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Modelling climate-weather change process including extreme weather hazards for port oil piping transportation system

Keywords

climate-weather change process, semi-Markov model, extreme weather hazard states, port oil transportation system

Abstract

The climate-weather change process for the critical infrastructure operating area is considered and its states are defined. Further, the semi-Markov process is used to create a general probabilistic model of the climate-weather change process for the critical infrastructure operating area. To construct this model the vector of probabilities of the climate-weather change process staying at the initials climate-weather states, the matrix of probabilities of the climate-weather change process transitions between the climate-weather states, the matrix of conditional distribution functions and the matrix of conditional density functions of the climate-weather change process conditional sojourn times at the climate-weather states are defined. Preliminary applications of the proposed model to the climate-weather change process for the port oil transportation system operation area are presented.

1. Introduction

The analysis of the safety of the climate-weather change processes for the real critical infrastructures operating areas is very difficult, especially when their operation conditions are changing in time. The fixing of the complexity of the climate-weather change processes and their influence on changing in time their operation processes and their components' safety parameters isn't usually simple. The climate-weather change processes often have the strong influence (explicit or not) on the critical infrastructures safety. Some of the extreme weather events define a set of different climate-weather states of the critical infrastructures in which the considered system could change its operation process and its components safety parameters. The semi-Markov modelling [12]-[14], [16], [22]-[24], [31] is a convenient tool for analyzing the climate-weather change processes described in this article. Moreover, there are defined parameters of climate-weather change process for port oil piping transportation system operating at under water Baltic Sea area and at land Baltic seaside area. All analyses included in this article could be found in [6].

2. Identification of climate-weather change process

Assume that we distinguish a, $a \in N$, parameters to define the climate-weather states in the fixed area. We mark by $w_1, w_2, ..., w_a$ the values they could take.
Next, after assuming that the possible values of the i-th parameter w_i, $i = 1,2,\ldots, a$, can belong to the interval $<b_i, d_i)$, $i = 1,2,\ldots, a$. we divide each of the intervals $<b_i, d_i)$, $i = 1,2,\ldots, a$, into n_i, $n_i \in N$, disjoint subintervals

$<b_{i1}, d_{i1}), <b_{i2}, d_{i2}),\ldots, <b_{in_j}, d_{in_j}),$

such that

$$<b_{i1}, d_{i1}) \cup \ldots \cup <b_{in_i}, d_{in_i}) = <b_i, d_i),$$

where $d_{ij_i} = b_{ij_i+1},\ j_i = 1,2,\ldots,n_i - 1,\ i = 1,2,\ldots,a.$

Consequently, the vector (w_1, w_2,..., w_a) which describes the climate-weather states can take values from the set of the a dimensional space points of the Descartes product

$$<b_1, d_1) \times <b_2, d_2) \times \ldots \times <b_a, d_a).$$

Moreover, this product is composed of the a dimensional space domains

$$<b_{1j_1}, d_{1j_1}) \times <b_{2j_2}, d_{2j_2}) \times \ldots \times <b_{aj_a}, d_{aj_a}),$$

where $j_i = 1,2,\ldots n_i$, $i = 1,2,\ldots, a$.

We call these domains the climate-weather states of the climate-weather change process. They are numerated from 1 up to the value $w = n_1 \cdot n_2 \cdot \ldots \cdot n_a$ and marked by $c_1, c_2,\ldots, c_w$.

Figure 1 presents the interpretation of the states of the climate-weather change process in the case $a = 2$. In this figure, we have $w = n_1 \cdot n_2$ climate-weather states of the climate-weather change process which are represented by the squares marked by $c_1, c_2,\ldots, c_w$.

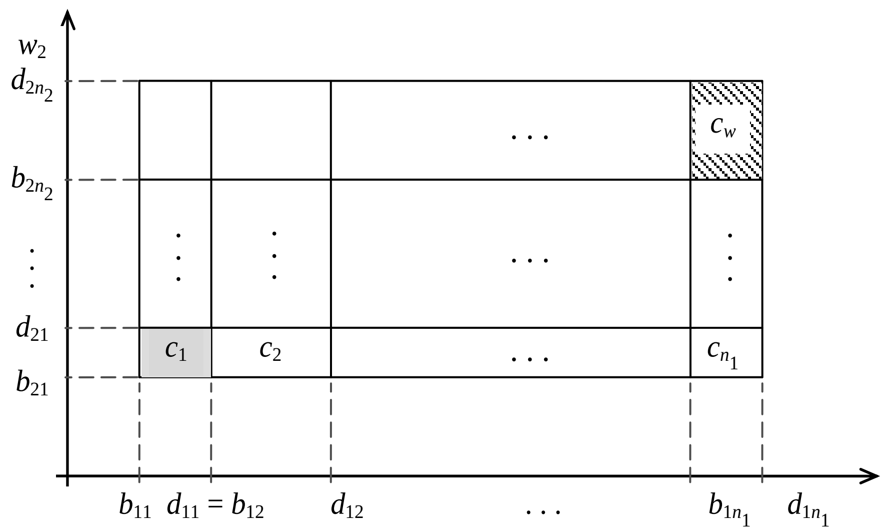

Figure 1. Interpretation of the two dimensional climate-weather states of the climate-weather change process

3. Semi-Markov model of climate-weather change process

During modelling the climate-weather change process for the critical infrastructure operating area, we will assume that the climate-weather in this area is taking w, $w \in N$, different climate-weather states $c_1, c_2,\ldots, c_w$.

Next, the climate-weather change process is marked by $C(t)$, $t \in <0, +\infty)$, with discrete operation states from the set $\{c_1, c_2,\ldots, c_w\}$.

We assume that the climate-weather change process $C(t)$ is a semi-Markov process. After that assumption it can be described by:

– the number of climate-weather states w, $w \in N$,

– the vector

$$[q_b(0)]_{1Xw} = [q_1(0), q_2(0),\ldots, q_w(0)] \quad (1)$$

of the initial probabilities

$$q_b(0) = P(C(0) = c_b),\ b = 1,2,\ldots, w,$$

of the climate-weather change process $C(t)$ staying at particular climate-weather states c_b at the moment $t = 0$;

– the matrix

$$[q_{bl}]_{w\text{x}w} = \begin{bmatrix} q_{11}\ q_{12} \ldots q_{1w} \\ q_{21}\ q_{22} \ldots q_{2w} \\ \ldots \\ q_{w1}\ q_{w2} \ldots q_{ww} \end{bmatrix} \quad (2)$$

of the probabilities of transitions q_{bl}, $b, l = 1,2,\ldots, w$, $b \neq l$, of the climate-weather change process $C(t)$

from the climate-weather states c_b to c_l, where by formal agreement

$q_{bb} = 0$ for $b = 1,2,\ldots, w$;

– the matrix

$$[C_{bl}(t)]_{w\times w} = \begin{bmatrix} C_{11}(t)\, C_{12}(t) \ldots C_{1w}(t) \\ C_{21}(t)\, C_{22}(t) \ldots C_{2w}(t) \\ \ldots \\ C_{w1}(t)\, C_{w2}(t) \ldots C_{ww}(t) \end{bmatrix} \quad (3)$$

of the conditional distribution functions

$C_{bl}(t) = P(C_{bl} < t),\ b, l = 1,2,\ldots, w,$

of the conditional sojourn times C_{bl} at the climate-weather states c_b when its next climate-weather state is c_l, $b, l = 1,2,\ldots, w,\ b \neq l,$ where by formal agreement

$C_{bb}(t) = 0$ for $b = 1,2,\ldots, w$.

Finally, the matrix

$$[c_{bl}(t)]_{w\times w} = \begin{bmatrix} c_{11}(t)\, c_{12}(t) \ldots c_{1w}(t) \\ c_{21}(t)\, c_{22}(t) \ldots c_{2w}(t) \\ \ldots \\ c_{w1}(t)\, c_{w2}(t) \ldots c_{ww}(t) \end{bmatrix} \quad (4)$$

of the conditional density functions of the climate-weather change process $C(t)$ conditional sojourn times C_{bl} at the climate-weather states corresponding to the conditional distribution functions $C_{bl}(t)$ is introduced, where

$$c_{bl}(t) = \frac{d}{dt}[C_{bl}(t)] \text{ for } b, l = 1,2,\ldots, w, b \neq l,$$

and by formal agreement

$c_{bb}(t) = 0$ for $b = 1,2,\ldots, w$.

4. Extreme weather hazard states of climate-weather change process

In Section 2 were distinguished a, $a \in N$, parameters which describe the climate-weather states in the fixed area. We marked by $w_1, w_2, ..., w_a$ the values these parameters can take.
Next, we assumed that the possible values of the i-th parameter w_i, $i = 1,2,\ldots, a$, can belong to the interval $<b_i, d_i)$, $i = 1,2,\ldots, a$ and each of the intervals $<b_i, d_i)$, $i = 1,2,\ldots, a$, were divided into n_i, $n_i \in N$, disjoint subintervals

$<b_{i1}, d_{i1}), <b_{i2}, d_{i2}), \ldots, <b_{in_j}, d_{in_j}),\ i = 1,2,\ldots, a.$

which were called the climate-weather parameter w_i, $i = 1,2,\ldots, a$, states. Some of these states of the climate-weather parameters can change the critical infrastructure operation process. They also could have dengerous influence on the critical infrastructure safety.
Hence, the states of the climate-weather parameter w_i that have most negative influence on the critical infrastructure operation and safety are called the 1st category extreme weather hazard state of the climate-weather parameter w_i, $i = 1,2,\ldots, a$.
Moreover, we define the climate-weather change process states by the vectors

$(w_1, w_2, ..., w_a)$

and mark by

$c_1, c_2, \ldots, c_w,\ w = n_1 \cdot n_2 \cdot \ldots \cdot n_a,$

according to Section 2, then each of the climate-weather change process state c_j, $j = 1,2,\ldots, w$, of the vector form $(w_1, w_2, ..., w_a)$ can be called:
– the a^{th} category extreme weather hazard state of the climate-weather change process if all a climate-weather parameters w_i, $i = 1,2,\ldots, a$, are at the 1st category extreme weather hazard state;
– the $(a\text{-}1)^{th}$ category extreme weather hazard state of the climate-weather change process if a-1 of climate-weather parameters w_i, $i = 1,2,\ldots, a$, are at the 1st category extreme weather hazard state;
– the $(a\text{-}2)^{th}$ category extreme weather hazard state of the climate-weather change process if a-2 of climate-weather parameters w_i, $i = 1,2,\ldots, a$, are at the 1st category extreme weather hazard state;
– …
– the 1st category extreme weather hazard state of the climate-weather change process if 1 of climate-weather parameters w_i, $i = 1,2,\ldots, a$, are at the 1st category extreme weather hazard state;
– the 0os category extreme weather hazard state of the climate-weather change process if none of climate-weather parameters w_i, $i = 1,2,\ldots, a$, are at the 1st category extreme weather hazard state.
Consequently, the a^{th} category extreme weather hazard state of the climate-weather change process is the most dangerous for the critical infrastructure operation and safety.

5. Climate-Weather Change Process for Port Oil Piping Transportation System Operation Area

5.1. Description of port oil piping transportation system

The port oil piping transportation system is operating at one of the Baltic Oil Terminals. It is designed for transporting oil products such like petrol and oil between the pier of Gdynia Port and Oil Terminal in Dębogórze. The considered terminal is composed of four parts *A*, *B* and *C*, linked by the piping transportation system with Pier, and a post *PB*. The scheme of this terminal is presented in *Figure 2*. More information about the port oil transportation system, its assets and interconnections between them could be found in [2]. Moreover, in *Figure 3* is shown where particular parts of the considered terminal are located.

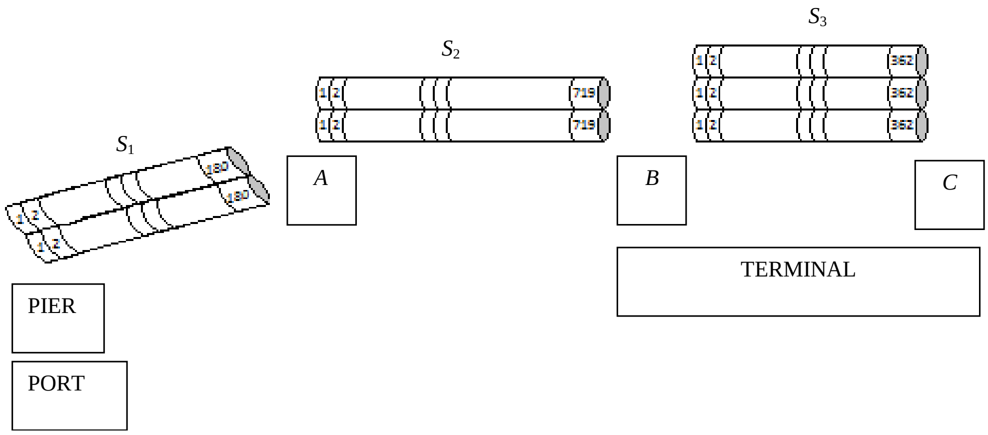

Figure 2. The scheme of the port oil transportation system

Figure 3. The port oil piping transportation system operating between the Gdynia Port and the Terminal in Dębogórze

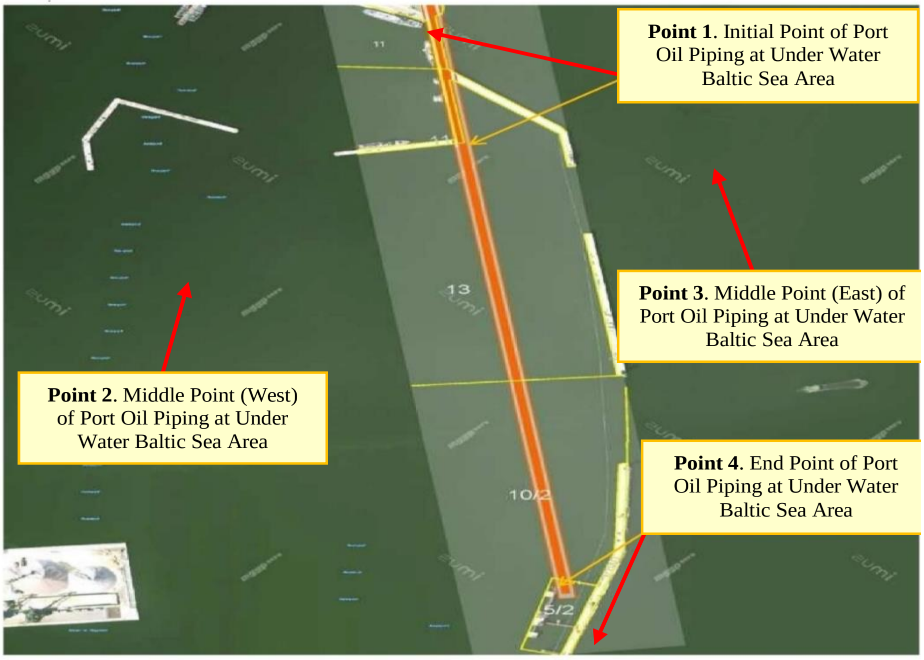

Figure 4. The port oil piping transportation system alignment in the Gdynia Port

In following subsections, we will analyze the climate-weather change process of the port oil piping transportation system operating at underwater Baltic Sea area (*Figure 4*) and at land Baltic seaside area (*Figure 3)*. In points 1-5 marked in above figures were obtained the climate-weather data.

5.2. Defining parameters of climate-weather change process of port oil piping transportation system operating at under water Baltic Sea area

We distinguish a = 2 parameters which mainly describe the climate-weather states of the port oil piping transportation system operating at under water Baltic Sea area. These parameters are: w_1 – the wave height measured in meters and w_2 – the wind speed measured in meters per second. Next, we assume that the possible values of the parameters in this area can belong respectively to the intervals $w_1 \in <0, 14)$ and $w_2 \in <0, 33)$ according to the data about ranges of hazard parameters in [29].
Moreover, the parameter w_1 values interval <0, 14) is divided into n_1 = 3 disjoint subintervals:

<0, 2), <2, 5), <5, 14)

and the parameter w_2 values interval <0, 33) into n_2 = 2 disjoint subintervals:

<0, 17), <17, 33).

Hence, the vector (w_1, w_2) which describes the climate-weather states can take values from the set of the following a = 2 dimensional space points of the Descartes products:

<0, 2) x <0, 17), <2, 5) x <0, 17),
<5, 14) x <0, 17), <0, 2) x <17, 33),
<2, 5) x <17, 33), <5, 14) x <17, 33).

We call these products the climate-weather states of the climate-weather change process. If all of them are sensible then they are numerated from 1 up to the value $w = n_1 \cdot n_2 = 3 \cdot 2 = 6$ and marked by c_1, c_2, …, c_6. When some of them are not possible to happen (are not sensible), then according to an expert opinion, we can omit them and their numeration can be changed.
Hence, based on the expert opinion, there are distinguished the following w = 6 climate-weather states:
– the climate-weather state c_1 – the wave height from 0 up to 2 m and the wind speed from 0 m/s up to 17 m/s;
– the climate-weather state c_2 – the wave height from 2 m up to 5 m and the wind speed from 0 m/s up to 17 m/s;
– the climate-weather state c_3 – the wave height from 5 m up to 14 m and the wind speed from 0 m/s up to 17 m/s;
– the climate-weather state c_4 – the wave height from 0 up to 2 m and the wind speed from 17 m/s up to 33 m/s;
– the climate-weather state c_5 – the wave height from 2 m up to 5 m and the wind speed from 17 m/s up to 33 m/s;

– the climate-weather state c_6 – the wave height from 5 m up to 14 m and the wind speed from 17 m/s up to 33 m/s.

Further, taking into account the agreement assumed in Section 4 and [29], the 1st category extreme weather hazard state of the climate-weather parameter w_1 is the interval <5, 14) and the 1st category extreme weather hazard state of the climate-weather parameter w_2 is the interval <17, 33).

Consequently, the 2nd category extreme weather hazard state of the climate-weather change process is c_6, the 1st category extreme weather hazard states of the climate-weather change process are c_3, c_4, c_5 and the 0os category extreme weather hazard states of the climate-weather change process are c_1, c_2.

The unknown parameters of the climate-weather change process semi-Markov model are:

– the initial probabilities $q_b(0)$, b = 1,2,…,6, of the climate-weather change process staying at the particular state c_b at the moment t = 0,

– the probabilities q_{bl}, b, l = 1,2,…,6, $b \neq l$, of the climate-weather change process transitions from the climate-weather state c_b into the climate-weather state c_l,

– the distributions of the climate-weather change process conditional sojourn times C_{bl}, b, l = 1,2,…,6, $b \neq l$, at the particular climate-weather change states and their mean values $M_{bl} = E[C_{bl}]$, b, l = 1,2,…,6, $b \neq l$.

The identification of these parameters of the climate-weather change process may be found in [20].

5.3. Defining parameters of climate-weather change process for port oil piping transportation system operating at land Baltic seaside area

We distinguish a = 2 parameters which mainly describe the climate-weather states of the port oil piping transportation system operating at land Baltic seaside area. These parameters are: w_1 – the air temperature measured in Celsius (°C) degrees and w_2 – the soil temperature measured in Celsius (°C) degrees. Next, we assume that the possible values of the parameters in this area can belong respectively to the intervals $w_1 \in < -25, 35)$ and $w_2 \in < -30, 37)$ according to the data about ranges of hazard parameters in [29].

Moreover, the parameter w_1 values interval $< -25, 35)$ is divided into n_1 = 6 disjoint subintervals:

<-25, -10), <-10, 0), <0, 10), <10, 20),
<20, 30), <30, 35)

and the parameter w_2 values interval <-30, 37) into n_2 = 6 disjoint subintervals:

<-30, -10), <-10, 0), <0, 10), <10, 20),
<20, 30), <30, 37).

Hence, the vector (w_1, w_2) which describes the climate-weather states can take values from the set of the following a = 2 dimensional space points of the Descartes products:

<-25, -10) x <-30, -10), <-10, 0) x <-30, -10),
<0, 10) x <-30, -10), <10, 20) x <-30, -10),
<20, 30) x <-30, -10), <30, 35) x <-30, -10),
<-25, -10) x <-10, 0), <-10, 0) x <-10, 0),
<0, 10) x <-10, 0), <10, 20) x <-10, 0),
<20, 30) x <-10, 0), <30, 35) x <-10, 0),
<-25, -10) x <0, 10), <-10, 0) x <0, 10),
<0, 10) x <0, 10), <10, 20) x <0, 10),
<20, 30) x <0, 10), <30, 35) x <0, 10),
<-25, -10) x <10, 20), <-10, 0) x <10, 20),
<0, 10) x <10, 20), <10, 20) x <10, 20),
<20, 30) x <10, 20), <30, 35) x <10, 20),
<-25, -10) x <20, 30), <-10, 0) x <20, 30),
<0, 10) x <20, 30), <10, 20) x <20, 30),
<20, 30) x <20, 30), <30, 35) x <20, 30),
<-25, -10) x <30, 37), <-10, 0) x <30, 37),
<0, 10) x <30, 37), <10, 20) x <30, 37),
<20, 30) x <30, 37), <30, 35) x <30, 37).

We call these products the climate-weather states of the climate-weather change process. If all of them are sensible then they are numerated from 1 up to the value $w = n_1 \cdot n_2 = 6 \cdot 6 = 36$ and marked by c_1, c_2, …, c_{36}. When some of them are not possible to happen (are not sensible), then according to an expert opinion, we can omit them and their numeration can be changed.

Hence, based on the expert opinion, there are distinguished the following w = 36 climate-weather states:

– the climate-weather state c_1 – the air temperature from -25°C up to -10°C and the soil temperature from -30°C up to -10°C;

– the climate-weather state c_2 – the air temperature from -10°C up to 0°C and the soil temperature from -30°C up to -10°C;

– the climate-weather state c_3 – the air temperature from 0°C up to 10°C and the soil temperature from -30°C up to -10°C;

– the climate-weather state c_4 – the air temperature from 10°C up to 20°C and the soil temperature from -30°C up to -10°C;

– the climate-weather state c_5 – the air temperature from 20°C up to 30°C and the soil temperature from -30°C up to -10°C;

– the climate-weather state c_6 – the air temperature from 30°C up to 35°C and the soil temperature from -30°C up to -10°C;
– the climate-weather state c_7 – the air temperature from -25°C up to -10°C and the soil temperature from -10°C up to 0°C;
– the climate-weather state c_8 – the air temperature from -10°C up to 0°C and the soil temperature from -10°C up to 0°C;
– the climate-weather state c_9 – the air temperature from 0°C up to 10°C and the soil temperature from -10°C up to 0°C;
– the climate-weather state c_{10} – the air temperature from 10°C up to 20°C and the soil temperature from -10°C up to 0°C;
– the climate-weather state c_{11} – the air temperature from 20°C up to 30°C and the soil temperature from -10°C up to 0°C;
– the climate-weather state c_{12} – the air temperature from 30°C up to 35°C and the soil temperature from -10°C up to 0°C;
– the climate-weather state c_{13} – the air temperature from -25°C up to -10°C and the soil temperature from 0°C up to 10°C;
– the climate-weather state c_{14} – the air temperature from -10°C up to 0°C and the soil temperature from 0°C up to 10°C;
– the climate-weather state c_{15} – the air temperature from 0°C up to 10°C and the soil temperature from 0°C up to 10°C;
– the climate-weather state c_{16} – the air temperature from 10°C up to 20°C and the soil temperature from 0°C up to 10°C;
– the climate-weather state c_{17} – the air temperature from 20°C up to 30°C and the soil temperature from 0°C up to 10°C;
– the climate-weather state c_{18} – the air temperature from 30°C up to 35°C and the soil temperature from 0°C up to 10°C;
– the climate-weather state c_{19} – the air temperature from -25°C up to -10°C and the soil temperature from 10°C up to 20°C;
– the climate-weather state c_{20} – the air temperature from -10°C up to 0°C and the soil temperature from 10°C up to 20°C;
– the climate-weather state c_{21} – the air temperature from 0°C up to 10°C and the soil temperature from 10°C up to 20°C;
– the climate-weather state c_{22} – the air temperature from 10°C up to 20°C and the soil temperature from 10°C up to 20°C;
– the climate-weather state c_{23} – the air temperature from 20°C up to 30°C and the soil temperature from 10°C up to 20°C;
– the climate-weather state c_{24} – the air temperature from 30°C up to 35°C and the soil temperature from 10°C up to 20°C;
– the climate-weather state c_{25} – the air temperature from -25°C up to -10°C and the soil temperature from 20°C up to 30°C;
– the climate-weather state c_{26} – the air temperature from -10°C up to 0°C and the soil temperature from 20°C up to 30°C;
– the climate-weather state c_{27} – the air temperature from 0°C up to 10°C and the soil temperature from 20°C up to 30°C;
– the climate-weather state c_{28} – the air temperature from 10°C up to 20°C and the soil temperature from 20°C up to 30°C;
– the climate-weather state c_{29} – the air temperature 20°C up to 30°C and the soil temperature from 20°C up to 30°C;
– the climate-weather state c_{30} – the air temperature from 30°C up to 35°C and the soil temperature from 20°C up to 30°C;
– the climate-weather state c_{31} – the air temperature from -25°C up to -10°C and the soil temperature from 30°C up to 37°C;
– the climate-weather state c_{32} – the air temperature from -10°C up to 0°C and the soil temperature from 30°C up to 37°C;
– the climate-weather state c_{33} – the air temperature from 0°C up to 10°C and the soil temperature from 30°C up to 37°C;
– the climate-weather state c_{34} – the air temperature from 10°C up to 20°C and the soil temperature from 30°C up to 37°C;
– the climate-weather state c_{35} – the air temperature from 20°C up to 30°C and the soil temperature from 30°C up to 37°C;
– the climate-weather state c_{36} – the air temperature from 30°C up to 35°C and the soil temperature from 30°C up to 37°C.

Further, taking into account the agreement assumed in Section 4 and [29], the 1st category extreme weather hazard state of the weather parameter w_1 are intervals

$$<-25, -10), <20, 30), <30, 35)$$

and the 1st category extreme weather hazard state of the weather parameter w_2 are intervals

$$<-30, -10), <-10, 0), <30, 37).$$

Consequently, the 2nd category extreme weather hazard state of the climate-weather change process are

$$c_1, c_5, c_6, c_7, c_{11}, c_{12}, c_{25}, c_{26}, c_{29}, c_{30}, c_{31}, c_{35}, c_{36},$$

the 1st category extreme weather hazard states of the climate-weather change process are

$c_2, c_3, c_4, c_8, c_9, c_{10}, c_{13}, c_{17}, c_{18}, c_{19}, c_{23}, c_{24}, c_{26}, c_{27}, c_{28}, c_{32}, c_{33}, c_{34}$

and the 0^{os} category extreme weather hazard states of the climate-weather change process are

$c_{14}, c_{15}, c_{16}, c_{20}, c_{21}, c_{22}$.

The unknown parameters of the climate-weather change process semi-Markov model are:
– the initial probabilities $q_b(0)$, $b = 1,2,\dots,36$, of the climate-weather change process staying at the particular state c_b at the moment $t = 0$,
– the probabilities q_{bl}, $b, l = 1,2,\dots,36$, $b \neq l$, of the climate-weather change process transitions from the climate-weather state c_b into the climate-weather state c_l,
– the distributions of the climate-weather change process conditional sojourn times C_{bl}, $b, l = 1,2,\dots,36$, $b \neq l$, at the particular climate-weather change states and their mean values $M_{bl} = E[C_{bl}]$, $b, l = 1,2,\dots,36$, $b \neq l$.
The identification of above parameters of the climate-weather change process may be found in [19].

6. Conclusions

The probabilistic models of the climate-weather change processes for the port oil piping transportation system operating at under sea water and at land Baltic seaside area which are made in this article and for the maritime ferry operating at Gdynia port area and at Baltic Sea open waters which are made in [21] are the basis for the considerations in articles [17]-[20]. In these articles are shown statistical methods of identification and are identified the unknown parameters of the climate-weather change processes for the port oil piping transportation system operating at under sea water and at land Baltic seaside area and for the maritime ferry operating at Gdynia port area and at Baltic Sea open waters.

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