} \qquad (13)$$

Similarly, the mean time to failure of the immune system working or incapacitated will consist in:

$$MTTF_{SS} = \int_0^\infty R(t)dt = \frac{1}{A}\left(1 + \frac{\lambda_s}{C}\right) \qquad (14)$$

If the immune system is repaired (i.e. from state 1 to state 0) in terms of the rate « , using the Markov method, we will get the following system of differential equations:
Exponential distribution function is generally a good indication of the service time. This means that the density function m can be represented like the following:

$$m(t) = \frac{1}{-}e^{-\frac{t}{-}}$$

Thus, the repair rate of the item at time t is obtained as follows:

$$\mu\ (t) = \int_0^t \frac{1}{\theta} e^{\frac{t}{\theta}} dt$$

In this formula, θ equals the average length of service.

$$\frac{dp_{0(t)}}{dt} + Ap_0(t) = p_1(t) \qquad (15)$$

$$\frac{dp_1(t)}{dt} + Dp_1(t) = p_0(t)\lambda_s \qquad (16)$$

$$D = \lambda_{ri} + \lambda_{rs} + \mu$$

$$\frac{dp_2(t)}{dt} = p_1(t)\lambda_{ri} \qquad (17)$$

$$\frac{dp_3(t)}{dt} = p_1(t)\lambda_{rs} \quad (18)$$

$$\frac{dp_4(t)}{dt} = p_0(t)\lambda_r \quad (19)$$

At time t=0, $P_0(0)=1$, $P_1(0)=P_2(0)=P_3(0)=P_4(0)$

By substituting equations (15) to (19), we will have:

$$p_0(t) = e^{-At} + \mu\lambda_s\left[\frac{e^{-At}}{(r_1+A)(r_2+A)} + \frac{e^{r_1 t}}{(r_1+A)(r_1-r_2)} + \frac{e^{r_2 t}}{(r_1+A)(r_2-r_1)}\right] \quad (20)$$

$$r_1, r_2 = \frac{-E \pm \sqrt{E^2-4F}}{2}$$

$$E = A + C + \mu$$

$$F = \lambda_{ri}\lambda_s + \lambda_{rs}\lambda_s + \lambda_{ri}\lambda_r + \lambda_{rs}\lambda_r + \mu\lambda_r$$

$$p_1(t) = \lambda_s\left[\frac{e^{r_1 t} - e^{r_2 t}}{(r_1-r_2)}\right] \quad (21)$$

$$p_2(t) = \frac{\lambda_{ri}\lambda_s}{r_1 r_2}\left[1 + \frac{(r_1 e^{r_2 t} - r_2 e^{r_1 t})}{(r_2-r_1)}\right] \quad (22)$$

$$p_3(t) = \frac{\lambda_{rs}\lambda_s}{r_1 r_2}\left[1 + \frac{(r_1 e^{r_2 t} - r_2 e^{r_1 t})}{(r_2-r_1)}\right] \quad (23)$$

$$p_4(t) = \frac{\lambda_r}{A}(1 - e^{-At}) + \mu\lambda_s\lambda_r\left[\frac{1}{r_1 r_2 A} - \frac{e^{-AT}}{A(r_1+A)(r_2+A)} + \frac{e^{r_1 t}}{r_1(r_1+A)(r_1-r_2)} + \frac{e^{r_2 t}}{r_2(r_2+A)(r_2-r_1)}\right] \quad (24)$$

The reliability of the robot and its associated immune system working along with the possibility of repairing the immune system consist in:

$$R_{rsr}(t) = e^{-At} + \mu\lambda_s\left[\frac{e^{-At}}{(r_1+A)(r_2+A)} + \frac{e^{r_1 t}}{(r_1+A)(r_1-r_2)} + \frac{e^{r_2 t}}{(r_1+A)(r_2-r_1)}\right] \quad (25)$$

The reliability of robot working normally with or without the immune system of the immune system (with the possibility of the immune system repair) from the equations (20) and (21) consist in:

$$R_{ssr}(t) = e^{-At} + \frac{\lambda_s(e^{r_1 t} - e^{r_2 t})}{(r_1-r_2)} + \mu\lambda_s\left[\frac{e^{-At}}{(r_1+A)(r_2+A)} + \frac{e^{r_1 t}}{(r_1+A)(r_1-r_2)} + \frac{e^{r_2 t}}{(r_1+A)(r_2-r_1)}\right] \quad (26)$$

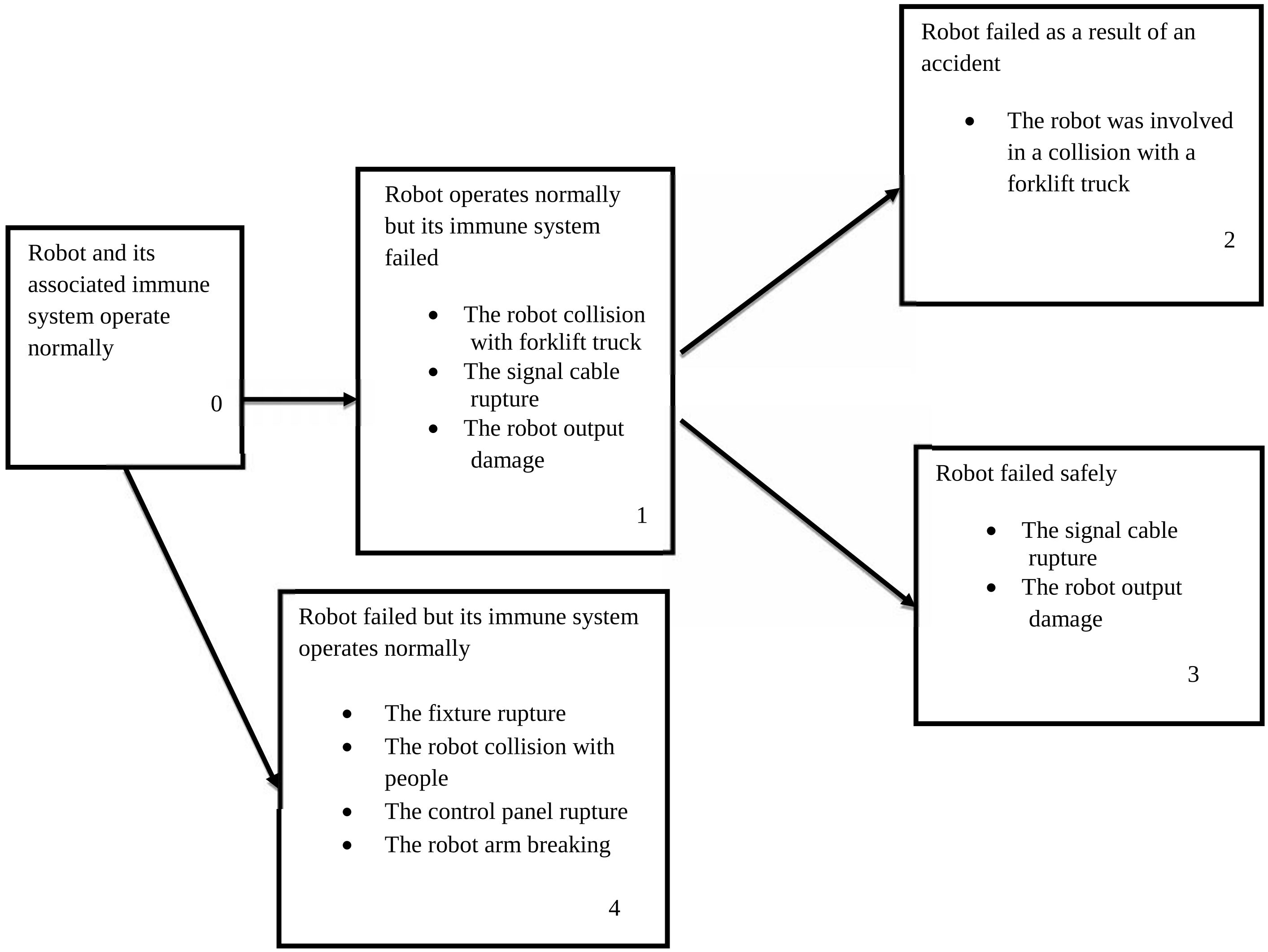
Finally, the mean time to failure of the immune system with the possibility of the repair of the immune system working will consist in:

$$MTTF_{rsr} = \int_0^\infty R_{rsr}(t)dt = \frac{1}{A}\left(1 + \frac{\mu\lambda_s}{F}\right) \quad (27)$$

Findings (The implementation of the model for the existing robots at Haierplasr Company)

The designed model was implemented on the robots in the Haierplast Company (among the subsidiary companies of Entekhab Industrial Group (SNOWA) parent company, considered to be one of the largest and most advanced plastic manufacturing companies in the region). The robots are of the type of UO DO STAR and have 3 axes in the directions of X, Y, and Z.

Based on what was mentioned above, the graph below depicts the transition for these robots:



Graph 2 - Transition systems for robots under study (Haierplast Company)

The table below shows the types of failures, time and length of service calculated for industrial robots. It should be noted that all calculations are considered for the period of 5 years.

Table 2 – Status types of failures, time and length of service for industrial robots

Row	Failure / Potential risk	Time	Length of Service
1	The robot collision with forklift truck	Occurred only once in the third year	4 days
2	The fixture rupture	Once every 6 months	1 day
3	The robot collision with people	Rarely, once a year	1 day
4	The control panel rupture	Once every 4 months	2 days
5	The robot arm breaking	Once a year	5 days
6	The signal cable rupture	Once every 9 months	2 days
7	The robot output damage	Once every 6 months	1 day

Based on the above table and equations, the following calculations can be made.

Table 3 - values were calculated

Definition	Value	Entry
Hazard rate from 0 to 4	0.183	λ_r
Hazard rate from 1 to 2	$21*10^{-7}$	λ_{ri}
Hazard rate from 0 to 1	0.44	λ_s
Hazard rate from 1 to 3	0.237	λ_{rs}
Probability of normal functioning	0.044	$p_0(t)$
Probability of robot immune system failure	0.299	$p_1(t)$
The probability that robot failed as a result of an accident	$3*10^{-6}$	$p_2(t)$
The probability that robot failed safely	0.375	$p_3(t)$
The probability that robot failed but its immune system operates normally	0.281	$p_4(t)$
Reliability of robot and its associated immune system operating normally	0.044	R_{rsu}
Reliability of robot working normally with or without successful functioning of the immune system	0.34	R_{ss}
Mean time to failure of the robot system along with the immune system working	1.605	$MTTF_{rs}$
Mean time to failure of the immune system working or incapacitated	4.585	$MTTF_{ss}$
The rate of the robot immune system repair	0.097	µ
The probability of normal functioning after applying the repair rate	0.064	$p_0(t)$
The probability of failure after applying the repair rate	0.26	$p_1(t)$
The probability that robot failed as a result of an accident after applying the repair rate	$3*10^{-6}$	$p_2(t)$
The probability that robot failed safely after applying the repair rate of unsafe failures	0.34	$p_3(t)$
The probability that robot failed but the immune system working normally	0.33	$p_4(t)$
Reliability of robot/its associated immune system operating normally along with the possibility of the immune system change	0.06	R_{rsr}
Reliability of robot operating normally with or without the immune system (with the possibility to repair the immune system)	0.32	R_{ssr}
Mean time to failure of robot with the possibility of repair along with the immune system working	2.02	$MTTF_{rs}$

Calculation of PSI index for states 1 and 4

In connection with the mentioned failure in states 1 and 4, the indicators of AFR, ASR, and FSI are calculated as follows (over 5 years):

Table 4 - Severity Index - Repeat for states 1 and 4 (FSI)

FSI	ASR	AFR	Useful working time	Lost working time	Lost working day	Number of accidents	State
0.57	13.75	24.01	178045.71	1954.29	19	11	1
1.1	43.75	91.15	172800	7200	70	35	4

Conclusion

In this study, a safety analysis model of industrial robots was developed based on the Markov chain. This model can be used alongside other safety analysis techniques in order to improve the robot safety level. Also, the developed model was implemented in Haierplast Company. The results testify that the probability that the robot was incapacitated as a result of an accident is close to zero. And the chance of failure in which the immune system did not work, in relation to the failures in which the robot immune system was incapacitated is higher with a difference of about 0.01. Further, the calculation of the indicators listed in FSI for failure states of 1 and 4, the diagram of transmission system for industrial robots is the proper measure of comparative studies. It can be noted that failures in which the robot immune system has been incapacitated can play an important role in safety assessment of industrial robots. Despite the fact that the number of these failures is lower than the ones in which the immune system has not been incapacitated as well as having allocated less amount of lost hours, their PSI index is approximately half of the amount of safe failures. On the other hand, according to Gerami and Rocky (2010), if the FSI index is less than 0.1 in a manufacturing unit during a year, the plant bears a relatively high level of safety [14]. Therefore, we can say that Haierplast production complex possesses a medium to high level of safety. For future research, it is suggested that the efficiency of the model compared to other safety analysis techniques. Also researchers can develop this model to another modern technologies, that is widely used today and with high sensitivity to the critical point, for example surgical robots, some devices based on artificial intelligence in Planes and some systems in nuclear industries.

In the end, we appreciate the efforts and cooperation of the respected staff of Haierplast Company.

REFERENCES

1. Hu, J. J., Huang C. N., Wang H. W., Shieh P. H. Safety-based human-robot collaboration in cellular manufacturing: A case study of power protector assembly. Advanced Robotics and Intelligent Systems (ARIS) international Conference; 2013.
2. Vicentini, F., Pedrocchi, N., Malosio, M., Tosatti, L. M. SafeNet: A methodology for integrating general-purpose unsafe devices in safe-robot rehabilitation systems. Computer Methods and Programs in Biomedicine; 2014.
3. Vick, A., Kruger, J. Safe Physical Human-Robot Interaction through Sensorless External Force Estimation for Industrial Robots. Communications in Computer and Information Science 374, 616-620; 2013.
4. Oberer, S., Schraft, R. D. Robot-Dummy Crash Tests for Robot Safety Assessment. IEEE International Conference on Robotics and Automation; 2007.
5. Haddadin, S., Schaffer, A. A., Hirzinger, G. Safety Evaluation of Physical Human-Robot Interaction via Crash-Testing. Robotics and Mechatronics international Conference; 2007.
6. Althoff, D., Kuffner, J. J., Wollherr, D., Buss, M. Safety assessment of robot trajectories for navigation in uncertain and dynamic environments. Autonomous Robots Journal; 2012.
7. Tan, J.T.C., Feng, D., Ye, Z., Kato, R. Safety design and development of human-robot collaboration in cellular manufacturing. Automation Science and Engineering international Conference; 2009.
8. Fryman, J., Matthias, B. Safety of Industrial Robots: From Conventional to Collaborative Applications. 7th German Conference on Robotics in Munich, Germany; 2012.
9. Matthias, B., Kock, S., Jerregard, H., Kallman, M., Lundberg, I., Mellander, R. Safety of collaborative industrial robots: Certification possibilities for a collaborative assembly robot concept. 2011 IEEE International Symposium on Assembly and Manufacturing (ISAM); 2011.
10. Augustsson, S. Human and Robot Interaction basedon safety zones in a shared work environment. University West publication; 2013.
11. Lacevic, B., Rocco, P., Zanchettin, A. M. Safety Assessment and Control of Robotic Manipulators Using Danger Field. Robotics, IEEE Transactions on (Volume:29); 2013.
12. Kimura, T., Okamoto, M., Oga, K., Okuda, S., Matsuda, T., Nagi, T., Hamada, S., Hata, Y., Tadokoro, S. Research on standardization, safety standards and competitiveness enhancement of special environment robots in Japan. Humanitarian Technology Conference; 2013.
13. Meyn, S., Tweedie, R. L. Markov chains and stochastic stability. Cambridge university press; 2009.
14. Gerami, F., Rocky, K. Safety Engineering with functional approach. Isfahan Jahad-Daneshgahi press; 2010.