Ship Grounding Damage Estimation Using Statistical Models

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Abstract: This paper presents a generalizable and computationally fast method of estimating maximum grounding damage extent in case of grounding based on damage statistics of groundings in Finnish waters. The damage is measured in relative maximum damage depth into the bottom structure, total damage length as well as the damage two-dimensional area.

Keywords: Ship groundings, damage estimation, statistical models, Bayesian Belief Networks

1. INTRODUCTION

Groundings are among the most frequent of maritime accidents, sometimes with catastrophic consequences for human life and the maritime environment such as the Exxon Valdez and Costa Concordia accidents. In order to mitigate risk, procedures such as IMO's [1] Formal Safety Assessment (FSA) have been presented where the cost-effectiveness of various risk control options is evaluated. In order to do this, first general and reliable risk analysis tools are required.

Various models have been presented for modeling ship structural damage caused by groundings, see e.g. Wang et al. [2] for a comprehensive overview. The use of these models in a comprehensive risk analysis is challenging: The detailed models that are usually based on the Finite Element Method (FEM), which not only is very computationally intensive [3, 4] but usually also models only a limited number of grounding scenarios for a very limited number of ship and rock types, see e.g. van de Wiel and van Dorp [5]. This limits applicability in more comprehensive risk analysis, where one would be interested in e.g. modeling the grounding damage on all expected groundings in a given sea area over a certain time period.

More general models based on accident statistics such as IMO [6], Zhu, James and Zhang [7] and Papanikolaou et al. [8] on the other hand can be used quite generally, but the usual limitation in these models is not linking the ship particulars (velocity, mass, etc.) with the resulting damage. The damage is usually modeled with an (empirical) statistical distribution that can be used directly to estimate damage as a percentage of total ship length, beam or draft. However, if the ship particulars are not linked with the resulting damage, one ends up with models where a tanker of 100 000 DWT sailing at 5 knots has the same probability of having a grounding damage extending 1/10 of ship draft as a 5000 DWT tanker sailing at 15 knots in case of a grounding [9]. Montewka, et al. [10] developed a function for expected grounding oil spill volume as a function of ship size, however other ship particulars such as velocity and other local conditions are not taken into account.

Besides these, there are simplified analytical grounding damage models (e.g. Cerup-Simonsen, Törnqvist and Lützen [11], Zhang, [12], Zhu, James and Zhang [7]) which usually estimate either the damaged volume of steel or damage extent along one dimension when damage extent along the other dimension(s) are known. In order to use these models in more comprehensive risk analysis one must combine the analytical models with models that estimate the damage along the other dimensions first. For this reason these models alone are not enough to estimate grounding damage. Some of the models presented in this paper can be used to estimate the damage along the other dimension(s) for the simplified analytical models.

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When it comes to making a grounding consequence analysis for a large number of ships sailing in a given sea area, a further challenge arises: The availability of information regarding grounding depths and/or the bottom shape. Models that are not just based on non-dimensional damage extent such as IMO [6] require detailed information regarding the bottom. This information is incomplete for most cases and therefore usually grounding damage models use relatively simplified assumptions or consider limited cases, see e.g. Zhu, James and Zhang [7] and van de Wiel and van Dorp [5]. This makes the outcome of the models reliant on the assumptions.

Table 1: Overview of different grounding damage model types

Model type	Computation	Info needed on bottom	Link ship size and speed with damage	Generally applicable	Other requirements
FEM	Slow	Detailed	Yes	Each case needs own simulation	
Statistical	Fast	No	No/limited	Yes, many or all ships	
Analytical	Fast	Detailed	Yes	Yes	Damage extent**
This model	Fast	No	Yes	Yes*	

*Model is limited by the available data, which e.g. did not include ships over 57 000 tonnes, see table 2.
**In order to model damage depth, width or length, one or two of the three aforementioned must usually be known in advance.

1.1. Aim

This paper aims at presenting different generalizable and computationally fast grounding damage assessment models based on grounding statistics– without requiring knowledge of the grounding depth, bottom type or damage extent along other dimensions first. In this way the models presented here overcome some of the limitations presented in table 1.

Models presented here link the ship particulars such as velocity, mass and double bottom height with the resulting maximum height of damage bottom structure in groundings as well as the resulting bottom damage length and area.

1.2. Methodology

Detailed grounding damage from accidents in Finnish waters is analyzed using Bayesian Belief Networks as well as different regression models. The models describe grounding damage extent based on grounding velocity, ship size and other factors.

2. DATA

The data used for the analysis consists of 18 ship grounding damage cases from Luukkonen [13], who measured ship grounding damage in Finnish territorial waters, see table 2. These cases were classified as dry cargo, tankers, roro or passenger vessels. In this paper, one case with missing double bottom height as well as one case where the grounded vessel had a draft of less than 2 meters were left out from the data. The following variables from the report are included in the analysis:

v_1 = initial velocity right before grounding [kn]
v_2 = velocity after grounding (0 if ship stuck)
Δv = velocity reduction during grounding (v_1- v_2)
E = grounding energy [MJ], calculated as

$$E = \frac{1}{2}\,(1 + C_a) m (v_1^2 - v_2^2), \qquad (1)$$

where
C_a = 0.1 is the added surge mass and
m = displacement [tonnes]
d = maximum vertical depth of damaged material [m]
l = total damage length [m] (can exceed ship length if multiple damage tracks on bottom, see figure 1)
s = total damage length [m] from aft to fore (cannot exceed ship length L, see figure 1)
L = ship length [m]
T = ship draft [m]
A = bottom 2-dimensional damage area [m^2]
DB_H = ship double bottom height [m]

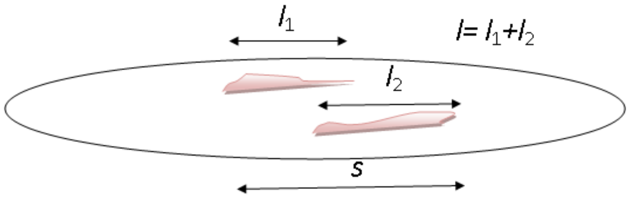

Figure 1: Example of grounding damage seen from below, indicating how *l* and s are calculated

The relevant data is presented in the following table:

Table 2: Grounding damage data, adapted from Luukkonen [13]

E [MJ]	DB_H [m]	max d [m]	l [m]	s [m]	A [m^2]	L [m]	T[m]	m [tonnes]	v1 [kn]	v2 [kn]	Δv
690.9	1.35	1.35	156.6	93.6	638	159.2	9.1	21100	15	0	15
208.1	1.8	1.5	125	108.9	475	150	9.5	22700	8	1	7
380.3	1.8	1.6	93.8	101.5	549	150	9.5	22100	13.5	8	5.5
2.9	1.2	0.75	7.2	7.2	20	130	6.1	8980	1.5	0	1.5
86.9	1.2	1.2	14.4	50.4	45	130	6.1	8780	18	16	2
3.2	1.2	0.65	13.6	13.6	15	130	6.1	9830	1.5	0	1.5
342.3	1.9	1.9	172.4	92.2	1124	146	7.3	12000	14	0	14
43.6	1.99	0.98	33.7	37.2	152	180.5	11.7	57000	2.5	1	1.5
57.8	1.18	0.8	22.5	22.5	100	142.4	5.8	11025	6	0	6
487.3	1.2	1.2	118.4	107.2	929	139.8	5.9	12829	19	10	9
115.5	1.6	0.95	25.3	25.3	79	118.5	6.4	9800	9	0	9
33.6	2.1	0.8	8.8	8.8	20	171.6	6.8	25673	3	0	3
144.1	1.9	1	28.8	28.8	120	146	8.5	14200	10	5.5	4.5
174.2	1.95	1.95	67	50.2	327	126.5	6.6	9050	11.5	0	11.5
53.9	1.5	1.1	16.1	32.9	35	134.3	7.3	16100	12	11	1
300.1	1.8	2	98.3	46.8	479	128.8	8.2	12200	13	0	13
244.8	1.2	1.5	60.8	60.8	442	130	6.1	8582	14	0	14
24.5	1.8	0.6	23.4	40.2	61	129	8.2	18700	3	0	3

The ship displacements were relatively small ranging from ~8500 to 57 000 tonnes. Interestingly, in half of the cases the velocity at the start of the grounding accident was above 10 knots. In 7 of the cases the maximum damage extent *d* was equal to or exceeded the double bottom height. The problem in the data is the that *d* does not tell us whether the damaged bottom structure material ruptured or just deformed, thus is difficult to know when exactly the double bottom structure was penetrated.

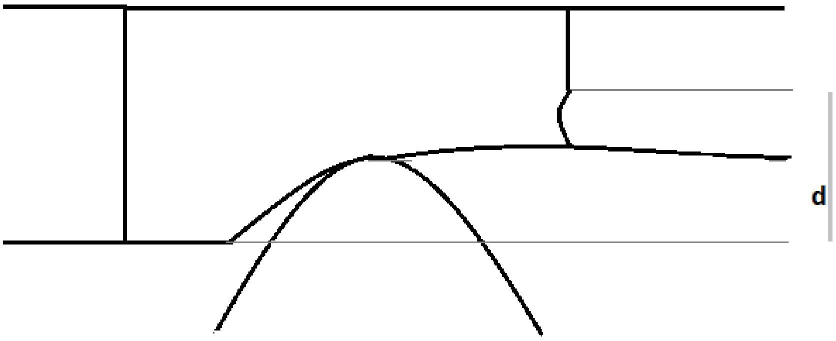

Figure 2: Example of maximum damage depth *d* in a grounding scenario

2.1. Data Analysis

To find out which variables influenced grounding damage the most, first qualitative visual analysis was used where the different variables were plotted against each other in a two-dimensional co-ordinate system. This was done to see which kind of (if any) dependency existed between variables. Furthermore, quantitative analysis was carried out; the correlation between the different variables was calculated.

Most notably, collision energy *E* has a positive, statistically significant correlation (2-way test, 5 % significance level) with: d (r = 0.577), $d \geq DB_H$ (0.622), l (0.867), s (0.805), v_1 (0.709), A (0.819) and Δv (0.745).

The damage area *A* seems to follow a linear dependency with the collision energy especially when the collision energy is no more than 300 MJ as illustrated in the following Figure 1 (with the linear equation as well as the coefficient of determination R^2):

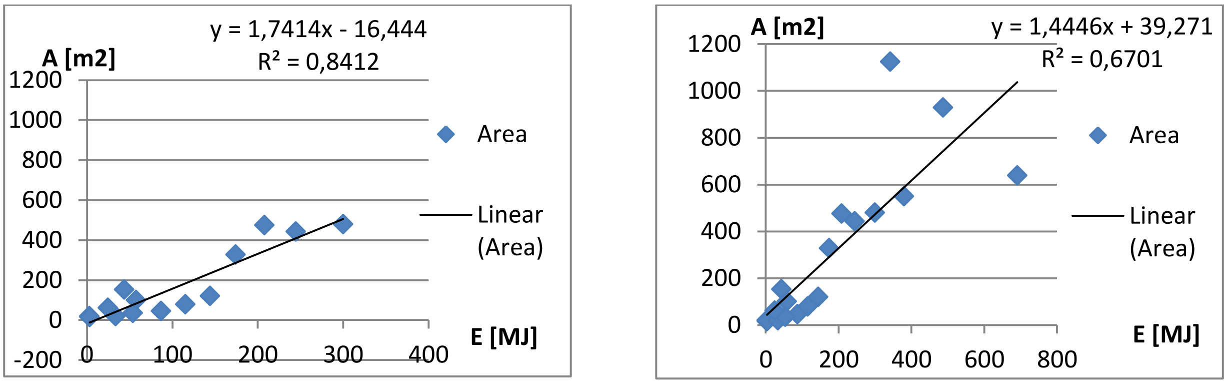

Figure 3: Damage area *A* [m^2] as a function of grounding energy *E* [MJ].
Left: cases with E < 300 MJ, right: all cases.

The total damage length *l* also depends quite linearly on the energy:

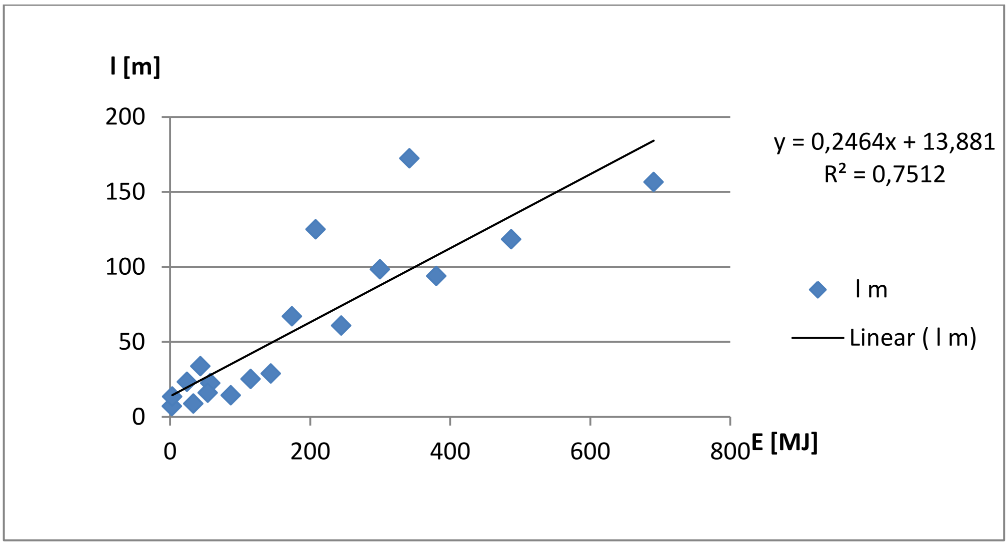

Figure 4: Damage total length *l* [m] as a function of grounding energy *E* [MJ].

The maximum damage depth *d* also depends somehow linearly on the grounding energy but only in the cases where $E < 400$ MJ.

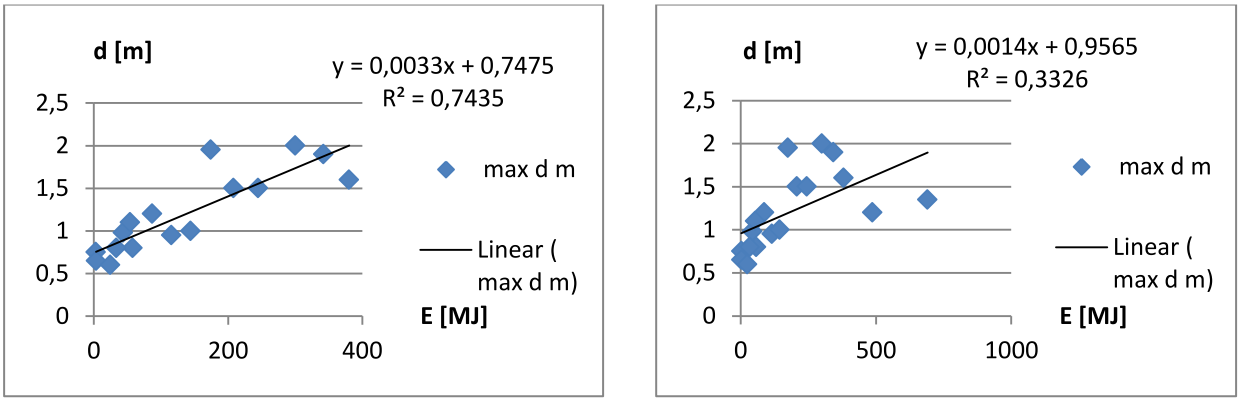

Figure 5: Damage maximum depth *d* [m] as a function of grounding energy *E* [MJ].
Left: cases with *E* < 400 MJ, right: all cases.

In order to estimate whether *d* equals or exceeds DB_H, a logistic regression model is used which has the following form [14]:

$$\Pr(d \geq DB_H) = \frac{1}{1+e^{-z}}, \tag{2}$$

where $z = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n$, x_i being the predictor variables and b_i their coefficients.

If $\Pr(d \geq DB_H) > 0.5$, it is assumed that that the grounding damage in the case equaled or exceeded the double bottom height and vice versa. Trying with different predictor variables *x*, the best prediction was achieved with just the grounding energy *E*:

$$\Pr(d \geq DB_H) = \frac{1}{1 + e^{2.475 - 0.011\,E}} \qquad (3)$$

This model correctly classifies 83.3 % of the cases from Luukkonen [13], performing significantly better for the $d < DB_H$ cases (prediction accuracy: 90.9 %) compared to the cases where $d \geq DB_H$ (accuracy: 71.4 %).

Table 3: Correct Classification Table

Observed in Luukkonen's data	Logistic regression model prediction*		
	$d \geq DB_H$		Percentage Correct
	0	1	
$d \geq DB_H =$ 0	10	1	90.9
$d \geq DB_H =$ 1	2	5	71.4
Overall Percentage			83.3

*The cut value is 0.5

Adding other variables such as initial velocity or double bottom height causes one or more of the x-variables to have a p-value of more than 0.05; i.e. that the variables are no longer statistically significant. The same problem is present in the other regression models presented earlier.

A logistic regression model for estimating whether $d > DB_H$ or not in case of grounding could not be constructed: The correct classification % was 0 (0/2 correct).

From equation 2 the cut-off point between $d \geq DB_H$ or not is at 225 MJ, which according to the model means that if the collision energy is 225 MJ or greater, then $d \geq DB_H$. This, however, is not entirely true: As can be seen in Table 1 there were 2 cases where MJ < 225 but still $d \geq DB_H$ and 1 case where E = 380.3 MJ but still $d < DB_H$. Looking at the cases there seems to be no obvious reason for the difference, this might be connected to bottom shape and type; information which is not included in the data.

Simplified this means that ships sailing in high-risk grounding areas can keep the probability of damage depth exceeding double bottom height low by keeping their velocity below a certain threshold, namely energy < 225 MJ (assuming v_2= 0). As the grounding energy also depends on the mass, heavier vessels must sail slower to avoid $d \geq DB_H$ in case of grounding as illustrated in Figure 4:

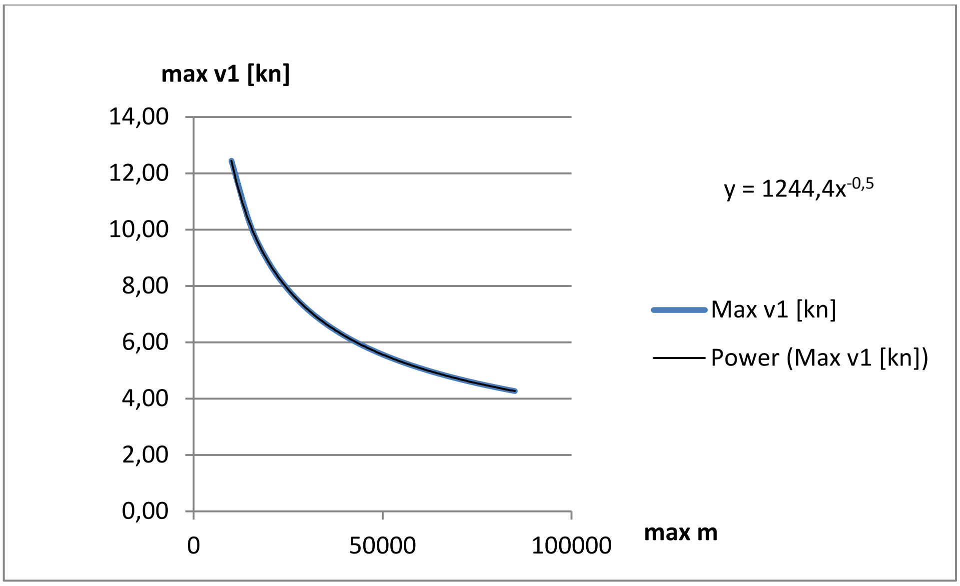

Figure 6: Maximum allowed velocity to avoid $d \geq DB_H$ in case of grounding

Though it must be noted that the vessels in this study had a displacement of 8500 – 57 000 tonnes, meaning extrapolating the results beyond this range might not be accurate, especially towards the lighter vessels as the allowed velocity grows drastically as the mass decreases; different (size) vessels have different hull strength. Note that one case with a displacement (~mass) of 9050 tonnes had a energy below 225 MJ (174.2) still had $d \geq DB_H$ with $v_1 = 11.5$ and $v_2 = 0$ meaning that any results obtained here should be interpreted with care. Luukkonen (1999) noted that groundings with energy of less than 144 MJ resulted in only damage to the ship shoulder or bow.

2.2. Bayesian Belief Networks

Even though the logistic regression model described above is fairly accurate, it cannot describe $d > DB_H$ nor take several x-variables into account with the given data. To make a more sophisticated model where more ship particulars can be used in estimation, two Bayesian Belief Networks (BBN) were constructed to estimate whether $d \geq DB_H$ and $d > DB_H$.

The structure of the BBN is based on the previously calculated correlations and a qualitative understanding of the causal effect dependencies. The network was built and learned using GeNIe software. See DSL [15] for further information on GeNIe and BBNs. For other applications of BBNs in maritime risk analysis see e.g. Goerlandt and Montewka [16], Hänninen et al. [17] or Montewka et al. [18]. The data for the BBNs shown in figures 7 and 8 was discretized as follows:

Table 4: Discretized data for BBN

GeNIe category tag	m (disp) [tonnes]	$d \geq DB_H$	$d > DB_H$	E [MJ]	DB_H [m]	v1 [kn]	Δv
s1	<10 000	0	0	< 50	<1.3	<4	<3
s2	10 -15 000	1	1	50-150	1.3-1.6	4-12	3-7
s3	15- 22 000			150-300	1.6-1.85	12-15	7-12
s4	>22 000			>300	>1.85	>15	>12

The so-called naïve Bayesian networks had the best prediction accuracies. Multi-level networks with many nodes and complex interdependencies could not achieve the same correct classification rates in terms of $d \geq DB_H$ and $d > DB_H$.

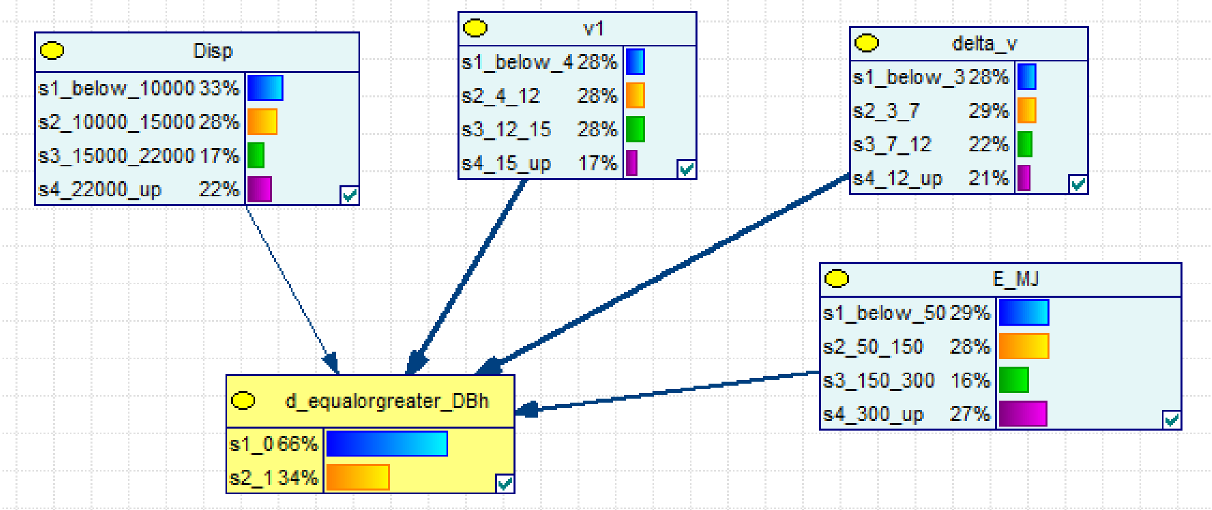

Figure 7: Discrete BBN for estimating $d \geq DB_H$ in grounding

This BBN can predict $d \geq DB_H$ with 100 % accuracy regardless of validation method (k-fold, leave one out). The thickness of the arrows in the figure indicates how significantly the different variables affect the results with v_1 and Δv being the most important variables.

The BBN for $d > DB_H$ looks as follows:

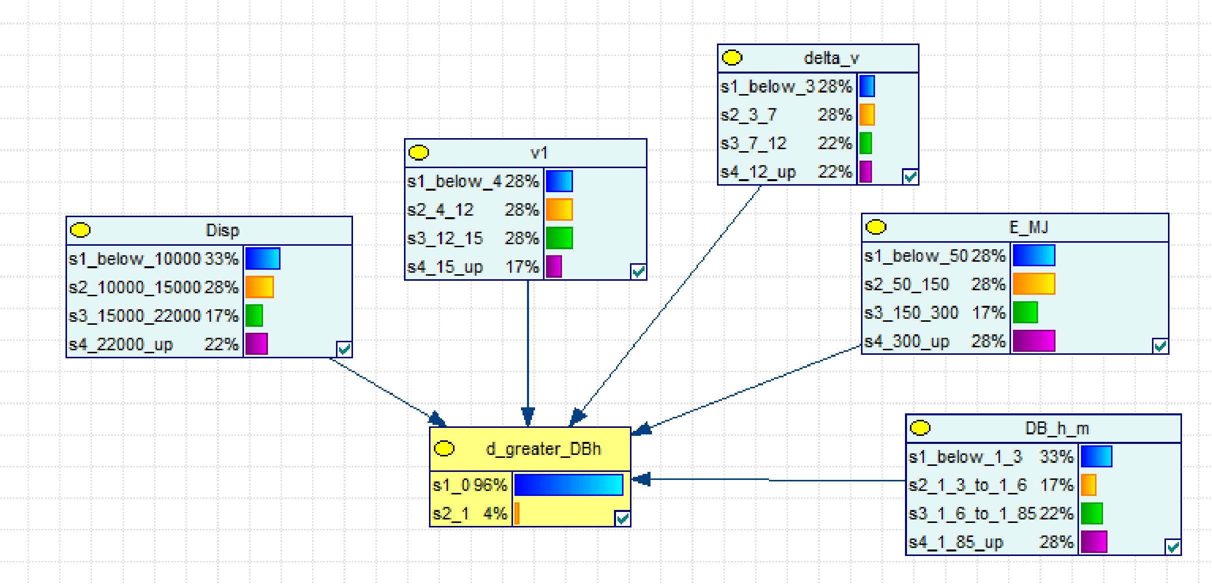

Figure 8: Discrete BBN for estimating $d > DB_H$ in grounding

Also in this case a 100 % prediction accuracy is achieved with k-fold validation (k=2). However, there are only 2 cases with $d > DB_H$ which means that in this model there is a noticeable deal of uncertainty.

3. CONCLUSIONS AND DISCUSSION

The models presented here could relatively accurately predict damage length and area in grounding situations. Surprisingly, this is possible even though information regarding bottom and grounding depth is missing. The most important equations are as follows:

Ship bottom damage area based on grounding energy:

$$A = 39.27 + 1.44\,E \tag{4}$$

Total damage length:

$$l = 13.88 + 0.25\,E \tag{5}$$

Damage depth (if $E < 400\ MJ$):

$$d = 0.75 + 0.0033\,E \tag{6}$$

Probability of $d \geq DB_H$:

$$\Pr(d \geq DB_H) = \frac{1}{1 + e^{2.475 - 0.011\,E}} \tag{3}$$

Furthermore, this paper presents a logistic regression model and two BBNs to predict whether the maximum damage extent is equal to or greater than the double bottom height. Knowing damage extent in one dimension (together with grounding energy, bottom shape and depth) can be used in models such as the ones presented by e.g. Cerup-Simonsen, Törnqvist and Lützen [11], Zhang [12] or Zhu, James and Zhang [7] to estimate the damage extent along the other dimensions as well.

Knowledge of damage extent along all dimensions (width, depth and length) can be used comprehensive risk analysis; e.g. to assess oil spill size in case of groundings. However, as stated in Luukkonen [13], d describes the maximum depth of damaged bottom structure – this means that having $d \geq DB_H$ does not equal that the inner bottom is actually penetrated. Also, the data is relatively limited with only 18 observations from Finnish territorial waters, based on ships with displacement of ~8500 to 57 000 tonnes. For these reasons, further research is proposed: Similar analysis should be run for a larger data set, the exact point where the inner bottom is ruptured should be recorded along with the grounding water depth and the bottom shape.

3.1. Acknowledgements

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