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RESULTS COMPARISON OF ANALYTICAL AND SIMULATION MODELLING OF OIL SPILL DOMAIN MOVEMENT AT PORT WATER AREA

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Abstract

A theoretical background of process of changing hydro-meteorological conditions impact on oil spill trajectory is presented. Probabilistic procedures, analytical and simulation, to oil spill domain movement modelling are proposed considering the impact of hydro-meteorological conditions. The procedures are practically applied to prediction of oil spill domain movement at Karlskrona seaport water area. The discussion and comparison of results are also presented.

Keywords: oil spill, stochastic modelling, Monte Carlo prediction, Karlskrona seaport

I. Introduction

Closed sea areas are more vulnerable to various types of pollution [2], [5]. The Baltic Sea is one of the smallest seas through which pass the busiest communication routes in the world. Over the years, an increase in ship traffic has been observed, including the transfer of gas carriers, oil tankers, container ships and transit traffic [11]. Hazardous materials, for instance crude oil, constitute a very high percentage of the shipping transport. The Baltic Sea was recognized as a particularly sensitive sea area by the International Maritime Organization in 2005 [10]. This status is intended to help more effectively protect areas contaminated by ships. The threats mainly come from the damaged tankers or offshore, polluting large water areas and coasts [5]. Collision between ships carrying dangerous materials may also cause pollution of the marine environment.

There are several ways to protect the marine environment and improve shipping safety. One is to predict the behavior of oil spill trajectory and domain at the water area. The movement of this domain can be predicted based on statistical data from sea experiments. Based on the models given in [3]-[4], one of the accurate and effective methods to determine the spill area and its movement may be a stochastic method supplemented by considering and applying the Monte Carlo simulation approach to solve this problem. Those methods proposed in this paper are applied to the movement prediction of the oil spill domain movement at Karlskrona harbour in order to minimize the potential environmental consequences.

II. Theoretical background

I. Process of changing hydro-meteorological conditions

We denote by $A(t)$ the process of varying hydro-meteorological conditions in the sea water area where the oil spill happened. Then, we assume that $A = \{1,2,...,m\}$ is the set of all possible states of $A(t)$ in which it may stay at the moment t, $t \in <0,T>$, $T > 0$. Further, we assume a semi-

Markov model [7]-[8] of the process $A(t)$ and denote by θ_{ij} its conditional sojourn time in state i while its next transition will be done to state j, where $i, j \in \{1,2,...,m\}$, $i \neq j$. The process $A(t)$ is described by the following parameters [3]-[4], [7]-[8]:

- the vector $[p(0)]_{1\times m}$ of probabilities $p_i(0)$ of the process' initial states at $t = 0$;
- the matrix $[p_{ij}]_{m\times m}$ of transitions' probabilities p_{ij} between the particular states, where $\forall\ i = 1,2,...,m$, $p_{ii} = 0$;
- the matrix $[W_{ij}(t)]_{m\times m}$ of distribution functions $W_{ij}(t)$ of θ_{ij} at the particular states;
- the expected values $M_{ij} = E[\theta_{ij}]$ of its conditional sojourn times θ_{ij} at the particular states

III. Modelling oil spill trajectory

Let T be time of experiment and k be the hydro-meteorological process state, $k = 1,2,\ldots,m$. We suppose that the central point $(m^k_X(t), m^k_Y(t))$ of oil spill domain is placed in the oil spill domain $D^k(t)$, $t \in <0,T>$, $T > 0$, with a fixed probability p. From [3], we have

$$P\Big((X^k(t),Y^k(t)) \in D^k(t)\Big) = \iint_{D^k(t)} \varphi_t^k(x,y)dxdy = p,\ \ t \in <0,T>,\ k = 1,2,\ldots,m, \tag{1}$$

where

$$D^k(t) = \{(x,y): \frac{1}{1-(\rho^k_{XY}(t))^2}[\frac{(x-m^k_X(t))^2}{(\sigma^k_X(t))^2} - 2\rho^k_{XY}(t)\frac{(x-m^k_X(t))(y-m^k_Y(t))}{\sigma^k_X(t)\sigma^k_Y(t)} + \frac{(y-m^k_Y(t))^2}{(\sigma^k_Y(t))^2}] \leq c\}$$

is the domain bounded by an ellipse being the projection on the plane $0xy$ of the curve resulting from the intersection (Figure 3 in [3]) of the density function surface π^k_1 and the plane π^k_2, for $t \in <0,T>$, $k = 1,2,\ldots,m$:

$$\pi^k_1 = \{(x,y,z): z = \varphi^k_t(x,y), (x,y) \in R^2\}, \tag{2}$$

$$\pi^k_2 = \{(x,y,z):\ z = \frac{1}{2\pi\sigma^k_X(t)\sigma^k_Y(t)\sqrt{1-(\rho^k_{XY}(t))^2}}(1-p)\exp[c^2]], (x,y) \in R^2\}. \tag{3}$$

Considering the varying hydro-meteorological conditions, for a fixed time-step Δt, we assume that s_i is a number of steps corresponding to the successive hydro-meteorological process' states $k_1, k_2, ..., k_{n+1}$, such that

$$(s_i - 1)\Delta t < \sum_{j=1}^{i} E[\theta_{k_j k_{j+1}}] \leq s_i\Delta t,\ i = 1,2,...,n,\ \ s_n\Delta t \leq T. \tag{4}$$

Therefore, assuming parametric form of oil spill central point drift trend curve

$$K^{k_i}: \begin{cases} x^{k_i} = x^{k_i}(t) \\ y^{k_i} = y^{k_i}(t), \end{cases}\quad t \in \langle 0,T\rangle,\ i = 1,2,...,n,$$

at each hydro-meteorological process' state k_i, we obtain the sequences of oil spill domains

$$\overline{D}^{k_i}((s_{i-1}+1)\Delta t), \overline{D}^{k_i}((s_{i-1}+2)\Delta t), \ldots, \overline{D}^{k_i}(s_i\Delta t), \tag{5}$$

where $\overline{D}^{k_i}(t)$, for t equal to $(s_{i-1}+ 1)\Delta t$, $(s_{i-1}+ 2)\Delta t$, ..., $s_i\Delta t$, are defined by (1) with expected values, standard deviations and radiuses as follows:

$$m_X^{k_i}(t) := m_X^{k_{i-1}}(s_{i-1}\Delta t) + m_X^{k_i}(a_i \Delta t),\ m_Y^{k_i}(t) := m_Y^{k_{i-1}}(s_{i-1}\Delta t) + m_Y^{k_i}(a_i \Delta t),$$

$$\bar{\sigma}_X^{k_i}(t) := \sigma_X^{k_i}((s_{i-1}+a_i)\Delta t) + \sum_{j=1}^{i} r^{k_j}(b_j \Delta t),\ \bar{\sigma}_Y^{k_i}(t) := \sigma_Y^{k_i}((s_{i-1}+a_i)\Delta t) + \sum_{j=1}^{i} r^{k_j}(b_j \Delta t),\ r^{k_j}(t) := r^{k_j}(b_j \Delta t),$$

for $a_i = 1,2,...,b_i$, $b_i = 1,2,...,s_i - s_{i-1}$, $i = 1,2,...,n$, $j = 1,2,...,i$.

The oil spill domain in the experiment is described by the sum of domains (5).

IV. Modelling oil spill domain analytical and simulation prediction procedures

The general stochastic (analytical and simulation) prediction procedures of the oil spill trajectory and its domain movement at varying hydro-meteorological conditions, based on the models from [3]-[4] and described shortly in Section II, are given in the scheme presented below.
Generally, the simulation procedure consists of the following steps:

- we input data described in Section II;
- we select the initial state at the moment $t = 0$, by generating realizations from the distribution defined in Section I by the vector $[p(0)]_{1\times m}$ of probabilities of the process' initial states, using formula $k_i := k_i(q)$, $i \in \{1,2,...,m\}$, where q is a randomly generated number from the uniform distribution on the interval $\langle 0,1)$;
- we can fix the next operation state of the process of changing hydro-meteorological conditions at oil spill area and denote by $k_{i+1} = k_{i+1}(g)$, $i \in \{1,2,...,m\}$, $i \neq i+1$, the sequence of the realizations of the operation process' consecutive states generated from the distribution defined in Section I by the matrix $[p_{ij}]_{m\times m}$ of transitions' probabilities p_{ij}, where g is a randomly generated number from the uniform distribution on the interval $\langle 0,1)$;
- we can use several methods generating draws from a given probability distribution from the given in Section I matrix $[W_{ij}(t)]_{m\times m}$ of distribution functions $W_{ij}(t)$ of θ_{ij}, e.g. an *inverse transform method*, a *Box-Muller transform method*, *Marsaglia and Tsang's* rejection sampling; using the inverse transform method, the realization is generated from $t_{k_i k_{i+1}}^{(i)}(h) := W_{k_i k_{i+1}}^{-1}(h)$;
- we put some values equal to zero for the conveniece to start the procedure;
- we generate the inital state, next state and realisation $t_{k_i k_{i+1}}^{(i)}(h)$ of the conditional sojourn time, then substitute $i := j$ and repeat drawing another randomly generated numbers g and h (selecting the states k_{i+1} and generating realizations $t_{k_i k_{i+1}}^{(i)}(h)$), until the sum $\sum_{j=1}^{i} t_{k_j k_{j+1}}$ of all generated realisations reach a fixed experiment time T;
- we calculate the necessary parameters and get (5);
- we obtain the sequences of oil spill domains for varying hydro-meteorological conditions.

The analytical approach has the same input data, but the approach is different in a following way:

- we can either fix the states k_i and k_{i+1}, or take the generated states;
- we select $M_{k_j k_{j+1}}$, check the condition $(s_i - 1)\Delta t < \sum_{j=1}^{i} M_{k_j k_{j+1}} \le s_i \Delta t$, and find new $M_{k_j k_{j+1}}$;
- the output data are the sequences of domains for varying hydro-meteorological conditions.

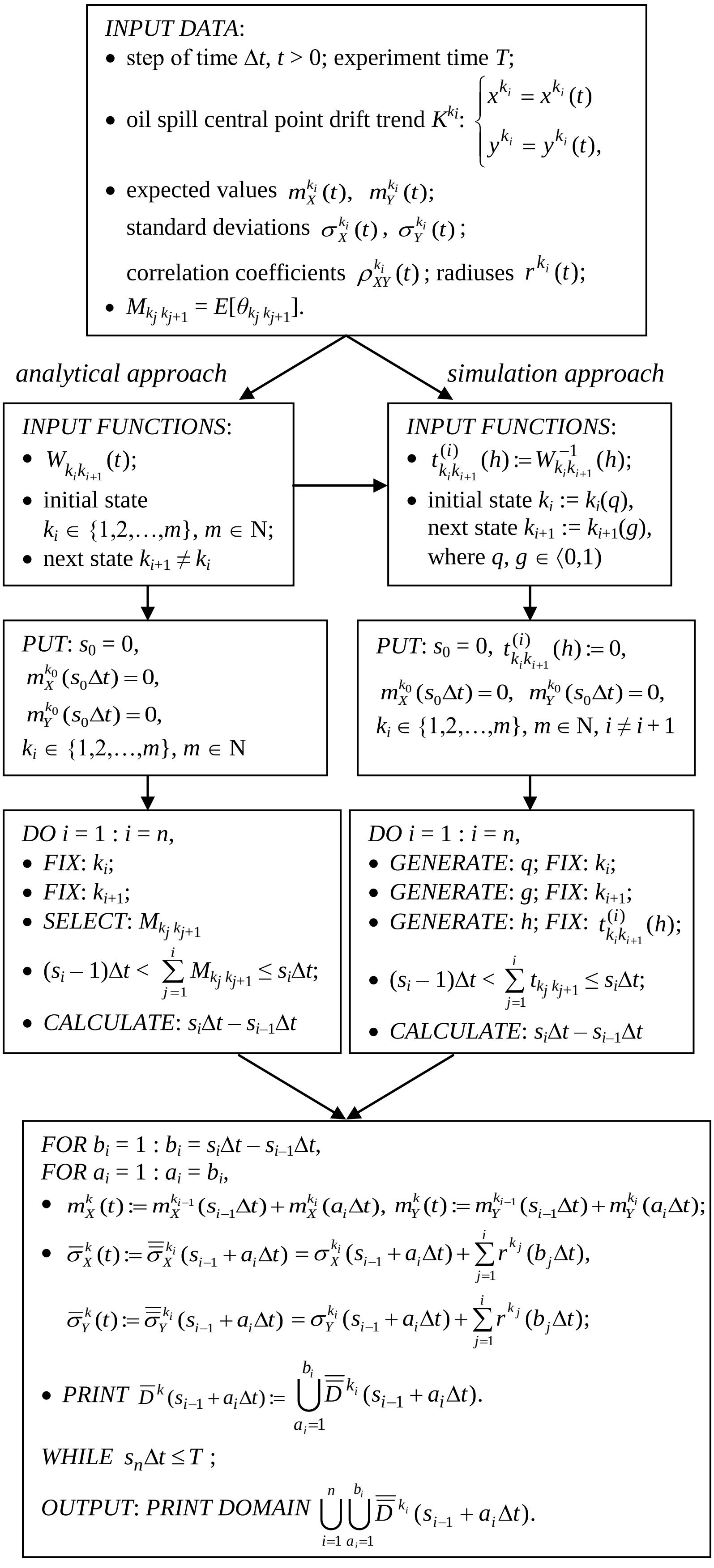

Figure 1: *Oil spill trajectory and domain movement analytical and simulation prediction procedures*

V. Application

I. Process of changing hydro-meteorological conditions at Karlskrona seaport area

After discussion with experts, we assume the selected hydro-meteorological factors having crucial influence on the oil spill trajectory in port areas [6]:

- wind speed,
- wind direction,
- sea level height,
- direction of currents,
- visibility difficulties (e.g. fog, icing).

The statistical data were collected in Marches [9] for six years of the experiment. March is the month, where the weather in Sweden is changing rapidly, from the noticeable strong wind and storm to calm breeze, that is why, this factor is the major one in the investigation. The strongest winds (>33 m/s) did not occur in the considered area. Second notable parameter that the experts suggested to include is the wave height. Considering the above, there were distinguished m = 6 states of the process $A(t)$, $t \in$ <0,T>, $T > 0$, i.e.

- k = 1 – the wave height from 0 up to 2 m and the wind speed from 0 m/s up to 17 m/s;
- k = 2 – the wave height from 2 m up to 5 m and the wind speed from 0 m/s up to 17 m/s;
- k = 3 – the wave height from 5 m up to 14 m and the wind speed from 0 m/s up to 17 m/s;
- k = 4 – the wave height from 0 up to 2 m and the wind speed from 17 m/s up to 33 m/s;
- k = 5 – the wave height from 2 m up to 5 m and the wind speed from 17 m/s up to 33 m/s;
- k = 6 – the wave height from 5 m up to 14 m and the wind speed from 17 m/s up to 33 m/s.

On the basis of the statistical data [6], it was possible to evaluate the following unknown basic parameters of the semi-Markov model of the process of changing hydro-meteorological conditions at the considered area, where the oil spill happened, according to Section I and [1]:

- the initial probabilities:

$$p_1(0) = 0.324,\ p_2(0) = 0.018,\ p_3(0) = 0.447,\ p_4(0) = 0.029,\ p_5(0) = 0.182,\ p_6(0) = 0; \quad (6)$$

- the probabilities of transitions from the state i into the state j:

$$p_{12} = 0.12,\ p_{13} = p_{63} = 0.67,\ p_{14} = p_{42} = 0.03,\ p_{15} = 0.18,\ p_{21} = 0.25,\ p_{23} = 0.11,\ p_{24} = 0.64,\ p_{31} = 0.6,$$
$$p_{32} = p_{36} = p_{46} = 0.01,\ p_{34} = 0.15,\ p_{35} = 0.23,\ p_{41} = 0.01,\ p_{43} = 0.95,\ p_{51} = 0.37,\ p_{53} = 0.63,\ p_{65} = 0.33, \quad (7)$$

where the rest probabilities are equal to 0.

The hypotheses on the distributions of this process' conditional sojourn times at the particular states were verified for the sets containing at least 30 realizations coming from the experiment (Table 1). The random samples that were not sufficiently large have the empirical CDF-s. The remaining distribution functions could not be evaluated because the corresponding states have not happened during the experiment.

Table 1: *The distribution functions of the verified sojourn times*

Distribution	Sojourn times	Expected values
Exponential	θ_{12}, θ_{15}	31.55, 36.1
Chimney	θ_{13}, θ_{31}, θ_{43}	39.49, 35.86, 15.77
Gamma	θ_{34}, θ_{35}, θ_{51}, θ_{53}	17.56, 26.75, 43.45, 20.45
empirical CDF	θ_{14}, θ_{21}, θ_{23}, θ_{32},	7.12, 7.29, 5, 15,
	θ_{36}, θ_{41}, θ_{42}, θ_{46}, θ_{63}, θ_{65}	77.5, 3, 3, 3, 4.5, 6

II. Oil spill domain in varying hydro-meteorological conditions at Karlskrona seaport water area

We arbitrarily assume, that $T = 48\,h$ and after discussion with experts, the points $(m_X^{k_i}(t), m_Y^{k_i}(t))$, $t \in \langle 0,48 \rangle$ for each hydro-meteorological state k_i, create a curve

$$K^{k_i}: \begin{cases} x^{k_i} = t^2 \\ y^{k_i} = k_i \cdot t, \end{cases} \quad t \in \langle 0, 48 \rangle,\ k_i \in \{1,2,\ldots,6\}, i = 1,2,\ldots,n. \tag{8}$$

Moreover, after assuming arbitrarily the remaining parameters, we have

$$\overline{D}^{k_i}(t) = \{(x,y): \frac{1}{1-0.8^2}[\frac{(x-t^2)^2}{(\overline{\sigma}_X^{k_i}(t))^2} - 1.6\frac{(x-t^2)(y-k_i \cdot t)}{\overline{\sigma}_X^{k_i}(t)\overline{\sigma}_Y^{k_i}(t)} + \frac{(y-k_i \cdot t)^2}{(\overline{\sigma}_Y^{k_i}(t))^2}] \le 5.99\}, \tag{9}$$

where $\overline{\sigma}^{k_i}(t)$, $t \in \langle 0,48 \rangle$, are defined in Section II, substituting

$$\sigma^{k_i}(t) = 0.1 + 0.2t,\ r^{k_i}(t) = 0.5 + 0.5t,\ t \in \langle 0,48 \rangle, k_i \in \{1,2,\ldots,6\}, i = 1,2,\ldots,n. \tag{10}$$

Having all the parameters determined, we select the initial state at the moment $t = 0$, by generating realizations from the distribution defined by (6) using formula $k_i := k_i(q)$, $i \in \{1,2,\ldots,m\}$, i.e.

$$k_1(q) = \begin{cases} 1, & 0 \le q < 0.324 \\ 2, & 0.324 \le q < 0.342 \\ 3, & 0.342 \le q < 0.789 \\ 4, & 0.789 \le q < 0.818 \\ 5, & 0.818 \le q < 1; \end{cases}$$

where q is a randomly generated number from the uniform distribution on the interval $\langle 0,1)$. Then, we can fix the next operation state of the process of changing hydro-meteorological conditions at oil spill area and denote by $k_{i+1} = k_{i+1}(g)$, $i \in \{1,2,\ldots,m\}$, $i \ne i+1$, the sequence of the realizations of the operation process' consecutive states generated from the distribution defined by (7), where g is a randomly generated number from the uniform distribution on the interval $\langle 0,1)$, i.e.

$$k_2(g) = \begin{cases} 2, & 0 \le g < 0.12 \\ 3, & 0.12 \le g < 0.79 \\ 4, & 0.79 \le g < 0.82 \\ 5, & 0.82 \le g < 1, \end{cases} \text{ if } k_1(q) = 1;$$

$$k_2(g) = \begin{cases} 1, & 0 \le g < 0.25 \\ 3, & 0.25 \le g < 0.36 \\ 4, & 0.36 \le g < 1, \end{cases} \text{ if } k_1(q) = 2;$$

$$k_2(g) = \begin{cases} 1, & 0 \le g < 0.6 \\ 2, & 0.6 \le g < 0.61 \\ 4, & 0.61 \le g < 0.76 \\ 5, & 0.76 \le g < 0.99 \\ 6, & 0.99 \le g < 1, \end{cases} \text{ if } k_1(q) = 3;$$

$$k_2(g) = \begin{cases} 1, & 0 \le g < 0.01 \\ 2, & 0.01 \le g < 0.04 \\ 3, & 0.04 \le g < 0.99 \\ 6, & 0.99 \le g < 1, \end{cases} \text{ if } k_1(q) = 4;$$

$$k_2(g) = \begin{cases} 1, & 0 \le g < 0.37 \\ 3, & 0.37 \le g < 1, \end{cases} \text{ if } k_1(q) = 5;$$

$$k_2(g) = \begin{cases} 3, & 0 \le g < 0.67 \\ 5, & 0.67 \le g < 1, \end{cases} \text{ if } k_1(q) = 6;$$

and so on. For the analytical approach, we assume that the process of changing hydro-meteorological conditions $A(t)$ in succession takes these simulated states. Thus, we proceed with procedures from Section II, taking the input data from this section. We get:

- for $i = 1$, we generate $g \cong 0.456$, $q \cong 0.88$ and select $k_1(0.456) = 3$, $k_2(0.88) = 5$:

analytical approach

- we select the conditional mean value $M_{35} = 26.75$ of the sojourn time θ_{35};
- we check the condition $(s_1 - 1) = s_0 = 0 < M_{35} = 26.75 \le s_1$;
- hence, $s_1 = 27$ and $s_1 - s_0 = s_1 - 0 = 27$;
- consequently, we draw 1,2,...,27 ellipses;
- we compare s_1 with the experiment time: $s_1 = 27 < 48 = T$;
- we draw the sequence of the oil spill domains for $a_1 = 1,2,\ldots,b_1$, $b_1 = 1,2,\ldots,27$, (Figure 2);

simulation approach

- we generate $h_1 = 0.7$, $h_2 = 0.9$ and select the realisation $t^{(1)}_{k_1k_2} = t^{(1)}_{35} = 5.593$ of the sojourn time θ_{35};
- we check the condition $(s_1 - 1) = s_0 = 0 < t^{(1)}_{35} = 5.593 \le s_1$;
- hence, $s_1 = 6$ and $s_1 - s_0 = s_1 - 0 = 6$;
- consequently, we draw 1,2,...,6 ellipses;
- we compare s_1 with the experiment time: $s_1 = 6 < 48 = T$;
- we draw the sequence of the oil spill domains for $a_1 = 1,2,\ldots,b_1$, $b_1 = 1,2,\ldots,6$, (Figure 4);

- for $i = 2$, $k_2 = 5$ and we generate $q \cong 0.217$ to select $k_3(0.217) = 1$:

analytical approach

- we select the conditional mean value $M_{51} = 43.45$ of the sojourn time θ_{51};
- we check the condition $(s_2 - 1) = s_1 = 27 < M_{35} + M_{51} = 26.75 + 43.45 \le s_1$;
- hence, $s_2 = 70.2$ and $70.2 > 48 = T$, thus $s_2 = 48$ and $s_2 - s_1 = 48 - 27 = 21$;
- consequently, we draw 1,2,...,21 ellipses;
- we draw the sequence of the oil spill domains for $a_2 = 1,2,\ldots,b_2$, $b_2 = 1,2,\ldots,21$, (Figure 2);

simulation approach

- we generate $h_1 = 0.2$, $h_2 = 0.6$ and select the realisation $t^{(2)}_{k_2k_3} = t^{(2)}_{51} = 11.928$ of the sojourn time θ_{51};
- $t^{(1)}_{k_1k_2} + t^{(2)}_{k_2k_3} = t^{(1)}_{35} + t^{(2)}_{51} = 5.593 + 11.928 = 17.521$;
- we check the condition $(s_2 - 1) < 17.521 \le s_2$;
- hence, $s_2 = 18$ and $s_2 - s_1 = 18 - 6 = 12$;
- consequently, we draw 1,2,...,12 ellipses;
- we compare s_2 with the experiment time: $s_2 = 18 < 48 = T$;
- we draw the sequence of the oil spill domains for $a_2 = 1,2,\ldots,b_2$, $b_2 = 1,2,\ldots,12$, (Figure 4);

- for $i = 3$, $k_3 = 1$ and we generate $q \cong 0.469$ to select $k_4(0.469) = 3$:

simulation approach

- we generate $h = 0.3$ and select the realisation $t^{(3)}_{k_3k_4} = t^{(3)}_{13} = 10.587$ of the sojourn time θ_{13};
- $t^{(1)}_{k_1k_2} + t^{(2)}_{k_2k_3} + t^{(3)}_{k_3k_4} = t^{(1)}_{35} + t^{(2)}_{51} + t^{(3)}_{13} = 5.593 + 11.928 + 10.587 = 28.108$;
- we check the condition $(s_3 - 1) < 28.108 \le s_3$;
- hence, $s_3 = 29$ and $s_3 - s_2 = 29 - 18 = 11$;
- consequently, we draw 1,2,...,11 ellipses;
- we compare s_3 with the experiment time: $s_3 = 29 < 48 = T$;
- we draw the sequence of the oil spill domains for $a_3 = 1,2,\ldots,b_3$, $b_3 = 1,2,\ldots,11$, (Figure 4);

- for $i = 4$, $k_4 = 3$ and we generate $q \cong 0.758$ to select $k_5(0.758) = 1$:

simulation approach

- we generate $h = 0.45$ and select the realisation $t^{(4)}_{k_4k_5} = t^{(4)}_{31} = 19.367$ of the sojourn time θ_{31};
- $t^{(1)}_{k_1k_2} + t^{(2)}_{k_2k_3} + t^{(3)}_{k_3k_4} + t^{(4)}_{k_4k_5} = t^{(1)}_{35} + t^{(2)}_{51} + t^{(3)}_{13} + t^{(4)}_{31} = 5.593 + 11.928 + 10.587 + 19.367 = 47.475$;
- we check the condition $(s_4 - 1) < 47.475 \le s_4$;
- hence, $s_4 = 48$ and $s_4 - s_3 = 48 - 29 = 19$;
- consequently, we draw 1,2,...,19 ellipses;

- we compare s_4 with the experiment time: $s_4 = 48 = T$;
- we draw the sequence of the oil spill domains for $a_4 = 1,2,\ldots,b_4$, $b_4 = 1,2,\ldots,19$, (Figure 4).

The results for the analytical approach – an oil spill trajectory and sequence of domains for $t = 27$ *h* and 47 *h* and the results for the simulation approach – an oil spill trajectory and sequence of domains for $t = 6$ *h*, $t = 18$ *h*, $t = 29$ *h* and 47 *h* are presented below. To clearly indicate the changing in time hydro-meteorological conditions, there were omitted the starting states in the Figures 2 and 3. The oil spill domain movement at the moment $t = 48h$ is illustrated in Figures 3 and 5.

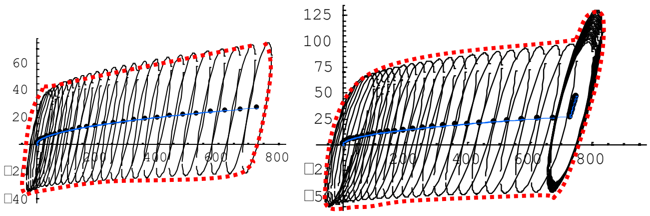

Figure 2: *Oil spill trajectory and sequence of domains for t = 27 h and 47 h (analytical approach).*

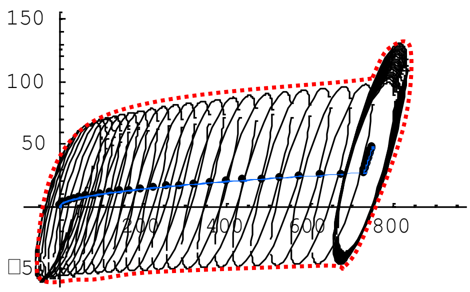

Figure 3: *The final oil spill domain at the moment t = 48 h (analytical approach).*

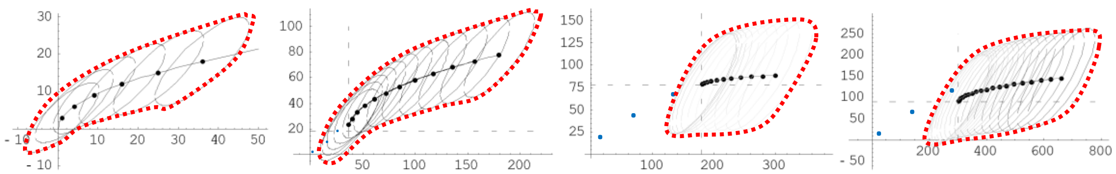

Figure 4: *Oil spill trajectory and sequence of domains for t = 6 h, t = 18 h, t = 29 h and 47 h (simulation approach).*

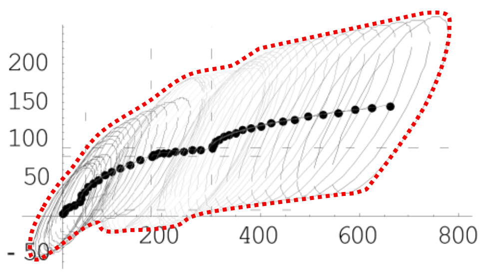

Figure 5: *The final oil spill domain at the moment t = 48 h (simulation approach).*

VI. Discussion

We can notice that the oil spill domains illustrated in Figures 3 and 5 are slightly different. The results obtained for the analytical approach could be improved to better reflect the real oil spill domain impacted by the hydro-meteorological process' changes. These two methods are the aproximate methods, thus, to improve the results of the analytial approach, we can change the hydro-meteorological state, e.g. at the moment $t = 18\ h$ and then start the procedure from Section II from the beginning. Moreover, during the experiments and in real-life situations, the real hydro-meteorological data can be identified as a result of the conducted experiment or as data collected on an ongoing basis (real-time data). The improvement of the methods of the oil spill domains determination gives the possibility of identifying the pollution size and the reduction of time of its consequences elimination.

VII. Conclusion

The paper presents the comparison of the methods of stochastic prediction of oil spill domain movement prediction impacted by changing hydro-meteorological conditions: analytical approach and Monte Carlo simulation approach, applied at Karlskrona seaport water area. The following two significant parameters were considered: the wave height and the wind speed. There were obtained the oil spill trajectory and sequences of oil spill domains for varying hydro-meteorological conditions.

Author's current research is related to the further development of the simulation procedures to take into account more relevant factors, e.g. the density (thickness) of different chemicals. The final effect of the research should be a model for rapid simulation of the situation at sea during a disaster. Then, the searched domain can be easily found for rescue action organizing.

References

[1] Biały, J., Rurak, A., Tomaszewska, J. Toruń, A., Woch, M., Zieja, M. and Żurek, J. (2018). Statistical Analysis of the Volume of Passenger Air Traffic in Europe in years 2004-2015, 2018, INAIR 2018: Aviation on the Growth Path, *Transportation Research Procedia* 35: 72-79, doi: 10.1016/j.trpro.2018.12.014.

[2] Bogalecka, M. (2019). Consequences of maritime critical infrastructure accidents with chemical releases, *TransNav - International Journal on Marine Navigation and Safety of Sea Transportation* 13(4): 771-779, doi: 10.12716/1001.13.04.09.

[3] Dąbrowska, E. and Kołowrocki, K. (2019). Modelling, identification and prediction of oil spill domains at port and sea water areas, *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 10(1): 43-58.

[4] Dąbrowska, E. and Kołowrocki, K., (2020). Hydro-meteorological change process impact on oil spill domain movement at sea, in Theory and Applications of Dependable Computer Systems, *Proceedings of the Fifteenth International Conference on Dependability of Computer Systems*, DepCos-Relcomex, Springer, 165-175.

[5] Fingas, M. (2016). Oil Spill Science and Technology, 2nd edn. Elsevier.

[6] Gdynia Maritime University Safety Interactive Platform, http://gmu.safety.umg.edu.pl/ (accessed 08.2021).

[7] Grabski, F. (2014). Semi-Markov Processes: Application in System Reliability and Maintenance, Elsevier.

[8] Kołowrocki, K. (2014). Reliability of Large and Complex Systems, Elsevier.

[9] Kołowrocki, K. and Kuligowska, E. (2018). Operation and climate-weather change impact on maritime ferry safety, in Safety and Reliability - Safe Societies in a Changing World, S. Haugen, A. Barros, C. VanGulijk, T. Kongsvik, J.E. Vinnem, Eds. CRC Press-Balkema, ESREL – 28th Annual International European Safety and Reliability Conference, 849-857, doi: 10.1201/9781351174664-107

[10] Marine Knowledge Centre. (2009). International shipping and world trade facts and figures, IMO Document.

[11] McCay, D.F., Reich, D., Michel, J., Etkin, D., Symons, L., Helton D. and Wagner, J. (2012). Oil spill consequence analyses of potentially-polluting shipwrecks, *AMOP*: 751-774.