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# Safety analysis of the system of crude oil transhipment

**Keywords**

crude oil transfer system, system's safety, operation process, human factor, crude oil transhipment safety

**Abstract**

This chapter presents safety analysis of the crude oil transfer system that considers both its operation process and the human factor. The system's safety is highly influenced by tasks performed during the crude oil transfer process, thus, its conditional safety characteristics are determined for individual operational states, which correspond to performed tasks. Moreover, human error and mistakes during the transhipment operations at the terminal can significantly affect the process' safety. In light of this, the paper proposes an approach that allows for inclusion of the human factor in the system's safety analysis. Finally, the unconditional safety characteristics for the system are determined. Specifically, the mean values in safety states and safety states' subsets are compared when the human factor is both included and excluded. Results are presented for a crude oil transfer system consisting of one transhipment line and four transhipment lines.

## 1. Introduction

Continuous development of maritime transport, evolution of the port industry, and growth in global trade pose new organizational and logistical challenges for analysis and improvement of crude oil transhipment's safety. Specifically, prior research suggests the need for renewed analysis of the safety [18]–[19] of individual systems constituting links of the crude oil transport networks [14] and the safety of operations related to the human factor. For example, Fabiano et al. [11] investigate the impact that development of container transport, and related changes, had on port safety, in particular on safety performance of port activities. Presenting a statistical study of the human factor and occupational accidents, the authors analyse the relationship between work organization, job experience, productivity, and occupational accidents [11].

Severe consequences of a potential oil spill or leakage, which can result from accidents during the crude oil transfer [5]–[6], [13], motivate the importance of examination and analysis of crude oil transhipment process' safety. When analysing the safety of the crude oil transfer operations, it is important to consider both the technical condition of the system and the human participation in its operation. In this context, we analyse the crude oil transfer system as the man − technical object − environment system. As emphasized by the authors in [24], the inclusion of the operator's contribution to reliability and degradation analysis of the human − machine system is the primary purpose of human reliability analysis (HRA). More detailed literature review of human reliability analysis, defined as human performance, and methods of its assessment is presented at the beginning of Section 4.

This paper is organized as follows. Section 1 provides a brief introduction to the safety analysis of crude oil transhipment along with the motivation behind the developed here approach. Section 2 outlines the crude oil transfer process at the terminal. Section 3 presents the multistate approach to the system's safety analysis, description of the system and its components in the context of the presented approach, and the system's safety analysis, considering its operation process. Section 4 provides a brief literature review on the human factor analysis and presents the method used in this paper to include the human factor in the system's safety analysis. Sections 5 and 6 present the results of the safety

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analysis of crude oil transfer system considering both the human factor and the system's operating process. In Section 5, a crude oil transfer system consisting of a single loading line is analysed, while in Section 6, a system composed of four loading lines is analysed. Section 7 concludes this paper and proposes directions for further research.

## 2. Crude oil transfer system and its operation process

Below, we in turn characterize all operational states of the crude oil transfer process.

First, a tanker arrives at the oil terminal. The vessel has to be properly moored for cargo handling, and, throughout the entire duration of the cargo operations, its position has to be monitored and controlled. Moreover, in order to begin the oil transport process, the terminal's and the tanker's representatives have to discuss relevant technical and procedural issues.

A piping system line up agreement between the terminal and the tank farm, as well as between the terminal and the vessel is necessary to begin the crude oil loading process. The ship's manifold and the loading arms are then connected and the vessel can begin loading cargo from the terminal. This usually involves one to four arms.

Next, the lines are lined up by choosing dedicated tanks and pumps ashore and by opening and closing valves on relevant lines. At this point, one valve remains closed on each of terminal's loading arms. However, when tanker's readiness is confirmed, the remaining valves on marine loading arms open and the loading process begins. Initially, the transfer of crude oil proceeded at a slow rate. The oil ordinarily begins to flow due to gravity, but if necessary, pumps can be used to obtain the agreed upon initial rate. The initial loading rate is set to avoid creating static electricity inside the cargo tank and increase VOC (Volatile Organic Compounds) production. To avoid turbulent flow in an empty tank, the initial loading rate should be maintained until the last cargo tank is filled up to the drop line's level.

When results of the laboratory tests become available and tanks and pipes are checked against aberrations and leakages, the vessel sends to the terminal a signal indicating that the loading rate can be increased to the agreed upon maximum rate. This moment marks the start of loading cargo at full rate. Throughout the loading process, the infrastructure's integrity and all parameters have to be inspected, as the vessel must receive the cargo in accordance with the agreed upon parameters (pressure, temperature, loading rate). Vessels' tanks are customarily filled up to 95-98% of their capacity. "Topping off" is the final stage of the filling process. To avoid oil spills, at this stage, the loading rate is decreased to the maximum loading rate for a single cargo tank. When one tank is full, another tank opens to allow the cargo to flow inside. The topped off tank is then closed. When the last tank is topped off, the vessel sends information to the terminal to request pump stoppage and valve closure. In turn, the terminal confirms the stoppage request and the ship's manifold valves close. When loading lines' valves are closed on both the vessel's and the terminal's loading lines, cargo from pipelines is drained back to the shore's installation. The terminal then goes into the idle mode. Crude oil discharging/unloading follows a similar process. A piping system line up agreement between the terminal and the tank farm, as well as between the terminal and the vessel is necessary to begin the unloading process. The ship's manifold and the loading arms are then connected. The discharging process usually involves three arms. The line is lined up through the process of opening and closing relevant line's valves and choosing dedicated tanks and pumps on the ship. The unloading process begins when the readiness notice is circulated between the tank farm, the oil terminal, and the tanker. Loading arms' last valves are then opened and the ship's pumps facilitate the cargo's discharge at the initial rate. The initial discharging rate is set to allow for slow heaving up of the floating roof in shore cargo tanks and to leave enough volume slack to ensure the operation's safety. All cargo tanks are filled only up to 95% of their volume's capacity.

If no challenges arise and the tanker receives confirmation from the terminal, the vessel increases unloading rate to agreed maximum rate. The unloading process then continues at the full bulk discharging rate. Throughout the discharging, the infrastructure's integrity and all parameters have to be continuously inspected. Finally, at the final stage, the crude oil is discharged at a reduced rate, and the tanker finishes unloading the cargo by stripping all cargo tanks one by one.

During bulk discharging or at the end of the cargo's transfer, cargo tanks are washed with the crude oil itself to remove the residue. This process is known as COW (Crude Oil Washing). Then, the pumps stop, relevant valves are closed and the stripping operation begins. All liquids from the cargo tanks are collected in the Slop tank. Following internal stripping, residue cargo, which has remained in the Slop tank, bypasses the tanker's main lines and is transferred directly to the loading arm through the dedicated SD (Small Diameter) line. Once this process is complete, the loading arms are disconnected. A piping system line up agreement between tank farm and terminal has to be established to begin the internal recirculation process. Relevant valves are opened or closed; with one valve on each tank still remaining closed. After confirming readiness of both the terminal and the tank farm, the valves on dedicated tanks are opened and the recirculation by gravity begins. Next, relevant checks against line integrity and aberrations are made and cargo pumps start. During recirculation, infrastructure integrity and all parameters have to be continuously inspected. When the process of recirculation is finished, the pumps stop and the line valves close. When the terminal is in an idle mode, there is no transfer of cargo, however cargo is still inside shore pipelines [8]–[9].

In safety analysis of the crude oil transfer system, we have distinguished nine operational states $z_b$, $b = 1,2,\ldots,9$, related to different tasks performed by the system. The operation process of the crude oil transfer has an influence on safety of the oil terminal and the environment. These operational states are defined by various system tasks as follows [8]:

- $z_1$ – loading cargo with initially slow rate,
- $z_2$ – laboratory tests of exported crude oil,
- $z_3$ – loading cargo with full rate,
- $z_4$ – loading cargo with reduced rate,
- $z_5$ – unloading cargo with initially slow rate,
- $z_6$ – unloading cargo with full rate,
- $z_7$ – unloading cargo with reduced rate,
- $z_8$ – terminal idle mode, there is no transfer of cargo,
- $z_9$ – internal recirculation process.

From statistical identification of the system operation process, presented in details in [9], the limit transient probabilities $p_b$ of system being in operational states $z_b$, $b = 1,2,\ldots,9$, are determined

$$p_1 = 0.0034,\ \ p_2 = 0.0347,\ \ p_3 = 0.0818,$$
$$p_4 = 0.0021,\ \ p_5 = 0.0060,\ \ p_6 = 0.1433,$$
$$p_7 = 0.0043,\ \ p_8 = 0.7052,\ \ p_9 = 0.0192. \tag{1}$$

## 3. Safety analysis of the crude oil transfer system taking into account its operation process

Applying multistate approach to system's safety analysis [16], [21]-[22], we distinguish various safety states $u$, $u = 0,1,\ldots,\omega$, of a system and its components. The states degrades over time from the best state, denoted by $\omega$, to the worst state 0 in a safety sense. Subsequently, the conditional safety function of a system at operational state $z_b$, $b = 1,2,\ldots,v$, (here $v = 9$) is defined as a vector [16]

$$[\boldsymbol{S}(t,\cdot)]^{(b)} = \left[[\boldsymbol{S}(t,0)]^{(b)}, [\boldsymbol{S}(t,1)]^{(b)}, \ldots, [\boldsymbol{S}(t,\omega)]^{(b)}\right],$$
$$t \ge 0,\ b = 1,2,\ldots,v, \tag{2}$$

where its coordinate $[\boldsymbol{S}(t,u)]^{(b)}$ is defines as the probability that system is in the safety state subset $\{u,u+1,\ldots,\omega\}$, $u = 0,1,\ldots,\omega$, at the moment $t$, while it was in the safety state $\omega$ at the moment $t = 0$, i.e.

$$[\boldsymbol{S}(t,u)]^{(b)} = P(\boldsymbol{T}^{(b)}(u) > t),\ t \ge 0,\ u = 1,2,\ldots,\omega \tag{3}$$

where $\boldsymbol{T}^{(b)}(u)$ is a random variable representing the lifetime in safety state subset $\{u,u+1,\ldots,\omega\}$, $u = 0,1,\ldots,\omega$, of a system at operational state $z_b$, $b = 1,2,\ldots,v$.

Further, by (3), we replace $[\boldsymbol{S}(t,0)]^{(b)} = P(\boldsymbol{T}^{(b)}(0) > t)$, existing in (2), by 1.

In the safety analysis of the system of crude oil transfer in a port terminal, the following components have been distinguished: pipelines, pumps, outer and inner loading arms, valves, pipeline welds. Further, in the safety analysis of this system, they are considered as basic components. It is assumed that safety states of the system and its components are differently defined depending on the type of element and the specificity of its failure. Namely, there have been distinguished four safety states for pipelines and pipeline weldments, three safety states for outer and inner loading arms, two safety states for pumps and valves, and finally three safety states for the system of crude oil transfer. These safety states are described below in details. Based on approximate mean values of the components' lifetimes in safety states, obtained from experts exploiting the system, the failure rates of these components are estimated. The evaluated failure rates for two-state components and the intensities of departures from the safety state subsets for multistate components, are used in further safety analysis of the system as parameters of the components' exponential functions.

During crude oil loading the cargo, movement from storage tanks (oil reservoir on the wharf) through the pipeline system to tanks on a tanker takes place, during discharging the process is reversed. The scheme of crude oil transfer in the oil port terminal is given in *Figure 1*.

The system has the same structure in all operational states. For each of system components the safety parameters are given depending on performed tasks and operational state.

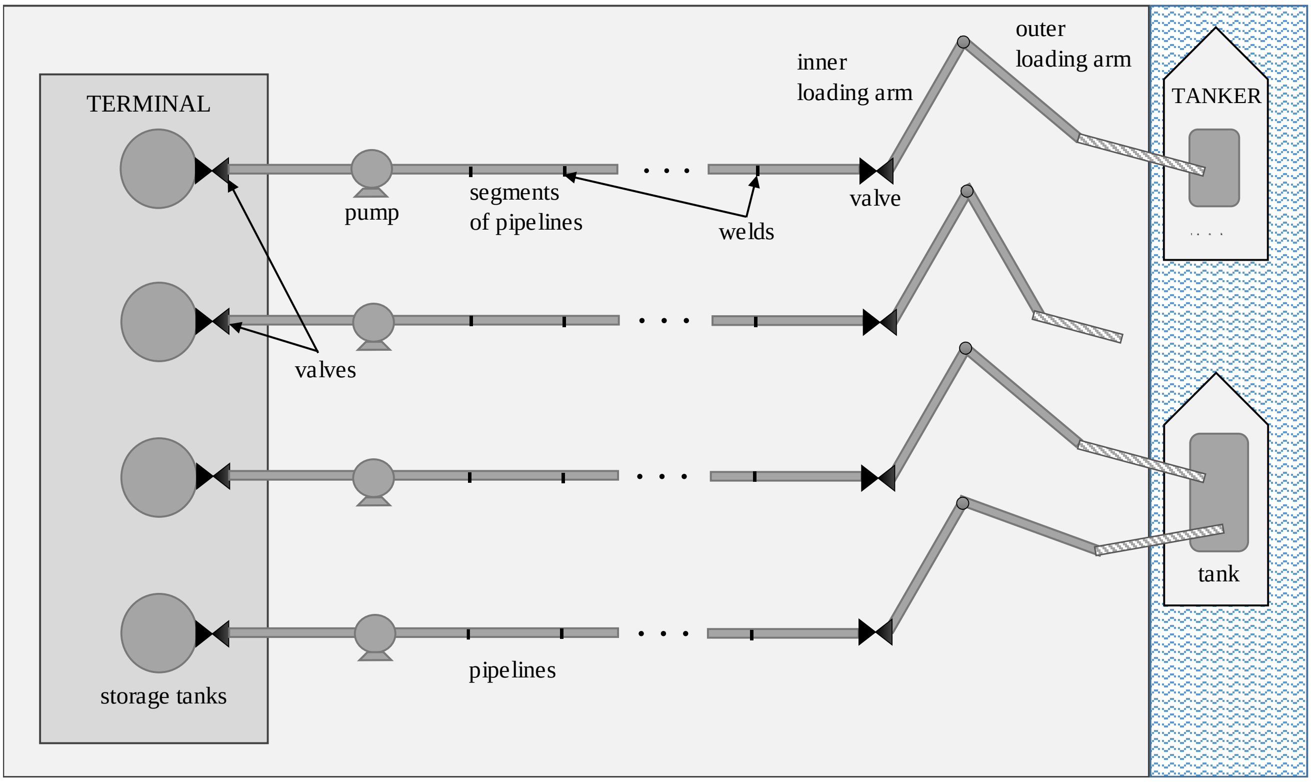


*Figure 1.* A scheme of crude oil transfer in the oil port terminal [9]

We assume that systems *S*, is composed of multistate components, with the safety functions given below.
For a component $E_1$ i.e. a valve, two following safety states are distinguished:

- state 1 – a valve is working properly without any defects,
- state 0 – a valve is failed.

Moreover, we assume that component $E_1$ has the conditional safety function at the operation state $z_b$, $b$ = 1,2,…,9, given by the vector

$$[S_1(t,\cdot)]^{(b)} = [1,[S_1(t,1)]^{(b)}],\ t \geq 0,\ \ b = 1,2,\ldots,9, \qquad (4)$$

with following exponential conditional safety function coordinates at the operational state $z_1$:

$$[S_1(t,1)]^{(b)} = \exp[-0.0333t],\ t \geq 0,\ b = 1, \qquad (5)$$

at the operational state $z_4$:

$$[S_1(t,1)]^{(b)} = \exp[-0.05t],\ t \geq 0,\ b = 4, \qquad (6)$$

and at the other operational states $z_2$, $z_3$, $z_5$, $z_6$, $z_7$, $z_8$ and $z_9$:

$$[S_1(t,1)]^{(b)} = \exp[-0.025t],\ t \geq 0,$$
$$b = 2,3,5,6,7,8,9. \qquad (7)$$

For a component $E_2$ i.e. a pipeline or a pipe segment, four safety states are distinguished:

- state 3 – a pipeline is new or after conservation with an anti-corrosion coating thickness of 100-330 μm (over 100 micrometres), pipeline without traces of corrosion,
- state 2 – a pipeline partially coated with the anti-corrosion coating (coating thickness less than 100 μm), corrosion losses of pipeline walls not exceeding 10% of the nominal wall thickness,
- state 1 – corrosion losses of pipeline walls not exceeding 30% of the nominal wall thickness,
- state 0 – corrosion losses of pipeline walls exceeding 30% of the nominal wall thickness, a pipeline is corroded and unusable.

Component $E_2$ has the conditional safety function at the operation state $z_b$, $b$ = 1,2,…,9,

$$[S_2(t,\cdot)]^{(b)} = [1,[S_2(t,1)]^{(b)},[S_2(t,2)]^{(b)},[S_2(t,3)]^{(b)}],$$
$$t \geq 0,\ \ b = 1,2,\ldots,9, \qquad (8)$$

where its coordinates are identical in all operational states and are given by:

$$[S_2(t,1)]^{(b)} = \exp[-0.0167t],$$
$$[S_2(t,2)]^{(b)} = \exp[-0.0333t],$$
$$[S_2(t,3)]^{(b)} = \exp[-0.0667t],\ t \geq 0,\ \ b = 1,2,...,9. \qquad (9)$$

For a component $E_3$ i.e. a pump, two following safety states are distinguished:

- state 1 – a pump is working properly without any defects,
- state 0 – a pump is failed.

Component $E_3$ has the conditional safety function at the operation state $z_b$, $b = 1,2,\ldots,9$, given by the vector

$$[S_3(t,\cdot)]^{(b)} = [1,[S_3(t,1)]^{(b)}],\ t \geq 0,\ b = 1,2,\ldots,9, \quad (10)$$

with following exponential coordinates at the operational states $z_1$, $z_5$ and $z_9$:

$$[S_3(t,1)]^{(b)} = \exp[-0.125t],\ t \geq 0,\ b = 1,5,9, \quad (11)$$

at the operational states $z_2$, $z_4$, $z_7$ and $z_8$:

$$[S_3(t,1)]^{(b)} = \exp[-0.1t],\ t \geq 0,\ b = 2,4,7,8, \quad (12)$$

at the operational states $z_3$ and $z_6$:

$$[S_3(t,1)]^{(b)} = \exp[-0.1667t],\ t \geq 0,\ b = 3,6. \quad (13)$$

For a component $E_4$ i.e. a pipeline or a pipe segment, four safety states have been distinguished:

- state 3 – a pipeline is new or after conservation with an anti-corrosion coating thickness of 100-330 μm (over 100 micrometres), pipeline without traces of corrosion,
- state 2 – a pipeline partially coated with the anti-corrosion coating (coating thickness less than 100 μm), corrosion losses of pipeline walls not exceeding 10% of the nominal wall thickness,
- state 1 – corrosion losses of pipeline walls not exceeding 30% of the nominal wall thickness,
- state 0 – corrosion losses of pipeline walls exceeding 30% of the nominal wall thickness, a pipeline is corroded and unusable.

Component $E_4$ has the conditional safety function at the operation state $z_b$, $b = 1,2,\ldots,9$, given by

$$[S_4(t,\cdot)]^{(b)} = [1,[S_4(t,1)]^{(b)},[S_4(t,2)]^{(b)},[S_4(t,3)]^{(b)}],$$
$$t \geq 0,\ b = 1,2,\ldots,9, \quad (14)$$

where its coordinates are identical in all operational states given by:

$$[S_4(t,1)]^{(b)} = \exp[-0.0167t],$$
$$[S_4(t,2)]^{(b)} = \exp[-0.0333t],$$
$$[S_4(t,3)]^{(b)} = \exp[-0.0667t],\ t \geq 0,\ b = 1,2,\ldots,9. \quad (15)$$

For a component $E_5$ i.e. a weld (weldments), four safety states are distinguished:

- state 3 – a weld is new or after conservation, a leak test has been performed,
- state 2 – welded structures are changed however no leaks are detected, pitting corrosion in pipeline weld zones not exceeding 10% of the nominal wall thickness,
- state 1 – advanced corrosion in pipeline weld zones, however no leaks are detected,
- state 0 – detected failure of a weld, including corrosion failures, loss of leak tightness on the weld.

Component $E_5$ has the conditional safety function at the operation state $z_b$, $b = 1,2,\ldots,9$, given by the vector

$$[S_5(t,\cdot)]^{(b)} = [1,[S_5(t,1)]^{(b)},[S_5(t,2)]^{(b)},[S_5(t,3)]^{(b)}],$$
$$t \geq 0,\ b = 1,2,\ldots,9, \quad (16)$$

where its coordinates are exponential functions and at the operational states $z_1$, $z_5$ and $z_9$ are given by:

$$[S_5(t,1)]^{(b)} = \exp[-0.0667t],$$
$$[S_5(t,2)]^{(b)} = \exp[-0.1t],$$
$$[S_5(t,3)]^{(b)} = \exp[-0.2t],\ t \geq 0,\ b = 1,5,9, \quad (17)$$

at the operational states $z_2$ and $z_8$:

$$[S_5(t,1)]^{(b)} = \exp[-0.04t],$$
$$[S_5(t,2)]^{(b)} = \exp[-0.05t],$$
$$[S_5(t,3)]^{(b)} = \exp[-0.1t],\ t \geq 0,\ b = 2,8, \quad (18)$$

at the operational states $z_3$ and $z_6$:

$$[S_5(t,1)]^{(b)} = \exp[-0.1t],$$
$$[S_5(t,2)]^{(b)} = \exp[-0.1667t],$$
$$[S_5(t,3)]^{(b)} = \exp[-0.3333t],\ t \geq 0,\ b = 3,6, \quad (19)$$

at the operational states $z_4$ and $z_7$:

$$[S_5(t,1)]^{(b)} = \exp[-0.0833t],$$
$$[S_5(t,2)]^{(b)} = \exp[-0.125t],$$
$$[S_5(t,3)]^{(b)} = \exp[-0.25t],\ t \geq 0,\ b = 4,7. \quad (20)$$

For a component $E_6$ i.e. a valve, two following safety states are distinguished:

- state 1 – a valve is working properly without any defects,
- state 0 – a valve is failed/ is leaking.

Component $E_6$ has the conditional safety function at the operation state $z_b$, $b = 1,2,\ldots,9$, given by the vector

$$[S_6(t,\cdot)]^{(b)} = [1,[S_6(t,1)]^{(b)}],\ t \geq 0,\ b = 1,2,...,9, \quad (21)$$

with following exponential coordinates at the operational states $z_1$, $z_2$, $z_3$, $z_4$, $z_5$, $z_6$ and $z_7$:

$$[S_6(t,1)]^{(b)} = \exp[-0.0667t],\ t \geq 0,$$
$$b = 1,2,3,4,5,6,7, \quad (22)$$

at the operational states $z_8$ and $z_9$:

$$[S_6(t,1)]^{(b)} = \exp[-0.125t],\ t \geq 0,\ b = 8,9. \quad (23)$$

For a component $E_7$ i.e. an inner or outer loading arm (outboard, inboard arms), three safety states are distinguished:

- state 2 – a loading arm is new or after conservation, a leak test has been performed, loading arm has been inspected confirming its proper functioning, and that there are no leaks,
- state 1 – traces of fatigue in a loading arm material, corrosion of loading arm walls not exceeding 30% of the nominal wall thickness, loading arm has been inspected confirming its proper functioning, and that there are no leaks,
- state 0 – a loading arm is failed, loss of leak tightness of a loading arm.

Component $E_7$ has the conditional safety function at the operation state $z_b$, $b = 1,2,\ldots,9$, given by the vector

$$[S_7(t,\cdot)]^{(b)} = [1,[S_7(t,1)]^{(b)},[S_7(t,2)]^{(b)}],\ t \geq 0,$$
$$b = 1,2,\ldots,9, \quad (24)$$

where its coordinates are exponential functions and at the operational states $z_1$ and $z_5$ are:

$$[S_7(t,1)]^{(b)} = \exp[-0.0667t],$$
$$[S_7(t,2)]^{(b)} = \exp[-0.125t],\ t \geq 0,\ b = 1,5, \quad (25)$$

at the operational states $z_2$, $z_8$ and $z_9$:

$$[S_7(t,1)]^{(b)} = \exp[-0.05t],$$
$$[S_7(t,2)]^{(b)} = \exp[-0.1t],\ t \geq 0,\ b = 2,8,9, \quad (26)$$

at the operational states $z_3$ and $z_6$:

$$[S_7(t,1)]^{(b)} = \exp[-0.1t],$$
$$[S_7(t,2)]^{(b)} = \exp[-0.2t],\ t \geq 0,\ b = 3,6, \quad (27)$$

at the operational states $z_4$ and $z_7$:

$$[S_7(t,1)]^{(b)} = \exp[-0.0833t],$$
$$[S_7(t,2)]^{(b)} = \exp[-0.1667t],\ t \geq 0,\ b = 4,7. \quad (28)$$

For a component $E_8$ i.e. a valve, two following safety states are distinguished:

- state 1 – a valve is working properly without any defects,
- state 0 – a valve is failed.

Component $E_8$ has the conditional safety function at the operation state $z_b$, $b = 1,2,\ldots,9$, given by the vector

$$[S_8(t,\cdot)]^{(b)} = [1,[S_8(t,1)]^{(b)}],\ t \geq 0,\ b = 1,2,\ldots,9, \quad (29)$$

with following exponential coordinates at the operational states $z_1$, $z_2$ and $z_4$:

$$[S_8(t,1)]^{(b)} = \exp[-0.1667t],\ t \geq 0,\ b = 1,2,4, \quad (30)$$

at the operational states $z_3$ and $z_6$:

$$[S_8(t,1)]^{(b)} = \exp[-0.1t],\ t \geq 0,\ b = 3,6, \quad (31)$$

at the operational states $z_5$ and $z_7$:

$$[S_8(t,1)]^{(b)} = \exp[-0.125t],\ t \geq 0,\ b = 5,7, \quad (32)$$

at the operational states $z_8$ and $z_9$:

$$[S_8(t,1)]^{(b)} = \exp[-0.0667t],\ t \geq 0,\ b = 8,9. \quad (33)$$

We distinguish following four safety states of the crude oil transfer system, concerned with the states of its components [7], [9]:

- state 3 – the system is in very good condition and it has been inspected confirming its proper functioning, all its components are in the best safety states,
- state 2 – the system is in good condition and is usable, the system has been inspected confirming its proper functioning, and that there are no leaks, (it means that situation in which the multistate components are in state 2 or in state better than 2, but not all i.e. the system is not in the state 3),
- state 1 – the system is in good condition and is usable, no significant traces of corrosion of system components, there are no leaks during oil transfer, (it includes situation in which at least one of the multistate components is in state 1),

- state 0 – the system is not usable if at least one of its components is failed and not serviceable i.e. the component is in the state 0, for example loss of leak tightness has been detected.

Next, the conditional safety function of system in each operational state is determined.

While analysing the crude oil transfer system consisting of a single transhipment line composed of the components $E_1$, $E_2$, $E_3$, $E_4$, $E_5$, $E_6$, $E_7$, $E_8$, described earlier in this Section, we conclude that all its components must be operational so that the system can transfer crude oil. Thereby, we analyse the oil transfer system, consisting of one transhipment line, as a multistate series system. The conditional safety function of the system at operation state $z_b$, $b = 1,2,\dots,9$, is the vector [7], [9]

$$[\boldsymbol{S}(t,\cdot)]^{(b)} = [1,[\boldsymbol{S}(t,1)]^{(b)},[\boldsymbol{S}(t,2)]^{(b)},[\boldsymbol{S}(t,3)]^{(b)}],$$
$$t \ge 0,\ b = 1,2,\dots,9, \tag{34}$$

with coordinates determined from formulae:

$$[\boldsymbol{S}(t,1)]^{(b)} = \prod_{i=1}^{8}[S_i(t,1)]^{(b)},\ t \ge 0,\ b = 1,2,\dots,9, \tag{35}$$

$$[\boldsymbol{S}(t,2)]^{(b)} = [S_1(t,1)]^{(b)} \cdot [S_2(t,2)]^{(b)} \cdot [S_3(t,1)]^{(b)}$$
$$\cdot [S_4(t,2)]^{(b)} \cdot [S_5(t,2)]^{(b)} \cdot [S_6(t,1)]^{(b)}$$
$$\cdot [S_7(t,2)]^{(b)} \cdot [S_8(t,1)]^{(b)}\ t \ge 0,\ b = 1,2,\dots,9, \tag{36}$$

$$[\boldsymbol{S}(t,3)]^{(b)} = [S_1(t,1)]^{(b)} \cdot [S_2(t,3)]^{(b)} \cdot [S_3(t,1)]^{(b)}$$
$$\cdot [S_4(t,3)]^{(b)} \cdot [S_5(t,3)]^{(b)} \cdot [S_6(t,1)]^{(b)}$$
$$\cdot [S_7(t,2)]^{(b)} \cdot [S_8(t,1)]^{(b)}\ t \ge 0,\ b = 1,2,\dots,9. \tag{37}$$

Consequently, assuming that system components have exponential conditional safety functions described by formulae (4)-(33), the coordinates given by (35)-(37) take following form at particular operation states:

- at the operational state $z_1$:

$$[\boldsymbol{S}(t,1)]^{(1)} = \exp[-0.5585t],\ t \ge 0, \tag{38}$$

$$[\boldsymbol{S}(t,2)]^{(1)} = \exp[-0.6833t],\ t \ge 0, \tag{39}$$

$$[\boldsymbol{S}(t,3)]^{(1)} = \exp[-0.8501t],\ t \ge 0, \tag{40}$$

- at the operational state $z_2$:

$$[\boldsymbol{S}(t,1)]^{(2)} = \exp[-0.4818t],\ t \ge 0, \tag{41}$$

$$[\boldsymbol{S}(t,2)]^{(2)} = \exp[-0.5750t],\ t \ge 0, \tag{42}$$

$$[\boldsymbol{S}(t,3)]^{(2)} = \exp[-0.6918t],\ t \ge 0, \tag{43}$$

- at the operational state $z_3$:

$$[\boldsymbol{S}(t,1)]^{(3)} = \exp[-0.5918t],\ t \ge 0, \tag{44}$$

$$[\boldsymbol{S}(t,2)]^{(3)} = \exp[-0.7917t],\ t \ge 0, \tag{45}$$

$$[\boldsymbol{S}(t,3)]^{(3)} = \exp[-1.0251t],\ t \ge 0, \tag{46}$$

- at the operational state $z_4$:

$$[\boldsymbol{S}(t,1)]^{(4)} = \exp[-0.5834t],\ t \ge 0, \tag{47}$$

$$[\boldsymbol{S}(t,2)]^{(4)} = \exp[-0.7417t],\ t \ge 0, \tag{48}$$

$$[\boldsymbol{S}(t,3)]^{(4)} = \exp[-0.9335t],\ t \ge 0, \tag{49}$$

- at the operational state $z_5$:

$$[\boldsymbol{S}(t,1)]^{(5)} = \exp[-0.5085t],\ t \ge 0, \tag{50}$$

$$[\boldsymbol{S}(t,2)]^{(5)} = \exp[-0.6333t],\ t \ge 0, \tag{51}$$

$$[\boldsymbol{S}(t,3)]^{(5)} = \exp[-0.8001t],\ t \ge 0, \tag{52}$$

- at the operational state $z_6$:

$$[\boldsymbol{S}(t,1)]^{(6)} = \exp[-0.5918t],\ t \ge 0, \tag{53}$$

$$[\boldsymbol{S}(t,2)]^{(6)} = \exp[-0.7917t],\ t \ge 0, \tag{54}$$

$$[\boldsymbol{S}(t,3)]^{(6)} = \exp[-1.0251t],\ t \ge 0, \tag{55}$$

- at the operational state $z_7$:

$$[\boldsymbol{S}(t,1)]^{(7)} = \exp[-0.4042t],\ t \ge 0, \tag{56}$$

$$[\boldsymbol{S}(t,2)]^{(7)} = \exp[-0.5625t],\ t \ge 0, \tag{57}$$

$$[\boldsymbol{S}(t,3)]^{(7)} = \exp[-0.7543t],\ t \ge 0, \tag{58}$$

- at the operational state $z_8$:

$$[\boldsymbol{S}(t,1)]^{(8)} = \exp[-0.4401t],\ t \ge 0, \tag{59}$$

$$[\boldsymbol{S}(t,2)]^{(8)} = \exp[-0.5333t],\ t \ge 0, \tag{60}$$

$$[\boldsymbol{S}(t,3)]^{(8)} = \exp[-0.6501t],\ t \ge 0, \tag{61}$$

- and at the operational state $z_9$:

$$[\boldsymbol{S}(t,1)]^{(9)} = \exp[-0.4918t],\ t \ge 0, \tag{62}$$

$$[\boldsymbol{S}(t,2)]^{(9)} = \exp[-0.6083t],\ t \ge 0, \tag{63}$$

$$[\boldsymbol{S}(t,3)]^{(9)} = \exp[-0.7751t],\ t \ge 0. \tag{64}$$

Using the conditional safety functions of crude oil transfer system, given by (38)-(64), the mean values $\boldsymbol{\mu}^{(b)}(1)$, $\boldsymbol{\mu}^{(b)}(2)$, $\boldsymbol{\mu}^{(b)}(3)$ of system conditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3} respectively, are determined. Their values counted in years, for the system consisting of one transhipment line at operational states $z_b$, $b = 1,2,\ldots,9$ are presented in *Table 1*.

*Table 1.* The mean values of conditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3}, of the system at operational states $z_b$, $b = 1,2,\ldots,9$ (in years)

| operational state $z_b$ | $\boldsymbol{\mu}^{(b)}(1)$ | $\boldsymbol{\mu}^{(b)}(2)$ | $\boldsymbol{\mu}^{(b)}(3)$ |
|---|---|---|---|
| $z_1$ | 1.791 | 1.463 | 1.176 |
| $z_2$ | 2.076 | 1.739 | 1.446 |
| $z_3$ | 1.690 | 1.263 | 0.976 |
| $z_4$ | 1.714 | 1.348 | 1.071 |
| $z_5$ | 1.967 | 1.579 | 1.250 |
| $z_6$ | 1.690 | 1.263 | 0.976 |
| $z_7$ | 2.474 | 1.778 | 1.326 |
| $z_8$ | 2.272 | 1.875 | 1.538 |
| $z_9$ | 2.033 | 1.644 | 1.290 |

From results presented in *Table 1* we conclude that mean conditional lifetimes of crude oil transfer system in safety state subsets are the shortest in operating states $z_3$ and $z_6$, and then in operating states $z_1$ and $z_4$. These are states related to crude oil transhipment with full or reduced rate. In these states, some components are heavily exploited, such as pumps during the full rate transfer or valves during reduced rate transfer of crude oil.

## 4. Human errors in crude oil transhipment process and their influence on the system safety

One of the fundamental methods used to assess the probability of human error while performing operations is cognitive reliability and error analysis method (CREAM) developed by Hollnagel [15]. This method is widely used for human reliability analysis across the literature. Some examples include studies of the tanker shipping industry [24], cargo operations [2]‒[3] and, more generally, marine engineering operations [4]. Yang et al. [23] present a modified CREAM for quantifying human failures in maritime engineering by incorporating fuzzy logic, evidential reasoning, and Bayesian network techniques. The authors [23] use the proposed method to assess human reliability during oil tanker’s cargo pumps shutdown scenarios. Akyuz [1] proposes quantified CREAM method to estimate human error probability (HEP), and thus to assess the risk of human error during the gas inerting operation of crude oil tankers. Ung [20] presents a weighted CREAM for maritime human reliability analysis and validates the proposed method through an oil tanker example, where he assesses human failure probability of discharging crude oil at the terminal.

Human errors in the crude oil transhipment process and human reliability analysis can affect the safety of the crude oil transfer system in no lesser way than the safety analysis of the technical system. This is evident in the Fault Tree Analysis (FTA) and FTA diagram for oil spill scenario in a port oil terminal, presented in [7]. Further, Fuentes-Bargues et al. [12] emphasize the significance of the human factor in a potential leak or fuel spill scenario in their risk analysis of a fuel storage terminal. Similarly, Chang and Lin in [10] present a study of storage tank accidents and conclude that one of the most common operational errors is overfilling.

Thus, the safety analysis of the crude oil transhipment process performed in this paper includes both the human factor and the technical system. Because detailed information on accidents and possible human errors or negligence, which may contribute to these accidents, as well as more detailed conditions and circumstances affecting human performance failure are unknown or undisclosed, detailed human reliability analysis

using CREAM is not possible. Therefore, this article proposes a simplified method.
We express human factor related to human errors and mistakes made during crude oil transfer and during the operation of the system in general. We assume the system is observed in $\Delta T$ time, and $Q_{he}(\Delta T)$ denotes the human factor related to human error during $\Delta T$ time of system operation, where $0 \le Q_{he}(\Delta T) \le 1$. We estimate the human factor $Q_{he}(\Delta T)$ from the following formula

$$Q_{he}(\Delta T) = \frac{\sum_{i=1}^{n_e(\Delta T)} e_i \cdot w_i}{n_{op}(\Delta T)}, \tag{65}$$

where:
$n_{op}(\Delta T)$ − number of transhipment operations realized during $\Delta T$ time of system exploitation,
$n_e(\Delta T)$ − number of human errors during $\Delta T$ time of system exploitation,
$e_i$ − $i$-th human error, $i = 1,\ldots,n_e(\Delta T)$,
$w_i$ − weight of $i$-th human error $e_i$, $i = 1,\ldots,n_e(\Delta T)$, where $0 \le w_i \le 1$, $i = 1,\ldots,n_e(\Delta T)$.
It is assumed that during one crude oil transhipment operation, only one human error can occur. If a human error has wide ramifications or it is concerned with other human errors or mistakes, then its weight is greater ranging from 0 to 1.
To take into account the human factor in safety analysis of crude oil transhipment process, we assume that it influences the intensity of system departure from the safety state subsets. More exactly, we assume that the intensity of system departure from the safety state subset $\{u,u+1,...,\omega\}$ including human factor is given by the following formula

$$\lambda_{he}(t,u) = \lambda(t,u) \cdot \left(1 + Q_{he}(\Delta T)\right),\ t \ge 0,$$
$$u = 1,2,...,\omega, \tag{66}$$

where $\lambda(t,u)$ denotes the intensity of system departure from the safety state subset $\{u,u+1,...,\omega\}$, $u = 1,2,...,\omega$, without human factor. We assume that human factor, defined by (65), is the same in all safety states $u = 1,2,...,\omega$.

## 5. Safety analysis of the crude oil transfer including human errors and system operation process

One of the system safety characteristics is the intensity of departure from the subsets of safety states $\{u,u+1,...,\omega\}$, $u = 1,2,...,\omega$, determined by the formula

$$\boldsymbol{\lambda}(t,u) = \frac{\boldsymbol{f}(t,u)}{\boldsymbol{S}(t,u)},\ t \ge 0,\ u = 1,2,...,\omega, \tag{67}$$

where $\boldsymbol{f}(t,u)$ denotes the coordinate of a system density function and $\boldsymbol{S}(t,u)$ is the coordinate of a system safety function.
Taking into account operational states and different tasks of a system, we can determine the intensity of departure from the subsets of safety states $\{u,u+1,...,\omega\}$, $u = 1,2,...,\omega$, of a system at operational state $z_b$, $b = 1,2,\ldots,v$,

$$[\boldsymbol{\lambda}(t,u)]^{(b)} = \frac{[\boldsymbol{f}(t,u)]^{(b)}}{[\boldsymbol{S}(t,u)]^{(b)}},\ t \ge 0,\ u = 1,2,...,\omega, \tag{68}$$

where $[\boldsymbol{f}(t,u)]^{(b)}$ denotes the coordinate of conditional density function of a system at operational state $z_b$, $b = 1,2,\ldots,v$, that is determined as follows

$$[\boldsymbol{f}(t,u)]^{(b)} = \frac{d}{dt}\left(-[\boldsymbol{S}(t,u)]^{(b)}\right),\ t \ge 0,$$
$$u = 1,2,...,\omega,\ b = 1,2,\ldots,v. \tag{69}$$

Applying (69), the coordinates of conditional density function of a system at operational state $z_b$, $b = 1,2,\ldots,9$, are determined. For the coordinates of conditional safety function of crude oil transfer system at the state $z_1$, given by (38)-(40), they take form

$$[\boldsymbol{f}(t,1)]^{(1)} = 0.5585 \cdot \exp[-0.5585t],\ t \ge 0, \tag{70}$$

$$[\boldsymbol{f}(t,2)]^{(1)} = 0.6833 \cdot \exp[-0.6833t],\ t \ge 0, \tag{71}$$

$$[\boldsymbol{f}(t,3)]^{(1)} = 0.8501 \cdot \exp[-0.8501t],\ t \ge 0. \tag{72}$$

Similarly, the coordinates of conditional density function of a system at other operational states are determined. And next, we find using formula (68), the intensities of system departure at particular operation states.
In particular case, as the coordinates of conditional safety function of crude oil transfer system are exponential, the intensities of departure are constant i.e. $[\boldsymbol{\lambda}(t,u)]^{(b)} = [\boldsymbol{\lambda}(u)]^{(b)}$ for $u = 1,2,3$, and $b = 1,2,\ldots,9$. Consequently, for considered system consisting of one transhipment line, applying (68), the intensities of departure $[\boldsymbol{\lambda}(1)]^{(b)}$, $[\boldsymbol{\lambda}(2)]^{(b)}$, $[\boldsymbol{\lambda}(3)]^{(b)}$ from the subsets of safety states $\{1,2,3\}$, $\{2,3\}$, $\{3\}$ respectively, for a system at operational state $z_b$, $b = 1,2,\ldots,9$, take values given in *Table 2*.

*Table 2.* The intensities of departure from the safety state subsets {1,2,3}, {2,3}, {3}, for crude oil transfer system at operational states $z_b$, $b = 1,2,\ldots,9$ (in years$^{-1}$)

| operational state $z_b$ | $[\boldsymbol{\lambda}(1)]^{(b)}$ | $[\boldsymbol{\lambda}(2)]^{(b)}$ | $[\boldsymbol{\lambda}(3)]^{(b)}$ |
|---|---|---|---|
| $z_1$ | 0.5585 | 0.6833 | 0.8501 |
| $z_2$ | 0.4818 | 0.5750 | 0.6918 |
| $z_3$ | 0.5918 | 0.7917 | 1.0251 |
| $z_4$ | 0.5834 | 0.7417 | 0.9335 |
| $z_5$ | 0.5085 | 0.6333 | 0.8001 |
| $z_6$ | 0.5918 | 0.7917 | 1.0251 |
| $z_7$ | 0.4042 | 0.5625 | 0.7543 |
| $z_8$ | 0.4401 | 0.5333 | 0.6501 |
| $z_9$ | 0.4918 | 0.6083 | 0.7751 |

Assuming that human error may vary depending on the type of operation performed, i.e. the operating state of crude oil transhipment system, we assume that human factor, defined by (65), can take different values $[Q_{he}(\Delta T)]^{(b)}$ in various operational states $z_b$, $b = 1,2,\ldots,9$.

Next, the intensity of system departure from the safety state subset $\{u,u+1,...,\omega\}$, $u = 1,2,...,\omega$, taking into account the system operation process and including human factor, by (66) is given by the following formula

$$[\boldsymbol{\lambda}_{he}(t,u)]^{(b)} = [\boldsymbol{\lambda}(t,u)]^{(b)} \cdot \left(1+[Q_{he}(\Delta T)]^{(b)}\right),\ t \ge 0,$$
$$u = 1,2,...,\omega,\ b = 1,2,\ldots,9. \tag{73}$$

In case of exponential safety function of the system, the formula (73) for intensity of system departure takes form

$$[\boldsymbol{\lambda}_{he}(u)]^{(b)} = [\boldsymbol{\lambda}(u)]^{(b)} \cdot \left(1+[Q_{he}(\Delta T)]^{(b)}\right),$$
$$u = 1,2,...,\omega,\ b = 1,2,\ldots,9. \tag{74}$$

Consequently, the conditional safety function of crude oil transfer system at operation state $z_b$, $b = 1,2,\ldots,9$, taking into account human factor expressed in (74), is given by a vector

$$[\boldsymbol{S}_{he}(t,\cdot)]^{(b)} = [1,[\boldsymbol{S}_{he}(t,1)]^{(b)},[\boldsymbol{S}_{he}(t,2)]^{(b)},[\boldsymbol{S}_{he}(t,3)]^{(b)}],$$
$$t \ge 0,\ b = 1,2,\ldots,9, \tag{75}$$

where its coordinates are:

$$[\boldsymbol{S}_{he}(t,1)]^{(b)} = \exp\left[-[\boldsymbol{\lambda}(1)]^{(b)}\, t \cdot \left(1+[Q_{he}(\Delta T)]^{(b)}\right)\right],$$
$$t \ge 0,\ b = 1,2,\ldots,9, \tag{76}$$

$$[\boldsymbol{S}_{he}(t,2)]^{(b)} = \exp\left[-[\boldsymbol{\lambda}(2)]^{(b)}\, t \cdot \left(1+[Q_{he}(\Delta T)]^{(b)}\right)\right],$$
$$t \ge 0,\ b = 1,2,\ldots,9, \tag{77}$$

$$[\boldsymbol{S}_{he}(t,3)]^{(b)} = \exp\left[-[\boldsymbol{\lambda}(3)]^{(b)}\, t \cdot \left(1+[Q_{he}(\Delta T)]^{(b)}\right)\right],$$
$$t \ge 0,\ b = 1,2,\ldots,9. \tag{78}$$

Based on consultations and arrangements with system operators, the values of human factor have been established. Their values are given in *Table 3*.

*Table 3.* The values of human factor related to human errors made during crude oil transfer process at operational states $z_b$, $b = 1,2,\ldots,9$

| operational state $z_b$ | $[Q_{he}(\Delta T)]^{(b)}$ | operational state $z_b$ | $[Q_{he}(\Delta T)]^{(b)}$ |
|---|---|---|---|
| $z_1$ | 0.15 | $z_6$ | 0.10 |
| $z_2$ | 0.05 | $z_7$ | 0.20 |
| $z_3$ | 0.10 | $z_8$ | 0.01 |
| $z_4$ | 0.25 | $z_9$ | 0.05 |
| $z_5$ | 0.15 | - | - |

Similarly as in Section 3, we determine the mean values $\boldsymbol{\mu}_{he}^{(b)}(1)$, $\boldsymbol{\mu}_{he}^{(b)}(2)$, $\boldsymbol{\mu}_{he}^{(b)}(3)$ of system conditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3}, respectively, taking into account human factor and its influence on the safety of crude oil transhipment process. Their values are counted in years in *Table 4*, from conditional safety functions of crude oil transfer system, given by (75)-(78), for the values of system intensities given in *Table 2* and the values of human factor given in *Table 3*.

*Table 4*. The mean values of conditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3}, of the system at operational states $z_b$, $b = 1,2,\ldots,9$, including human factor (in years)

| operational state $z_b$ | $\mu_{he}^{(b)}(1)$ | $\mu_{he}^{(b)}(2)$ | $\mu_{he}^{(b)}(3)$ |
|---|---|---|---|
| $z_1$ | 1.557 | 1.273 | 1.023 |
| $z_2$ | 1.977 | 1.656 | 1.377 |
| $z_3$ | 1.536 | 1.148 | 0.887 |
| $z_4$ | 1.371 | 1.079 | 0.857 |
| $z_5$ | 1.710 | 1.373 | 1.087 |
| $z_6$ | 1.536 | 1.148 | 0.887 |
| $z_7$ | 2.062 | 1.481 | 1.105 |
| $z_8$ | 2.250 | 1.857 | 1.523 |
| $z_9$ | 1.937 | 1.566 | 1.229 |

Next, we determine the unconditional safety function of a system, taking into account the system operation process and human errors occurring while system operation. It is determined, similarly as in [17], as a vector

$$\boldsymbol{S}_{he}(t,\cdot) = [1, \boldsymbol{S}_{he}(t,1),\ldots,\boldsymbol{S}_{he}(t,\omega)],\ t \ge 0, \tag{79}$$

where its coordinates, for enough large operation time, are given by

$$\boldsymbol{S}_{he}(t,u) = \sum_{b=1}^{v} p_b \cdot [\boldsymbol{S}_{he}(t,u)]^{(b)},\ t \ge 0,$$
$$u = 1,2,\ldots,\omega \tag{80}$$

and $p_b$, $b = 1,2,\ldots,v$, are the system operation process limit transient probabilities at states $z_b$, given in (1). The coordinates of conditional safety function $[\boldsymbol{S}_{he}(t,u)]^{(b)}$ of crude oil transfer system at operation state $z_b$, $b = 1,2,\ldots,9$, taking into account human factor, are given by formulae (76)-(78).

The safety function coordinates of the crude oil transfer system, given by formula (80), for the values of system intensities given in *Table 2* and the values of human factor given in *Table 3*, are illustrated in *Figure 2*.

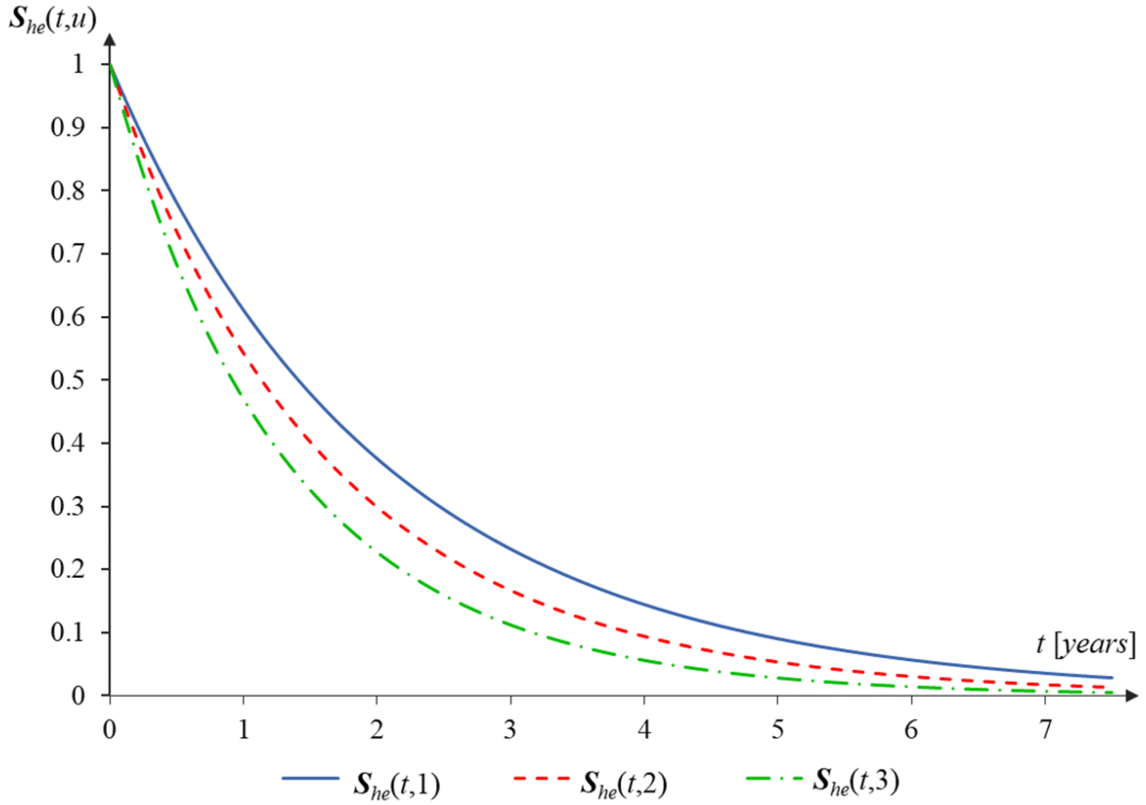


*Figure 2*. The graphs of the safety function coordinates for crude oil transfer system including human factor

Using the system unconditional safety function, we determine other basic safety characteristics, such as mean values and standard deviations of system unconditional lifetimes.

The mean values of system unconditional lifetimes in safety state subsets $\{u,u+1,...,\omega\}$, $u = 1,2,...,\omega$, taking into account human factor, are defined by the formula [17]

$$\boldsymbol{\mu}_{he}(u) = \sum_{b=1}^{v} p_b \cdot \boldsymbol{\mu}_{he}^{(b)}(u),\ u = 1,2,...,\omega \quad (81)$$

where

$$\boldsymbol{\mu}_{he}^{(b)}(u) = \int_0^\infty [\boldsymbol{S}_{he}(t,u)]^{(b)}\,dt,\ u = 1,2,...,\omega$$
$$b = 1,2,...,v. \quad (82)$$

The standard deviations of system unconditional lifetimes in safety state subsets $\{u,u+1,...,\omega\}$, $u = 1,2,...,\omega$, taking into account human factor, are determined from following formula [16]–[17]

$$\boldsymbol{\sigma}_{he}(u) = \sqrt{2\int_0^\infty t \cdot \boldsymbol{S}_{he}(t,u)dt - [\boldsymbol{\mu}_{he}(u)]^2},$$
$$u = 1,2,...,\omega \quad (83)$$

where the coordinates $\boldsymbol{S}_{he}(t,u)$ are given by (80) and $\boldsymbol{\mu}_{he}(u)$ by (81).

The mean values and standard deviations of unconditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3}, of crude oil transfer system including human factor, applying (81)-(83), and for values given in *Table 2* and *Table 3*, are presented in *Table 5*. To compare, the values of these safety characteristics of crude oil transfer system, without taking into account human errors and mistakes during crude oil transhipment process, are also given in *Table 5*.

*Table 5*. The mean values and standard deviations of unconditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3} of crude oil transfer system including and without human factor (in years)

| safety state subset | with human factor | | without human factor | |
|---|---|---|---|---|
| | $\boldsymbol{\mu}_{he}(u)$ | $\boldsymbol{\sigma}_{he}(u)$ | $\boldsymbol{\mu}(u)$ | $\boldsymbol{\sigma}(u)$ |
| {1,2,3} | 2.065 | 2.076 | 2.123 | 2.121 |
| {2,3} | 1.676 | 1.720 | 1.723 | 1.751 |
| {3} | 1.362 | 1.411 | 1.399 | 1.435 |

Using formula (81) and results given in *Table 5*, the unconditional mean values of system in individual safety states $u = 1,2,...,\omega$, are determined as follows [16]–[17]

$$\bar{\boldsymbol{\mu}}_{he}(u) = \boldsymbol{\mu}_{he}(u) - \boldsymbol{\mu}_{he}(u+1),\ u = 1,2,...,\omega - 1,$$
$$\bar{\boldsymbol{\mu}}_{he}(\omega) = \boldsymbol{\mu}_{he}(\omega). \quad (84)$$

The mean values of unconditional lifetimes in individual safety states 1, 2, 3 of crude oil transfer system, counted in years from formula (84) and using results given in *Table 5*, are presented in *Table 6*.

*Table 6*. The mean values of unconditional lifetimes in safety states 1, 2, 3 of crude oil transfer system including and without human factor (in years)

| safety state | with human factor | without human factor |
|---|---|---|
| | $\bar{\boldsymbol{\mu}}_{he}(u)$ | $\bar{\boldsymbol{\mu}}(u)$ |
| 1 | 0.389 | 0.399 |
| 2 | 0.315 | 0.325 |
| 3 | 1.362 | 1.399 |

From the results given in *Table 5* and *Table 6*, it follows that the mean values of unconditional lifetimes in both safety state subsets and individual safety states of the crude oil transfer system are lower by about 3% when the human factor is included compared to when it is excluded.

## 6. Safety analysis of the crude oil transfer system consisting of four transhipment lines

The system for crude oil transfer at the oil terminal consists of four loading lines. Cargo handling jetty is equipped with four loading arms, dedicated to crude oil transfer, connected to these lines. The transfer of crude oil may take place through one, two, three or four of these lines. How many lines carry out the crude oil transmission depends on many factors and, according to the system's operators, it is difficult to define it clearly. These four lines are shown in the scheme of crude oil transfer in *Figure 1*. A single line for crude oil loading/unloading and its components are described in Section 3. All lines are identical and their conditional safety functions in individual operational states are given by the formulae (34)-(37).

We assume that these four transhipment lines form a parallel safety structure. In this case, the conditional safety function of the crude oil transfer system, consisting of four lines, in operational state $z_b$, $b$ = 1,2,…,9 is the vector [9]

$$[\boldsymbol{S}_{4L}(t,\cdot)]^{(b)} = [1,[\boldsymbol{S}_{4L}(t,1)]^{(b)},[\boldsymbol{S}_{4L}(t,2)]^{(b)},[\boldsymbol{S}_{4L}(t,3)]^{(b)}],$$
$$t \geq 0, \ b = 1,2,\ldots,9, \quad (85)$$

with following coordinates

$$[\boldsymbol{S}_{4L}(t,u)]^{(b)} = 1-[1-[\boldsymbol{S}(t,u)]^{(b)}]^4, \ t \geq 0,$$
$$u = 1,2,3, \ b = 1,2,\ldots,9, \quad (86)$$

where $[\boldsymbol{S}(t,u)]^{(b)}$, $u = 1,2,3$, are the safety function coordinates for the single transhipment line in the operational state $z_b$, determined in (35)-(37).

Next, we determine the safety characteristics of the crude oil transfer system, which consists of four lines, by taking into account both the operation process and the human factor influencing the system's safety. We apply (86) and previous formulae (76)-(78) from Section 5, and values given in *Table 2* and *Table 3*, to include the human factor in the safety analysis. Consequently, we obtain the coordinates of conditional safety function of the crude oil transfer system, consisting of four lines, in the following form:

- at the operational state $z_1$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(1)} = 1-[1-\exp[-0.6423t]]^4, \ t \geq 0, \quad (87)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(1)} = 1-[1-\exp[-0.7858t]]^4, \ t \geq 0, \quad (88)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(1)} = 1-[1-\exp[-0.9776t]]^4, \ t \geq 0, \quad (89)$$

- at the operational state $z_2$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(2)} = 1-[1-\exp[-0.5059t]]^4, \ t \geq 0, \quad (90)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(2)} = 1-[1-\exp[-0.6038t]]^4, \ t \geq 0, \quad (91)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(2)} = 1-[1-\exp[-0.7264t]]^4, \ t \geq 0, \quad (92)$$

- at the operational state $z_3$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(3)} = 1-[1-\exp[-0.6510t]]^4, \ t \geq 0, \quad (93)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(3)} = 1-[1-\exp[-0.8709t]]^4, \ t \geq 0, \quad (94)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(3)} = 1-[1-\exp[-1.1276t]]^4, \ t \geq 0, \quad (95)$$

- at the operational state $z_4$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(4)} = 1-[1-\exp[-0.7293t]]^4, \ t \geq 0, \quad (96)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(4)} = 1-[1-\exp[-0.9271t]]^4, \ t \geq 0, \quad (97)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(4)} = 1-[1-\exp[-1.1669t]]^4, \ t \geq 0, \quad (98)$$

- at the operational state $z_5$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(5)} = 1-[1-\exp[-0.5848t]]^4, \ t \geq 0, \quad (99)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(5)} = 1-[1-\exp[-0.7283t]]^4, \ t \geq 0, \quad (100)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(5)} = 1-[1-\exp[-0.9201t]]^4, \ t \geq 0, \quad (101)$$

- at the operational state $z_6$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(6)} = 1-[1-\exp[-0.6510t]]^4, \ t \geq 0, \quad (102)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(6)} = 1-[1-\exp[-0.8709t]]^4, \ t \geq 0, \quad (103)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(6)} = 1-[1-\exp[-1.2761t]]^4, \ t \geq 0, \quad (104)$$

- at the operational state $z_7$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(7)} = 1-[1-\exp[-0.4850t]]^4, \ t \geq 0, \quad (105)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(7)} = 1-[1-\exp[-0.6750t]]^4, \ t \geq 0, \quad (106)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(7)} = 1-[1-\exp[-0.9052t]]^4, \ t \geq 0, \quad (107)$$

- at the operational state $z_8$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(8)} = 1-[1-\exp[-0.4445t]]^4, \ t \geq 0, \quad (108)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(8)} = 1-[1-\exp[-0.5386t]]^4, \ t \geq 0, \quad (109)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(8)} = 1-[1-\exp[-0.6566t]]^4, \ t \geq 0, \quad (110)$$

- and at the operational state $z_9$:

$$[\boldsymbol{S}_{4L\,he}(t,1)]^{(9)} = 1-[1-\exp[-0.5164t]]^4, \ t \geq 0, \quad (111)$$

$$[\boldsymbol{S}_{4L\,he}(t,2)]^{(9)} = 1-[1-\exp[-0.6387t]]^4, \ t \geq 0, \quad (112)$$

$$[\boldsymbol{S}_{4L\,he}(t,3)]^{(9)} = 1-[1-\exp[-0.8139t]]^4, \ t \geq 0. \quad (113)$$

The unconditional safety function of the system, taking into account the system operation process and the human factor, is determined, similarly as in Section 5, using formulae (79)-(80), where the coordinates of conditional safety function $[\boldsymbol{S}_{4L\,he}(t,u)]^{(b)}$, $u = 1,2,3$, of crude oil transfer system consisting of four lines, at operational states $z_b$, $b = 1,2,\ldots,9$, are given by formulae (87)-(113). The coordinates of that unconditional safety function are illustrated in *Figure 3*.

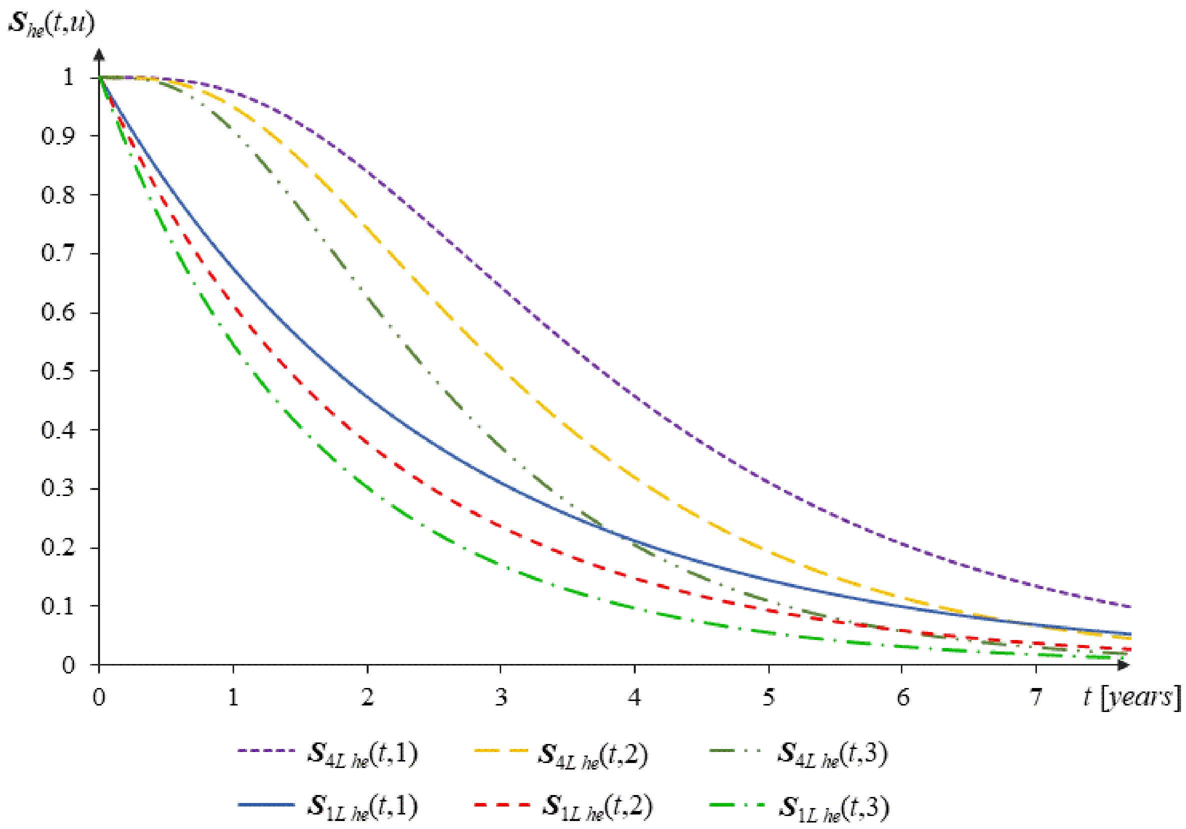


*Figure 3*. The graphs of the safety function coordinates for crude oil transfer system consisting of four lines and composed of one line

The mean values and standard deviations of unconditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3}, of crude oil transfer system consisting of four lines are calculated similarly as in Section 5, applying (81)-(83). Their values are given in *Table 7*, which presents results for both the case when the human factor is included and exclude.

*Table 7*. The mean values and standard deviations of unconditional lifetimes in safety state subsets {1,2,3}, {2,3}, {3} of crude oil transfer system consisting of four lines (in years)

| safety state subset | with human factor | | without human factor | |
|---|---|---|---|---|
| | $\boldsymbol{\mu}_{4L\,he}(u)$ | $\boldsymbol{\sigma}_{4L\,he}(u)$ | $\boldsymbol{\mu}_{4L}(u)$ | $\boldsymbol{\sigma}_{4L}(u)$ |
| {1,2,3} | 4.299 | 2.545 | 4.425 | 2.578 |
| {2,3} | 3.492 | 2.118 | 3.590 | 2.140 |
| {3} | 2.836 | 1.741 | 2.914 | 1.760 |

Next, using formula (84) and results given in *Table 7*, we obtain the unconditional mean values of system in individual safety states $u = 1,2,3$, and they are in *Table 8*.

*Table 8*. The mean values of unconditional lifetimes in safety states 1, 2, 3 of crude oil transfer system consisting of four lines (in years)

| safety state | with human factor | without human factor |
|---|---|---|
| | $\bar{\boldsymbol{\mu}}_{4L\,he}(u)$ | $\bar{\boldsymbol{\mu}}_{4L}(u)$ |
| 1 | 0.807 | 0.835 |
| 2 | 0.807 | 0.676 |
| 3 | 2.836 | 1.760 |

The differences between the mean values of unconditional lifetimes of crude oil transfer system, which consists of four lines, when human factor is included and excluded from analysis are similar to those obtained in Section 5 and are around 3%.

Comparison between the results obtained in this Section and the results for the single transfer line system of Section 5, demonstrates that extending the system to four transfer lines significantly increases the mean values of unconditional lifetimes of the transfer system, and the increase is of approximately 108%. The graphs of coordinates of unconditional safety function for crude oil transfer system in both cases are shown in *Figure 3*.

## 7. Conclusion

This chapter presents safety analysis of the system of crude oil transhipment at the terminal that takes into account the technical condition of the system and the human participation in its operation. A multistate approach has been used to conduct the system's safety analysis. The number of safety states and their description for the system and its components have been varied according to the type of the element and the specificity of its failure. Since, the system's operation process influences the safety of the oil terminal and the environment, it has been included in the safety analysis of the crude oil transfer system. The distinguished operational states are related to different tasks performed by the system. Moreover, the human factor, which can impact transhipment process' safety, has been included in the safety analysis of the crude oil transfer. As human errors and mistakes may depend on the type of operation performed, the human factor has been defined differently in various operational states. Finally, the safety characteristics for the crude oil transfer system have been determined and the results have been compared for cases when the human factor is included in and excluded from the analysis.

In future research, we are planning a more in-depth analysis of the human factor and its impact on the safety of the oil terminal. However, for this purpose, detailed information on accidents and possible human errors or negligence that may contribute to these accidents, as well as detailed information on conditions and circumstances affecting human performance failure will be necessary.

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