PORT TRANSPORTATION CRITICAL INFRASTRUCTURE SAFETY AND OPERATION COST JOINT OPTIMIZATION

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Abstract

To analyze jointly the system safety and its operation cost optimization, we propose the procedure of determining the optimal values of limit transient probabilities of the system operation process at the particular operation states that allows to find maximal system safety indicators, through applying the system safety model and linear programing. Next, to find the system conditional operation total cost during the fixed operation time, corresponding to this system maximal safety indicators, we replace the limit transient probabilities, existing in the formula for the system operation total cost during the fixed operation time, by their optimal values existing in the formulae for the coordinates of the system safety function after maximization. The proposed procedure is applied to the port oil terminal critical infrastructure and to fulfill in practice the obtained terminal optimal safety and operation cost results, the modification of its operation process is proposed.

Keywords: safety, operation cost, optimization, port oil terminal, piping transport

I. Introduction

To tie the investigation of the complex technical system safety together with the investigation of its operation cost, the semi-Markov process model [6], [8], [10], [24], [26], [28], can be used to describe this system operation process [16], [19]. The system operation process model, under the assumption on the system safety multistate model [30], can be used to construct the general safety model of the complex multistate system changing its safety structure and its components safety parameters during variable operation conditions [12], [15], [19]. Further, using this general model, it is possible to define the complex system main safety characteristics such as the system safety function, the mean values and standard deviations of the system lifetimes in the system safety state subsets and in the system particular safety states [2], [13]-[14], [19] and other system safety indicators can be introduced as well [9], [21]-[23], [27]. Using the system general safety model, it is possible to change the system operation process through applying the linear programming [11] for maximizing the system safety function [19] and finding the optimal values of the system limit transient probabilities at the particular operation states. Having the system operation process characteristics and the system conditional instantaneous operation costs at the operation states, it is also possible to create the system general operation total cost model during the fixed operation time [16], [18]. To analyze jointly the system safety and its operation cost optimization, in the case we prefer more the system safety maximization than the system operation cost minimization, we first apply the procedure of determining the optimal values of limit transient probabilities of the system operation process at the particular operation states that maximize the system safety. Next, to find the system conditional operation total cost during the fixed operation time, corresponding to this system maximal safety, we replace the limit transient probabilities at particular operation states, existing in the formula for the operation total cost, by their optimal values existing in the formula for the system maximal safety function coordinates. Whereas, in the case we prefer more the system operation cost minimization than the system safety maximization, then to analyze jointly the system safety and operation cost optimization, we first apply the procedure of determining the optimal values of limit transient probabilities of the system operation process at the particular operation states that minimize the system operation total cost during the fixed operation time and next we find the system conditional safety indicators, corresponding to this system minimal total operation cost.

II. Port oil terminal critical infrastructure operation and safety

2.1. Terminal description

The port oil terminal placed at the Baltic seaside is designated for receiving oil products from ships, storage and sending them by carriages or trucks to inland and in reverse way as well [22]. The considered terminal is composed of three parts *A*, *B* and *C*, linked by the piping transportation system with the pier. The main technical assets (components) of the port oil terminal critical infrastructure are: A_1 – port oil piping transportation system, A_2 – internal pipeline technological system, A_3 – supporting pump station, A_4 – internal pump system, A_5 – port oil tanker shipment terminal, A_6 – loading railway carriage station, A_7 – loading road carriage station, A_8 – unloading railway carriage station, A_9 – oil storage reservoir system.

The asset A_1, the port oil piping transportation system operating at the port oil terminal critical infrastructure consists of three subsystems:

- the subsystem S_1 composed of two pipelines, each composed of 176 pipe segments and 2 valves,
- the subsystem S_2 composed of two pipelines, each composed of 717 pipe segments and 2 valves,
- the subsystem S_3 composed of three pipelines, each composed of 360 pipe segments and 2 valves.

The asset A_1 operation is the main activity of the port oil terminal involving the remaining assets A_2 – A_9. The port oil transportation system is a series system composed of two series-parallel subsystems S_1, S_2, each containing two pipelines and one series-"2 out of 3" subsystem S_3 containing 3 pipelines. The subsystems S_1, S_2 and S_3 are forming a general series port oil transportation system safety structure presented in Figure 1.

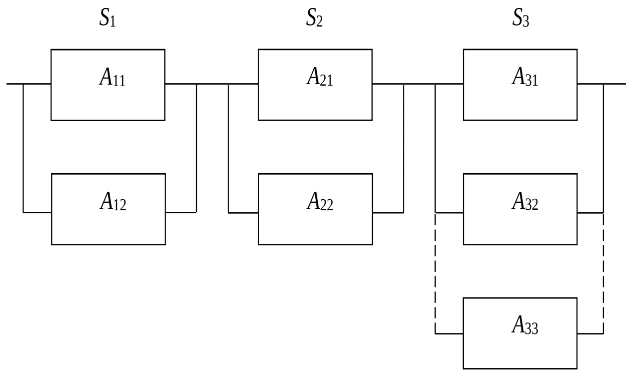

Figure 1: *The port oil piping transportation system safety structure*

2.2. Operation process

On the basis of the statistical data and expert opinions [7], it is possible to fix the port oil terminal critical infrastructure operation process number of operation states $\nu = 7$ and to define the following operation states [16]:

- the operation state z_1 – transport of one kind of medium from the terminal part B to part C using two out of three pipelines of the subsystem S_3 of the asset A_1 and assets A_2, A_4, A_6, A_7, A_9;
- the operation state z_2 – transport of one kind of medium from the terminal part C to part B using one out of three pipelines of the subsystem S_3 of the asset A_1 and assets A_2, A_4, A_8, A_9;
- the operation state z_3 – transport of one kind of medium from the terminal part B through part A to pier using one out of two pipelines of the subsystem S_1 and one out of two pipelines of the subsystem S_2 of the asset A_1 and assets A_2, A_4, A_5, A_9;
- the operation state z_4 – transport of one kind of medium from the pier through parts A and B to part C using one out of two pipelines of the subsystem S_1, one out of two pipelines in subsystem S_2 and two out of three pipelines of the subsystem S_3 of the asset A_1 and assets A_2, A_3, A_4, A_5, A_6, A_7, A_9;
- the operation state z_5 – transport of one kind of medium from the pier through part A to B using one out of two pipelines of the subsystem S_1 and one out of two pipelines of the subsystem S_2 of the asset A_1 and assets A_2, A_3, A_4, A_5, A_9;
- the operation state z_6 – transport of one kind of medium from the terminal part B to C using two out of three pipelines of the subsystem S_3, and simultaneously transport one kind of medium from the pier through part A to B using one out of two pipelines of the subsystem S_1 and one out of two pipelines of the subsystem S_2 of the asset A_1 and assets A_2, A_3, A_4, A_5, A_6, A_7, A_9;
- the operation state z_7 – transport of one kind of medium from the terminal part B to C using one out of three pipelines of the subsystem S_3, and simultaneously transport second kind of medium from the terminal part C to B using one out of three pipelines of the subsystem S_3 of the asset A_1 and assets A_2, A_4, A_6, A_7, A_8, A_9.

On the basis of the suitable statistical data coming from [7], it is possible to estimate the port oil terminal operation process characteristics [19]:

- the values of limit transient probabilities p_b, b = 1,2,…,7, at the particular operation states z_b, b = 1,2,…,7:

$$p_1 = 0.395,\ p_2 = 0.060,\ p_3 = 0.003,\ p_4 = 0.002,\ p_5 = 0.200,\ p_6 = 0.058,\ p_7 = 0.282; \tag{1}$$

- the expected values of the total sojourn times at the particular operation states z_b, b = 1,2,…,7, during the fixed operation time $\theta = 1$ year, expressed in days:

$$\hat{M}_1 = 144.175,\ \hat{M}_2 = 21.9,\ \hat{M}_3 = 1.095,\ \hat{M}_4 = 0.73,\ \hat{M}_5 \hat{M}_5 = 73, \hat{M}_6 = 21.17,\ \hat{M}_7\ \hat{M}_7 = 102.93. \tag{2}$$

Safety

We distinguish the following three safety states of the terminal and its components [16]:

- a safety state 2 – the components and the port oil terminal are fully safe,
- a safety state 1 – the components and the port oil terminal are less safe and more dangerous because of the possibility of environment pollution,
- a safety state 0 – the components and the port oil terminal are destroyed,

and we assume that there are possible the transitions between the components safety states only from better to worse ones.

After applying the procedure of the system safety maximization, we can get the optimal limit transient probabilities of the port oil terminal at the particular operation states [25]:

$$\dot{p}_1 = 0.46,\ \dot{p}_2 = 0.08,\ \dot{p}_3 = 0.002,\ \dot{p}_4 = 0.001,\ \dot{p}_5 = 0.15,\ \dot{p}_6 = 0.04,\ \dot{p}_7 = 0.267, \tag{3}$$

and the corresponding optimal safety function coordinates of the port oil terminal:

$$\dot{S}(t,1) = 0.46\exp[-0.12371t] + 0.08\exp[-0.12246t] + 0.002\exp[-0.131548t] + 0.001\exp[-0.146885t] + 0.15\exp[-0.131548t] + 0.04\exp[-0.146885t] + 0.267\exp[-0.12496t],\ t \geq 0, \quad (4)$$

$$\dot{S}(t,2) = 0.46\exp[-0.193913t] + 0.08\exp[-0.191913t] + 0.002\exp[-0.206087t] + 0.001\exp[-0.230261t] + 0.15\exp[-0.206087t] + 0.04\exp[-0.230261t] + 0.267\exp[-0.195913t],\ t \geq 0. \quad (5)$$

1. Port oil terminal critical infrastructure operation cost

The port oil terminal mean operation total cost during the operation time θ = 1 year is given by [16], [25]

$$\boldsymbol{\hat{C}}(\theta) \cong 0.395 \cdot 1553110.88 + 0.06 \cdot 268320.64 + 0.003 \cdot 58858.528 + 0.002 \cdot 90183.04 + 0.2 \cdot 130735.2 + 0.058 \cdot 655308.16 + 0.282 \cdot 1133107.008 \cong 1013630. \quad (6)$$

III. Joint system safety optimization and operation cost analysis

3.1. Port oil terminal operation cost corresponding to its maximal safety

To find, the system conditional operation total cost during the fixed operation time of one year, corresponding to the system maximal safety coordinates, we replace p_b, b = 1,2,…,7, given by (1) and existing in the formula (6) for the the system total operation cost, by $\dot{p}_b$, b = 1,2,…,7, given by (3) and existing in (4)-(5). This way, we get the port oil terminal conditional operation total cost during the fixed operation time of one year, corresponding to the system maximal safety coordinates, given by

$$\hat{C}(\theta)\ \hat{C}(\theta) \cong 0.46 \cdot 1503110.88 + 0.08 \cdot 268320.64 + 0.002 \cdot 58858.528 + 0.001 \cdot 90183.04 + 0.15 \cdot 130735.2 + 0.04 \cdot 655308.16 + 0.267 \cdot 1133107.008 \cong 1084467. \quad (7)$$

3.2. Discussion of results

Thus, if we prefer the high safety of the port oil terminal more than ensuring the terminal lower operation total cost, we can modify this system operation process through replacing approximately the limit transient probabilities at the operation states p_b, b = 1,2,…,7, at the particular operation states before the system safety maximization given by (1) by the values convergent to their optimal values $\dot{p}_b$, b = 1,2,…,7, after the terminal safety maximization given by (3). In practice, it is easier to modify the considered terminal operation process through replacing approximately the terminal total operation time mean values at the particular operation states during the fixed operation time of θ = 1 year, determined by (2) by their optimal values after the terminal safety maximization, determined according to the approximate formula from [17], after considering (3), given in days by:

$$\dot{\hat{M}}_1 = 167.9,\ \dot{\hat{M}}_2 = 29.2,\ \dot{\hat{M}}_3 = 0.73,\ \dot{\hat{M}}_4 = 0.365,\ \dot{\hat{M}}_5 = 54.75, \dot{\hat{M}}_6 = 14.6,\ \dot{\hat{M}}_7 = 97.455. \quad (8)$$

The procedure of the terminal operation process modification can be performed for other than the above fixed operation time of 1 year, dependently to the system operator comfort in the achievement of the best results of the system operation total times at the particular operation states convergence to their optimal values resulting from the performed system safety maximization.

IV. Conclusion

The proposed system safety and system operation cost optimization procedures can be used in safety and operation cost optimization of various real complex systems and critical infrastructures [9], [17], [23], [25]. Further research can be related to considering other impacts on the system safety and its operation cost, for instance a very important impact related to climate-weather factors [15], [20], [29] and resolving the issues of critical infrastructure [23] safety and operation cost optimization and discovering optimal values of safety, operation cost and resilience indicators of system impacted by the operation and climate-weather conditions [20]. These developments can also benefit the mitigation of critical infrastructure accident consequences [1], [3]-[5] and inside and outside dependences [14] and to minimize the system operation cost and to improve critical infrastructure resilience to operation and climate-weather conditions [15], [20], [29]. The proposed optimization procedures and perspective of future research can give practically important possibility of real systems effectiveness improvement through their new operation strategy application.

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