Statistical Estimation of Uncertainties Associated with Ship Operations in Fresh Water Ice

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ABSTRACT

Operational Time Window (OTW) and its confidence level are important for vessels operating in ice covered waters. This can be evaluated by quantifying all contributing factors in terms of their influence along with respective associated uncertainties. For a case study involving a barge operating in Lake Mälaren, Sweden, five criteria are evaluated, and associated uncertainties are quantified using Variation Mode and Effect Analysis (VMEA) to give individual contribution towards overall uncertainty. Ship resistance due to ice and ice loads dominated over other criteria with highest contributions to uncertainty at 28% and 72% respectively.

KEY WORDS: Variable Mode and Effect Analysis (VMEA), Ship Ice Resistance, Ice Loads, Fish Bone Method, Level Ice, Channel Ice, Confidence Interval, Uncertainty, Inland Waterways, Fresh Water Ice, Finnish-Swedish ice class regulations (FSICR)

INTRODUCTION

Inland Waterway Transportation (IWT) is a competitive alternative to road and rail transport, offering a sustainable and environment-friendly mode of transport (Wiegmans, Witte and Spit, 2015). It is also often the most economical inland transport mode with superior safety, high versatility, good reliability, low costs, high energy-efficiency, good carbon footprint, low noise levels and low infrastructure costs (Sihn, Pascher, Ott, Stein, Schumacher and Mascolo, 2015). In 2012, United Nations Economic Commission for Europe (UNECE) earmarked 29,172 km of Inland Waterways as E waterways (minimum dimensions of navigating vessels: 80.00 m x 9.50 m) in Europe. Sweden, a country characterized by its long coastline, lakes and inter connecting canals and rivers, is estimated to have IWW of 2052 km (CIA Statistics, 2018). This provides Swedish IWW with a huge potential to enhance existing transport network with IWT. However, due to geographical reasons, water bodies freeze for certain months during winter every year which impede usage of these water bodies.

Ships operating in ice are subjected to higher resistance and increased structural loads compared to open water. The difference can be attributed to ice properties like thickness, concentration, salinity, ambient temperature and its interaction with ship design variables like stem angle, flare angle (bow), hull strength etc. Several analytical, statistical, and numerical methods including class rules like Finnish-Swedish ice class regulations (FSICR) have been introduced in the past for estimating ship resistance and structural response in ice covered waters. However, these methods and existing research has been primarily focused on addressing sea water ice whose properties are very different from fresh water ice and direct application of these methods for prediction of ship performance in inland waterways is not accurate and subjected to associated uncertainty.

Avatar Logistics has plans to operate motorized barges in Lake Mälaren which is the third-largest freshwater lake in Sweden with an area spanning 1,140 km² and maximum depth 64 m. Between December and–April, the surface of the lake freezes with ice thickness less than 50 cm. The barge in mind is of length 135 m, breadth 11.45 m, max draught 3.4 m and max speed 13.7 knots, was originally designed to operate in open waters and its performance in ice covered waters is restricted. For the operator, it is of prime importance to know all factors influencing the OTW and its associated confidence interval CI.

Estimation of OTW is done by quantifying survivability of vessel against a set of external and internal conditions. CI on the other hand depends on the uncertainties associated with estimation of OTW. For a vessel operator, CI or reliability can be defined as the probability that the vessel conforms to estimated OTW over its lifetime. In engineering, one aims for high reliability and this is usually done by comparing system constraints with the ability of the vessel. In our case we can say, if the latter is greater than the system constraints with a 95% CI at all times during the design life, then vessels OTW can be called reliable. Reliability is subjected to three types of uncertainty sources which include (Svensson and Sandström, 2014),

1. Material uncertainties, external and internal loads and geometry
2. Modeling and Human Errors
3. Vaguely known and unknown sources of uncertainty

Methods to assess CI can be categorized under two groups (Svensson and Sandström, 2014).

1. Combining safety factors on essential sources based on the worst case

for all essential inputs.
2. Assign statistical distributions to all essential sources, perform a probabilistic evaluation and use a pre-determined low probability of failure to find a proper safety factor.

In engineering practice, it is common to find methodologies based on the first group, but these methods tend to overdesign. Statistically, simultaneous occurrence of a combination of worst cases is highly improbable. Besides, there is a lack of knowledge due to missing measurement / field data of the actual probability of occurrence, which is an additional drawback. The second group of methods is based on obtaining quantified probabilities of failure for different sources of uncertainty. This is usually done by observing the entire process of uncertainty propagation through the model for different design criteria. An associated drawback with those methods is that there is limited information on uncertainties and their statistical distributions. This consequently needs using advanced statistical methods based on inputs requiring expert judgement due to their subjective nature. For 2nd and 3rd type of uncertainties listed earlier, only rough estimates of their actual uncertainties and distributions are known.

In this paper, OTW is evaluated using 5 primary criteria, namely, Ship Resistance, Structural Loads, Machinery, Ship Strength, and Operations. These criteria are evaluated for their contributions to overall uncertainty using a statistical method VMEA (Variation Mode and Effect Analysis) which belongs to the second group of safety factor prediction. The inherent problem of weak knowledge on statistical uncertainties is solved by reducing the statistical complexity to second moment statistics (Johansson, Chakhunashvili, Barone, and Bergman, 2006). The approach helps reduce the uncertainty to a scalar measure of standard deviation for each source.

METHODOLOGY

VMEA helps identifying critical areas in terms of unwanted variation which can be used as a reliability tool to deduce confidence level of OTW for the barge. In our case VMEA helps to identify individual contributions of the uncertainties associated within the five identified primary criteria that are needed to assess overall confidence level of OTW. By identifying factors that cause the most uncertainty, design improvements can be guided to achieve a higher confidence level. There are three stages in which VMEA can be used. In the early pre-assessment stage, we use *basic* VMEA when only vague knowledge about the variation is available. The process helps identify different sources that could influence OTW. Further in the assessment process, when better judgements of the sources of uncertainties are available, *enhanced* VMEA is used, which is further developed into the *probabilistic* VMEA in the later design stages where more detailed information becomes available, and the goal is to verify the reliability targets and derive safety factors.

VMEA

The general procedure of VMEA is the same for all three levels. However, there is a difference in level of available information and implementation of steps. The broad methodology is as follows,

1. Target Variable Definition – the target variable is defined, i.e. the property to be studied. E.g., OTW, fatigue life etc.
2. Uncertainty Sources Identification - all sources of uncertainty that can have an impact on the target variable are identified.
3. Sensitivity Assessment – sensitivity coefficients of the sources of uncertainty with respect to the target variable are evaluated.
4. Uncertainty Size Assessment – quantify different sources of uncertainty.
5. Total Uncertainty Calculation - total resulting uncertainty in the output of the target function is calculated by combining contributions from all uncertainty sources.
6. Reliability and Robustness Evaluation - The result of the VMEA can be used to evaluate the reliability and robustness, e.g. to compare design concepts or to find the dominating uncertainties.
7. Improvement Actions - To identify uncertainty sources that can be improved and evaluated for their potential to increase reliability.

Identification of Sources of Uncertainty

There can be many possible sources that could influence OTW and contribute to uncertainty and it is important to consider all sources for the target variable. These should ideally include all three types of sources. A method to identify sources is by using a fishbone diagram. A

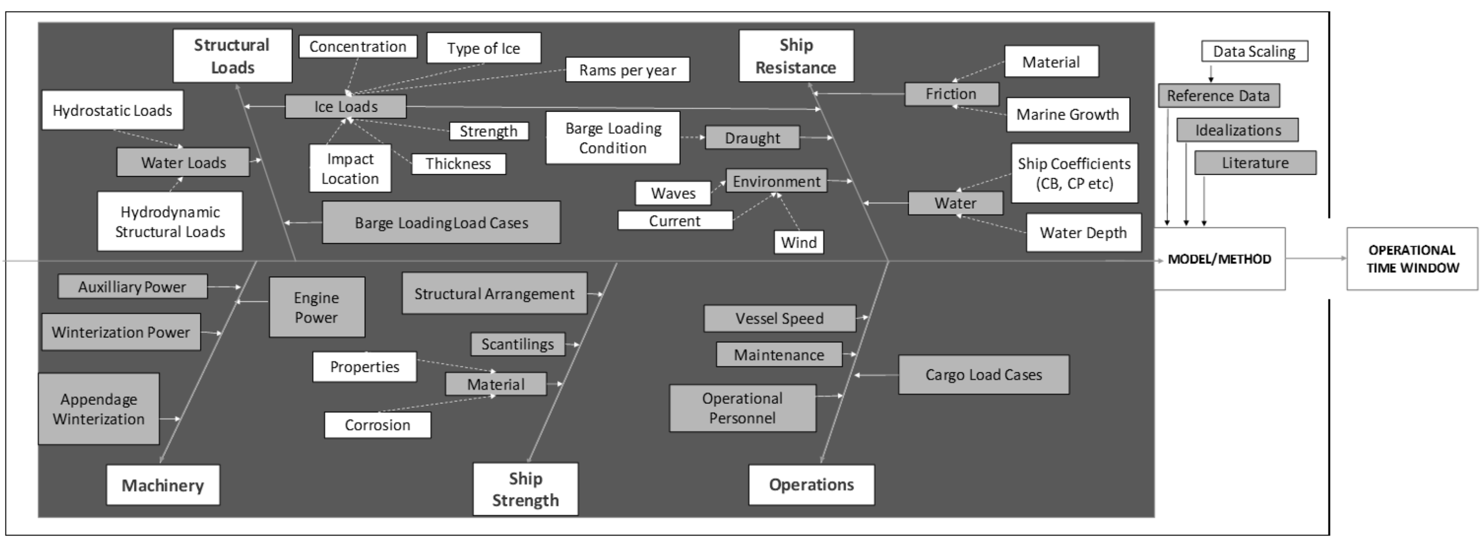


Fig. 1: Fish bone diagram depicting influence of different variables on the Operational Time Window for a barge. Area enclosed by grey box represent primary, secondary and tertiary dependencies influencing OTW. White boxes with bold alphabet represent primary criteria. Grey boxes represent secondary criteria while white boxes represent tertiary criteria. Influence on OTW by these dependencies depends on by efficiency of Method/Model box used to assess these.

fishbone (or Ishikawa) diagram is a graphical tool to explore and visualize the causes of a problem as well as the factors affecting the outcome of a process or the property of a product. The key steps to proceed with a fishbone diagram are:

1. Define Target Variable – (e.g., OTW)
2. Define major dependencies (e.g., primary criteria)
3. Brainstorm sources
4. Categorize sources
5. Determine secondary or tertiary dependencies
6. Add external filters if present on all dependencies

Fig. 1 shows a fish bone diagram developed to identify sources that influence OTW which is the target variable. Here primary criteria are *Ship Resistance, Structural Loads, Machinery, Ship Strength, and Operations*. The brainstorming step resulted in discovery of all possible mechanisms, conditions or events that contribute towards the objective function. Each outcome is then assigned to a respective primary criterion as a secondary criterion, with some criteria relating to multiple primary criteria. For example, Ice Loads is a secondary criterion for both Structural Loads and Ship Resistance. Tertiary criteria are added based on the level of detail one wants to achieve which are generally application dependent and decisions regarding this are based on the judgement of the analyst. In the final step, a method/model box is added through which all dependencies pass, and the global output gets skewed depending on the model efficiency. The process helps establish a cause-effect analysis that can facilitate the execution of VMEA, especially in its basic and enhanced formulations.

Basic VMEA

In basic VMEA, (Chakhunashvili, Johansson and Bergman, 2004) and (Johansson et al., 2006), the goal is to identify the most important sources of variation. The sizes of sources of variation and sensitivities to the studied product property are evaluated on a scale from 1 to 10. The strength of dependence of variables on objective function is characterized by summing the square of the product of sensitivity and variation size. Such an analysis helps indicate which sub-criteria or components are most critical, and thus need to be studied in more detail under enhanced VMEA. In this case for example it is of interest to identify the degree of dependencies for different criteria and how much uncertainty is transmitted in the evaluation of OTW. This step is largely subjective, and assessments are evaluated based on engineering experience, judgements, and informed guesses. Assessment is made using descriptions by Johansson, Chakhunashvili, Barone, and Bergman (2006) as given in Table 1 and Table 2. The importance of the different sources in basic VMEA is characterized by Variation Risk Priority Number (VRPN) which is calculated for each source as,

$$VRPN = \sum_i VRPN_i \text{ with } VRPN = c_i^2 \sigma_i^2 = \tau_i^2 \quad (1)$$

where $VRPN_i$ is the variation contribution due to source i, which is the square of the uncertainty, τ_i, which in turn is the product of the sensitivity, c_i, and the uncertainty, σ_i . VRPN's are used to calculate proportion on contribution to overall uncertainty for each source. The resulting uncertainties and the VRPNs are presented together with the proportion of the variance contributions of the sources. For selection of sources for enhanced VMEA, we calculated adjusted percentages from calculated proportions such that proportion of each tertiary source is divided by number of tertiary sources under the corresponding secondary sources. Then, sources that have a contribution of greater than 2% of adjusted percentage are included for analysis in enhanced VMEA.

Enhanced VMEA

Enhanced VMEA, (Chakhunashvili, Johansson and Bergman, 2009) follows the same steps as Basic VMEA but is more refined, looking further into the design process with the aim to understand and quantify the uncertainty sources in more detail. The main difference is that the sensitivities and uncertainty sizes are assessed in real physical units instead of a 1 to 10 scale. The assessment of uncertainties can be based on engineering judgement, but also be supported by initial testing, literature, and data sheets from manufacturers. Uncertainty for each source of uncertainty is represented by a measurable quantity that can be characterized by a nominal value and a standard deviation which represents the uncertainty size.

Table 1: Criteria for assessing sensitivity of sources in Basic VMEA (Johansson, Chakhunashvili, Barone, and Bergman, (2006)).

Sensitivity	*Criteria for assessing sensitivity*	*Score*
Very low	The uncertainty is (almost) not at all transmitted	1 - 2
Low	The uncertainty is transmitted to a small degree	3 - 4
Moderate	The uncertainty is transmitted to a moderate degree	5 - 6
High	The uncertainty is transmitted to a high degree	7 - 8
Very high	The uncertainty is transmitted to a very high degree	9 - 10

Table 2: Criteria for assessing uncertainty size of sources in Basic VMEA. (Johansson, Chakhunashvili, Barone, and Bergman, (2006)).

Uncertainty	*Criteria for assessing uncertainty size*	*Score*
Very low	The uncertainty source is considered to be almost *constant* in all possible conditions	1 - 2
Low	The uncertainty source exhibits *small fluctuations* in all possible conditions	3 - 4
Moderate	The uncertainty source exhibits *moderate fluctuations* in all possible conditions	5 - 6
High	The uncertainty source exhibits *high fluctuations* in all possible conditions	7 - 8
Very high	The uncertainty source exhibits *very high fluctuations* in all possible conditions	9 - 10

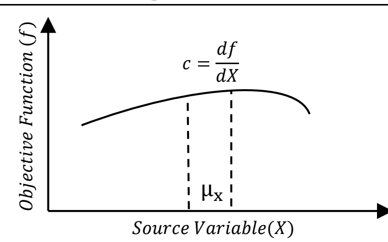


Fig. 2: Sensitivity of source depicted by slope across μ_x.

For a relationship between a target variable *Y* and an uncertainty source *X*, analytically described by a function *Y= f (X)*, mathematically, the sensitivity coefficient of *Y* to *X* is the first derivative of the function as,

$$c = \frac{df}{dX} \quad (2)$$

and the sensitivity is graphically represented by the slope of the curve (Fig. 2). The sensitivity will depend on the range μ_x which is spread across a range,

$$\mu_x \, \epsilon [(Median - 0.1.std), (Median + 0.1.std)] \quad (3)$$

where std is the standard deviation of source variable *'X'*. Then, sensitivity can be estimated as,

$$c = \frac{f(\mu_{x2}) - f(\mu_{x1})}{f(\mu_{x1})} \quad (4)$$

where, μ_{x1} and μ_{x2} are values of source variable 'X' at left and right bounds of μ_x. The sensitivity determines how much uncertainty is transferred to the target variable. The absolute value of sensitivity can theoretically range between 0 and +∞.

For the function $Y = f(X)$, Y has a range of values obtained for different uncertainty source values X. Then the standard deviation of Y gives the uncertainty size. For enhanced VMEA, it is advantageous to calculate standard deviation as a percentage of nominal value. The process helps normalize uncertainty sizes across different uncertainty sources in Table 1. This can be represented as,

$$s = \frac{std(Y)}{mean(Y)} \times 100\ \% \tag{5}$$

After assessing sensitivities and uncertainty sizes, the resulting uncertainties (τ_i) are calculated in the same way as for the basic VMEA as,

$$\tau_i = c_i \times s_i;\ variation = \tau_i^2 \tag{6}$$

RESULTS

Criteria shortlisting using basic VMEA

Criteria from Fig. 1 are assigned values for Sensitivity and Uncertainty size based on engineering judgment as shown in Table 3 by using criteria given in Table 1 and Table 2.

Uncertainty Size

In Table 3, under Structural Loads, uncertainty size is assigned very low for hydrostatic loads, hydrodynamic loads, and barge load cases since they are known or fixed by the operator for the barge under investigation. Influence due to ice loads is broken down into salinity, concentration, ice type, rams per year, ice thickness, impact location and evaluation method. Moderate uncertainty size is assigned to ice concentration, type, rams per year, thickness and evaluation method as these uncertainty sources are expected to exhibit moderate fluctuations for all possible conditions. Uncertainty size is assigned very low for salinity as Lake Mälaren is a fresh water body.

Under Ship Resistance, uncertainty size is assigned very low for draught of barge, current and waves, skin friction coefficient, ship design coefficients and operational depth as they are known. Uncertainty size is assigned moderate for wind as it is less predictable in the region. Resistance due to ice is split into ice concentration, ice type, thickness, and evaluation method as contributing factors. Uncertainty size is assigned as moderate for ice concentration and ice type and high for thickness and evaluation method. Under Operations, uncertainty size is assigned as very low for vessel speed, maintenance level, operating personnel, and cargo load cases as they are known or fixed by the operator.

Under Ship Strength, very low uncertainty size is assigned to structural arrangement, scantlings and material as the barge already exists and these criteria are fixed. Low uncertainty size is assigned to corrosion property of material. Under Machinery, very low uncertainty size is assigned to engine power, auxiliary power, winterization power and appendage winterization as they are known factors.

Sensitivity

In Table 3, under Structural Loads, moderate sensitivity is assigned to hydrostatic loads, hydrodynamic loads, and barge load cases due to expected moderate influence on structural loads relative to ice loads. Influence due to ice loads is broken down into salinity, concentration, ice type, rams per year, thickness, impact location and evaluation method. Very high sensitivity is assigned to evaluation method and high for concentration and type of ice due to the degree of influence they have in evaluation of structural loads. Low sensitivity is assigned to rams per year while very low sensitivity is assigned for impact location and ice thickness. Very low sensitivity is assigned for salinity in Lake Mälaren as it is a fresh water body.

Under Ship Resistance, very low sensitivity is assigned to current, waves and wind due to low influence and lack of current and waves in Lake Mälaren. Moderate sensitivity is assigned to draught and skin friction as additional ice strengthening of barge might influence change in ship coefficients for the barge. Resistance due to ice is split into concentration, ice type, thickness, and evaluation method as contributing factors. Low sensitivity is assigned to thickness and concentration while high sensitivity is assigned to ice type and evaluation method.

Under Operations, vessel speed, maintenance level, operating personnel, and cargo load cases are relatively known but since they have influence on operations that in turn influence OTW, high sensitivity is assigned to vessel speed, maintenance level, operating personnel, and cargo load cases. Under Ship Strength, high sensitivity is assigned to scantlings and structural arrangement while moderate sensitivity is assigned to material properties and corrosion characteristics. Under Machinery, high sensitivity is assigned to engine power and appendage winterization while low sensitivities are assigned for auxiliary power and winterization power.

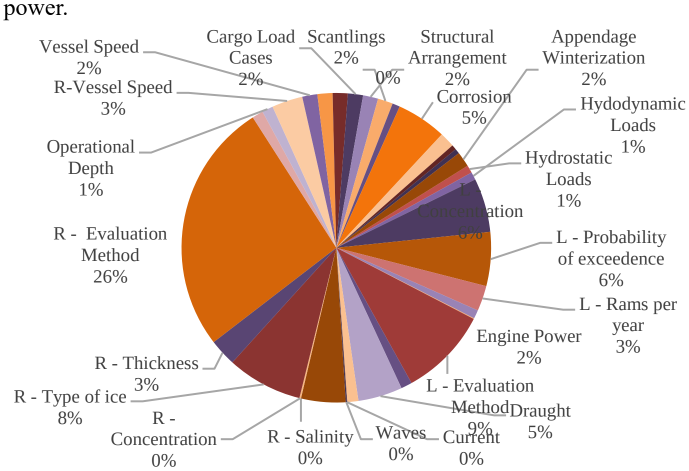


Fig. 3: Pie chart of uncertainty contributions of all criteria in Fig. 1 using Basic VMEA (R denotes criteria under Ice Resistance and L denotes criteria under Structural Loads due to ice).

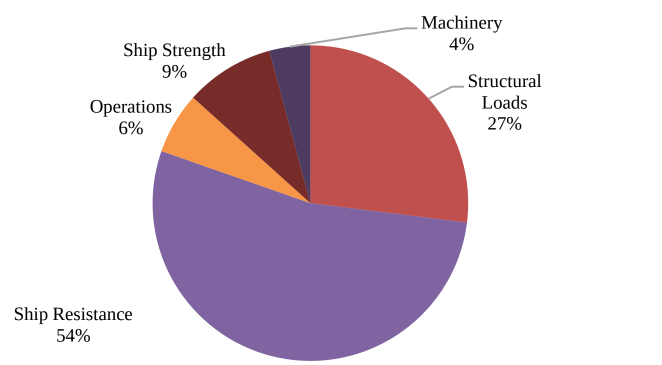


Fig. 4: Pie chart of uncertainty contributions from primary criteria in Fig. 1 using Basic VMEA.

Uncertainty contributions

All sensitivities and uncertainty sizes are shown in Table 3 for respective criteria and individual VRPN's are calculated using Eq. 1. VRPN for each criterion is then normalized against total VRPN to get individual contributions to overall uncertainty. In this case total VRPN is 12551 with maximum contributions from Evaluation Methods for Ship Resistance and Structural Loads. Fig, 3 shows individual percentage contributions for each criterion while Fig, 4 shows contributions from primary criteria as a pie chart. Ship Resistance and Structural Loads have the highest contributions to uncertainty with 54% and 27% respectively. Ship Strength had a contribution of 9% with contributions of 6% and 4% from Operations and Machinery. Under primary criteria, Ship Resistance and Structural Loads, Evaluation Methods have the highest contribution at 48% and 33% respectively. From the analysis, factors with a contribution greater than 2% are selected for analysis under Enhanced VMEA. List of chosen factors can be seen in Table 4.

Uncertainty estimation of chosen criteria using enhanced VMEA

Uncertainty size and sensitivity are calculated using Eq. 4 and Eq. 5 based on enhanced VMEA methodology. Largest contributors are shown in Fig. 5.

Uncertainty Size

In Table 4, under structural loads, under ice loads uncertainty size for ice concentration is calculated as 40.7% based on data collected by Swedish Meteorological and Hydrological Institute (SMHI) (2018) at 5 different locations in Lake Mälaren between 2003 and 2011. Uncertainty size for probability of exceedance is calculated as 68.2% based on information on distribution of type of ice collected by SMHI (2018). For estimating uncertainty size due to number of rams, we look at the following information. The barge operates at 11.4 knots when fully loaded and 13.7 knots when empty, duration of trip ranges between 4.3 h and 5.2 h. Rams per year are then calculated to range between 0.92 million to 1.11 million for a true hit proportion ratio of 0.5, loading frequency 1.07 s^{-1} (Kujala, Suominen and Riska, 2009) and event duration of 0.92 s. Using this information, uncertainty size of 13.2% based on the difference in number of rams is calculated.

For estimating the uncertainty size for the choice of evaluation method, design pressures due to ice loads are calculated based on deterministic method FSICR Ice Class rules (Trafi.fi, 2018) and probabilistic methods by Taylor, Jordaan, Li and Sudom, (2010) and Rahman, Taylor, Kennedy, Simões Ré, and Veitch (2015). According to Tõns, Freeman, Ehlers and Jordaan (2015), type of ice observed in Lake Mälaren can be classified as thin first year ice (0.3 m – 0.7 m). Ice thickness data from SMHI (2018) can be shown to be Weibull distributed with mean value 0.32 m. According to FSICR IC rules developed for sea conditions, design thickness of interacting ice is taken as 0.22 m. Then by FSICR design pressure is calculated by,

$$p = c_d . c_p . c_a . p_0 \tag{6}$$

Where p_0 = 5.6 MPa is the nominal ice pressure, c_d is influence from displacement, c_a is influence of load length and structural member response and c_p is adjustment due to location of impact on hull. Design pressure for transverse shell member in the forward region is calculated as 1.708 MPa. Assuming properties of fresh water ice in Lake Mälaren is similar to Lake Michigan, flexural strength is taken similar to Lake Michigan as 453 kPa (Tõns, Freeman, Ehlers and Jordaan, 2015 and Keinonen and Browne, 1991). For probabilistic methods, high pressure zone (HPZ) area A_c is calculated as the product of contact height h_c and contact length l_c. l_c is taken as frame spacing 0.5 m and h_c is calculated by Kujala (1994) as,

$$h_c = \frac{a_1(1+1.5(v_i sin\alpha_w)^{0.4})hi^{1.7}\sigma_f}{(\beta_n - 8.7^o)\sigma_{pc}}, \beta_n > 8.7^o \tag{7}$$

where a_1 = 7.02 is a constant, β_n = 55 degrees is normal frame angle and a_w = 45 degrees is waterline angle. A_c is then calculated as 0.096 m^2. According to Jordaan, Maes, Brown and Hermans (1993), relationship between nominal contact area a in m^2 and pressure α in MPa can be written as $\alpha = Ca^D$. For method by Taylor, Jordaan, Li and Sudom, (2010), North Bering dataset (1983) for extreme ice loads is most suitale to conditions in Lake Mälaren and is considered such that C = 0.28 and D = -0.62. For a probability of exceedance 0.5 and average ice concentration 0.85, design pressure is calculated as 3.63 MPa. For method by Rahman, Taylor, Kennedy, Simões Ré, and Veitch (2015), field test (2014) is used as reference dataset for calculation of α = 0.095 MPa. As opposed to method by Taylor, Jordaan, Li and Sudom, (2010), this method does not consider influence of contact area in estimation of α. For x0 = 0.02 in equation for extreme pressure (z_e) presented in Rahman, Taylor, Kennedy, Simões Ré, and Veitch (2015) and no. of events per km = 1550, design pressure is calculated as 0.952 MPa. Calculated design pressures due to the three methods are as shown in Fig. 11 with an observed uncertainty size of 66%.

Table 3: Table of uncertainty contributions and VRPN from different sources after BASIC VMEA.

INPUT			RESULT			
				Variation Contribution		
Source of Uncertainty	Sensitivity (c)	Uncertainty size (s)	Uncertainty	VRPN	Proportion	Adjusted percentages
Structural Loads						
Hydrostatic Loads	5	1	5	25	0.20	0.80
Hydodynamic Loads	5	1	5	25	0.20	0.80
Ice Loads						
L - Salinity	1	1	1	1	0.01	0.00
L - Concentration	7	5	35	1225	9.95	5.63
L - Probability of exceedence	7	5	35	1225	9.95	5.63
L - Rams per year	4	6	24	576	4.68	2.65
L - Thickness	2	7	14	196	1.59	0.90
L - Impact Location	1	4	4	16	0.13	0.07
L - Evaluation Method	9	5	45	2025	16.46	9.31
Barge Load Cases	6	1	6	36	0.29	1.16
Ship Resistance						
Draught	6	2	12	144	1.17	4.63
Wind	1	6	6	36	0.29	1.16
Current	1	1	1	1	0.01	0.03
Waves	2	1	2	4	0.03	0.13
Skin Fricion	6	2	12	144	1.17	4.63
Ice Resistance						
R - Salinity	1	1	1	1	0.01	0.01
R - Concentration	1	5	5	25	0.20	0.16
R - Type of ice	7	5	35	1225	9.95	7.89
R - Thickness	3	7	21	441	3.58	2.84
R - Evaluation Method	8	8	64	4096	33.28	26.37
Ship Coefficients	6	1	6	36	0.29	1.16
Operational Depth	3	2	6	36	0.29	1.16
Vessel Speed	5	2	10	100	0.81	3.22
Operations						
Vessel Speed	7	1	7	49	0.40	1.58
Maintenance Level	7	1	7	49	0.40	1.58
Operating personnel	7	1	7	49	0.40	1.58
Cargo Load Cases	7	1	7	49	0.40	1.58
Ship Strength						
Structural Arrangement	7	1	7	49	0.40	1.58
Scantlings	7	1	7	49	0.40	1.58
Material						
Properties	7	1	7	49	0.40	0.79
Corrosion	6	3	18	324	2.63	5.21
Machinery						
Engine Power	7	1	7	49	0.40	1.58
Auxiliarry Power	4	1	4	16	0.13	0.51
Winterization Power	4	1	4	16	0.13	0.51
Appendage Winterization	7	1	7	49	0.40	1.58
Total				12306	100	100

Under Ship Resistance, uncertainty size for operational draughts is calculated as 12% based on information from barge operator taken for different loading conditions. Uncertainty size for skin friction coefficient is calculated as 28.8% based on information from the operator. Uncertainty size for operational depth is 137% based on information from bathymetric charts (gpsnauticalcharts.com, 2018) of Lake Mälaren. Uncertainty size of 12% is calculated for vessel Speed based on information on range of operational speeds from barge operator. For resistance due to ice loads, uncertainty sizes for concentration, type of ice and thickness are calculated as 40.7%, 68.2% and 68.6% respectively based on ice information from SMHI (2018). Uncertainty size for choice of evaluation method is 42.6%, calculated based on methods by Riska, Wilhelmson, Englund and Leiviskä, (1997), Keinonen, Browne, Revill and Reynolds (1996), Lindqvist (1989), Jeong, Lee, and Cho (2010) and towing tank experiments carried out by Hu and Zhou (2016) for a 150 m barge having a beam of 21m and a draught of 9.5m which is comparable in size with the barge under investigation. The experiments were conducted for a relative ice-vessel velocity of 2.2 knots and ice thickness 0.63m. Under Ship Strength, uncertainty size due to corrosion is calculated as 28.6% assuming corrosion has a uniform distribution with information from DNV GL Rules (Rule Book - DNV-RP-C101, 2007).

Sensitivity

In Table 4, under structural loads, under ice loads, sensitivity to concentration of ice is calculated as 0.006 based on observing variation of ice compressive strength at different concentrations based on formula given by Kujala, (1994) for a range of concentrations, see fig. 14. For a probability of exceedance 0.5, ice thickness 0.22 m and ice concentration between 0.8-0.9, sensitivity of design pressure to probability of exceedance is calculated as 0.01 based on method by Taylor, Jordaan, Li and Sudom, (2010), see fig. 15. Sensitivity of design pressure to number of rams per km is estimated as 0.6 based on method by Rahman, Taylor, Kennedy, Simões Ré, and Veitch (2015), see fig. 12. Further, for the same ice thickness and ice concentration values, for the bow area, sensitivity of design pressure to choice of evaluation method is evaluated as 2.81 for deterministic method FSICR (Trafi.fi, 2018) and probabilistic methods based on Taylor, Jordaan, Li and Sudom, (2010) and Rahman, Taylor, Kennedy, Simões Ré, and Veitch (2015, see fig. 11.

Under Ship Resistance, sensitivity of frictional resistance due to draught and skin friction coefficient are calculated as 0.02 and 0.14 for the barge based on ITTC resistance formula (2001) (Ittc.info, 2018) shown in figs. 6 and 13. Sensitivity for total ship resistance and its dependence on speed for the barge is calculated as 0.26 based on Delft Series (Delftship.net, 2018, see fig. 10. Relative uncertainty due to influence of operational depth on resistance is seen to have no influence and is taken as 0 due to sufficient depth with no possibility for shallow water effects. For resistance due to ice loads, sensitivity to ice thickness is calculated as 0.64 using method by Riska, Wilhelmson, Englund and Leiviskä, (1997) for the barge, see fig. 6). Sensitivity of resistance on type of ice is calculated as 0.82 based on experiments done by Hu and Zhou (2016) for level ice and brash ice at concentrations of 40% and 90%, see fig. 8. Sensitivity due to choice of evaluation method is calculated as 2.11 based on evaluation methods by Riska, Wilhelmson, Englund and Leiviskä, (1997), Keinonen, Browne, Revill and Reynolds (1996), Lindqvist (1989), Jeong, Lee, and Cho (2010) and towing tank experiments carried out by Hu and Zhou (2016) for a 150 m barge having a beam of 21m and a draught of 9.5m, see fig. 7. Under Machinery, sensitivity for corrosion is taken as 0 as the barge is regularly inspected and undergoes regular maintenance based on information provided by the operator.

Uncertainty contributions

From Table 4, total uncertainty *(τ)* of 393 is observed with maximum contributions from structural loads and ship resistance primary criteria at 196 and 197 respectively. Fig, 5 shows percentage contributions for all secondary criteria on a scale of 100.

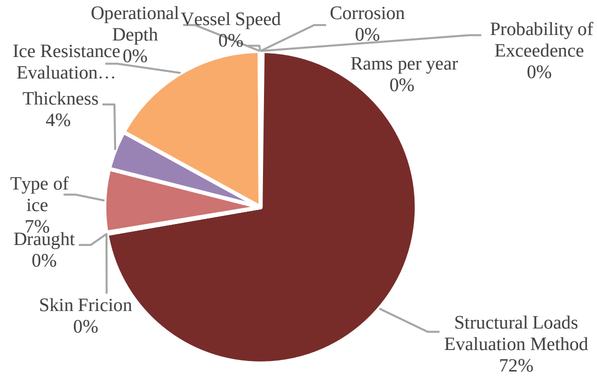


Fig. 5: Pie chart of uncertainty contributions from different sources after Enhanced VMEA

Table 4: Table of uncertainty contributions and VRPN from different sources after Enhanced VMEA

INPUT			RESULT		
Source of Uncertainty	Sensitivity	Uncertainty size (%)	Uncertainty (%)	Variation Contribution	
				VRPN	Proportion
Structural Loads					
Ice Loads					
Concentration	0.006	40.70%	0.24	0.06	0.0001
Probability of Exceedence	0.01	68.20%	0.68	0.47	0.0010
Rams per year	0.6	16.80%	10.08	101.61	0.21
Evaluation Method	2.81	66%	185.46	34395.41	72.17
Ship Resistance					
Draught	0.02	12%	0.24	0.06	0.0001
Skin Fricion	0.14	28.80%	4.03	16.26	0.03
Ice Friction					
Type of ice	0.82	68.20%	55.92	3127.49	6.56
Thickness	0.64	68.60%	43.90	1927.56	4.04
Evaluation Method	2.11	42.60%	89.89	8079.49	16.95
Operational Depth	0	137%	0.00	0.00	0.00
Vessel Speed	0.26	12%	3.12	9.73	0.02
Ship Strength					
Material					
Corrosion	0	10%	0.00	0.00	0.00
Total			393.57	47658.14	100.00

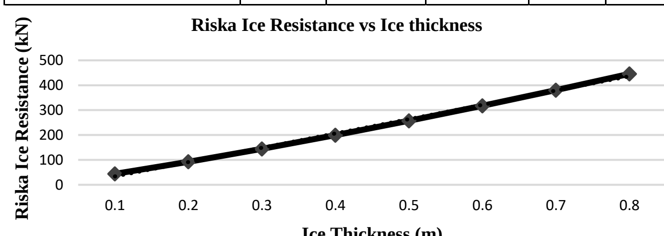
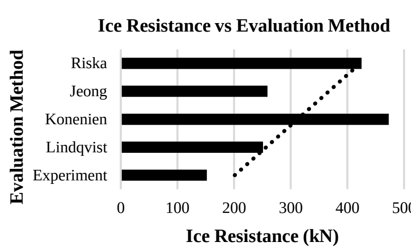


Fig. 6: Distribution of Ice Resistance for varying ice thickness (Riska, Wilhelmson, Englund and Leiviskä, (1997).



1: Riska, Wilhelmson, Englund and Leiviskä, (1997)
2: Jeong, Lee, and Cho (2010)
3: Keinonen, Browne, Revill and Reynolds (1996)
4: Lindqvist (1989)
5: Towing tank experiments carried out by Hu and Zhou (2016)

Fig. 7: Ice Resistance evaluated using different methods and experiments.

DISCUSSIONS

Interpretation of Results

On a scale of 100, primary criteria - Structural Loads and Ice Resistance constituted 72% and 28% of total uncertainty respectively. Evaluation methods for structural loads and ice resistance estimation in fresh water ice for inland waterways had the highest contribution to total uncertainty at 72% and 17% respectively. The results support the fact that there is lack of evaluation methods that sufficiently describe vessel behavior in ice covered fresh water bodies. If experiments are performed in fresh water ice covered waters and the data is used to calibrate existing methods or lead to development of new models, then overall uncertainty towards OTW has potential to be reduced by approximately 70%.

Third and Fourth largest sources of uncertainty are due to the big scatter on ice thickness and type of ice in Lake Mälaren. Since resistance on ice depends strongly on these factors, uncertainty due to them is nature dependent and cannot be reduced much. However, if the ship is designed conservatively for strong ice conditions, associated uncertainty can be reduced with acceptable loss in efficiency during minimal ice conditions.

Sensitivity evaluation for enhanced VMEA

From Fig. 1, primary criteria influence OTW and it can be seen from the hierarchy that secondary criteria constitute and influence primary criteria. For example, vessel speed, maintenance etc. constitute operations which in turn influences OTW. Ideally, sensitivity of a OTW to a particular secondary criteria t_{12} can be represented as,

$$Sensitivity = \frac{dOTW}{dt_{12}} = \frac{dOTW}{dt_1} . \frac{dt_1}{dt_{12}} \qquad (8)$$

Where, t_1 and t_{12} represent primary and secondary criteria with first index representing primary criteria number and second index representing secondary criteria number. Since each primary criterion can be represented as a sum of all secondary criteria, influence of a primary criterion on OTW can be written as a sum of influences from all secondary criteria. Hence, we can make the following simplification provided influence from all secondary criteria are considered. Sensitivity in Eq. 8 can then be approximated as,

$$\frac{dOTW}{dt_1} \sim 1 \; ; \; Sensitivity = \frac{dt_1}{dt_{12}} \qquad (9)$$

Ice Compressive Strength as measure of loads due to ice concentration

Due to non-availability of information for influence of ice concentration on the loads experienced by a vessel, it is assumed that compressive strength of ice gives a good indication of loads that a vessel might face when it comes in direct contact with ice.

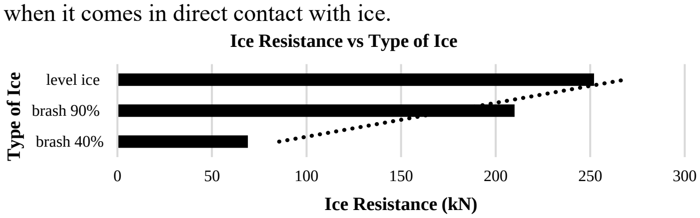


Fig. 8: Ice Resistance evaluated for different types of ice based on towing tank experiments carried out by Hu and Zhou (2016).

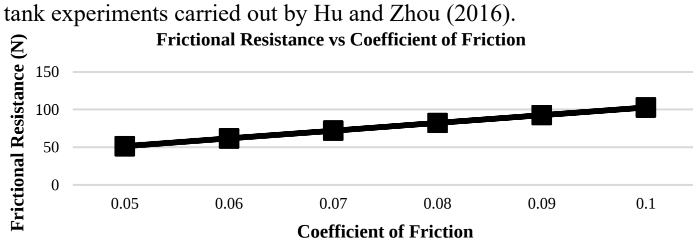


Fig. 9: Frictional Resistance component and its dependence on skin friction coefficient. (ITTC resistance formula (2002) (Ittc.info, 2018).

Other sources of uncertainty and limitation of data

There is a limitation on data available from field tests and towing tank tests. For example, data from only 6 experiments carried out by Hu and Zhou (2016) were available to assess resistance in brash ice at different concentrations. Further, the experiments were done in an environment to simulate a channel ice condition. Limitation of sufficient data and availability of indirect data increases a degree of uncertainty when used as input in VMEA. This may either overestimate or underestimate overall influence. Results obtained from enhanced VMEA are only indicative and should not be taken as absolute. However, the analysis shows relative importance of criteria and their respective contributions to overall uncertainty.

Further, for comparison between resistance methods Hu and Zhou (2016), carried out tests for ice thickness 0.63 m which is higher than that found in Lake Mälaren.

The endeavor within the paper is to try and include all sources that could influence OTW. However, there could be other sources that are not considered in the analysis that could have influence on OTW. Moreover, in Basic and Enhanced VMEA, unknown and vaguely known sources of uncertainty are not included. These however will be modeled in probabilistic VMEA.

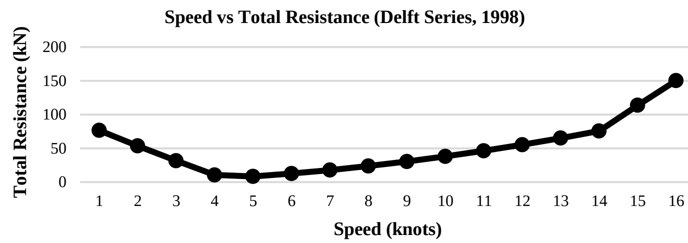


Fig. 10: Total Resistance and its dependence on velocity using Delft series. (Delftship.net, 2018).

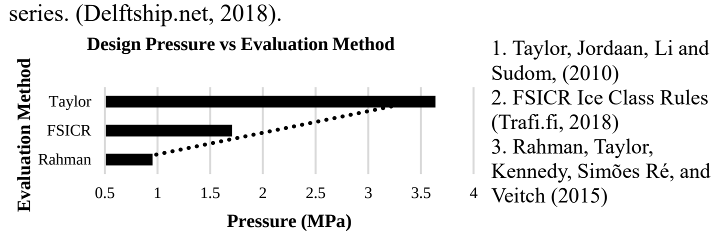


Fig. 11: Pressure evaluated using different evaluation methods.

Ice Resistance Evaluation Method Sensitivity

Sensitivity for choice of evaluation method for ice resistance estimation is found to be 2.11 for a vessel-ice relative speed of 2.2 knots. However, for 5.5 knots, sensitivity is 0.8 and for 11 knots, sensitivity is 0.64. The trend shows there is a reduction in overall uncertainty at higher speeds.

CONCLUSIONS

The paper presented an uncertainty evaluation of criteria influencing the OTW for a barge operating in fresh water ice conditions using VMEA. Criteria uncertainty were evaluated by finding the product of how much variation they exhibit in their distribution (uncertainty size) and how sensitive they are to change (sensitivity). Evaluations of sensitivity and uncertainty size were carried out using information from operator, statistical agencies, published literature and engineering judgment. The results suggest that primary criteria, Structural Loads and Ship Resistance had maximum associated uncertainty with evaluation methods as leading contributors. Evaluation methods for structural loads had 72% uncertainty contribution and evaluation method for ship resistance in ice covered waters had 17% contribution. The results can be explained by the observation that existing models describing ship behavior in fresh water ice is currently lacking. There are several methods and established literature for ship performance in sea water ice but since fresh water ice is very different in properties, these methods cannot be directly applied. The results point towards a need for experimental studies in fresh water ice for development of new methods or adaptation of existing methods. There is a potential for reducing overall OTW uncertainty by about 70% if evaluation methods for ship resistance and structural loads are developed to accurately describe ship performance in fresh water ice.

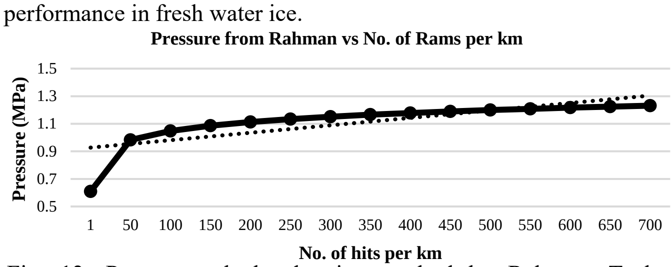


Fig. 12: Pressure calculated using method by Rahman, Taylor, Kennedy, Simões Ré, and Veitch (2015) for different rams per km.

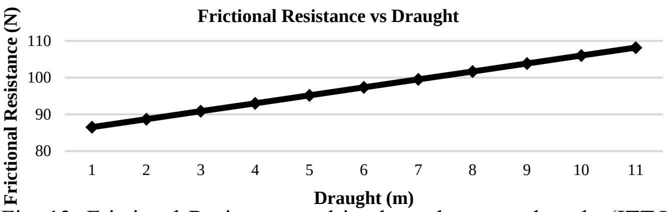


Fig. 13: Frictional Resistance and its dependence on draught (ITTC resistance formula (2002) (Ittc.info, 2018).

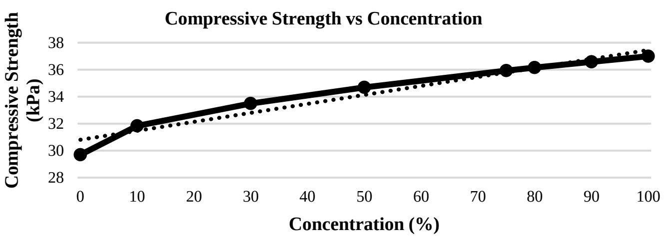


Fig. 14: Compressive strength of ice and its dependence on ice concentration (Kujala, 1994).

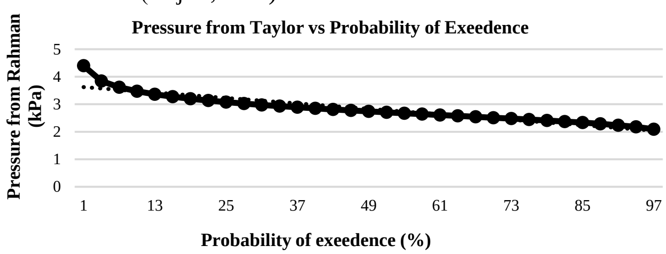


Fig. 15: Pressure and its dependence on probability of exceedance (Taylor, Jordaan, Li and Sudom, 2010).

REFERENCES

Chakhunashvili, A., Johansson, P. & Bergman, B. (2009): Robust product development using variation mode and effect analysis. In (Bergman et al., 2009), pp. 57-70.

Chakhunashvili, A.; Johansson, P. & Bergman, B. (2004): Variation Mode and Effect Analysis. Proceedings of the Annual Reliability and Maintainability Symposium, 364 - 369.

CIA Statistics, (2018). [online] Available at: https://www.cia.gov/library/publications/the-world-factbook/fields/print2093.html [Accessed 11 Jan. 2018].

Delftship.net. (2018). Home. [online] Available at: http://www.delftship.net/ [Accessed 11 Jan. 2018].

GPS Nautical Charts – Lake Mälaren, (2018). [online] Available at: https://www.gpsnauticalcharts.com/ [Accessed 11 Jan. 2018].

Hu, J. and Zhou, L. (2016). Further study on level ice resistance and channel resistance for an icebreaking vessel. International Journal of Naval Architecture and Ocean Engineering, 8(2), pp.169-176.

Ittc.info. (2018). Resistance Uncertainty Analysis, Example for Resistance Test. [online] Available at: https://ittc.info/media/2021/75-02-02-02.pdf [Accessed 11 Jan. 2018].

Jeong, S.Y., Lee, C.J., Cho, S.R., 2010. Ice resistance prediction for standard icebreaker model ship. In: Proceedings of the Twentieth (2010) International Offshore and Polar Engineering Conference, Beijing, China, 20e25 June 2010, pp. 1300e1304.

Johansson, P., Chakhunashvili, A., Barone, S. and Bergman, B. (2006). Variation Mode and Effect Analysis: a Practical Tool for Quality Improvement. Quality and Reliability Engineering International, 22(8), pp.865-876.

Jordaan, I., Maes, M., Brown, P., and Hermans, I., 1993, "Probabilistic Analysis of Local Ice Pressures", Journal of Offshore Mechanics and Arctic Engineering, 115(1), p. 83.

Keinonen, A., Browne, R.P., 1991. Icebreaker performance prediction. SNAME Transactions, Vol. 99, 1991, pp. 221-248.

Keinonen, A.J., Browne, R., Revill, C., Reynolds, A., 1996. Icebreaker Characteristics Synthesis. report TP 12812E. The Transportation Development Centre, Transport Canada, Ontario.

Kujala, P., 1994. On the statistics of ice loads on ship hull in the Baltic. Dissertation. Acta Polytechina Scandinavica, Mechanical Engineering Series No. 116. Helsinki. 98 p.

Kujala, P., Suominen, M., Riska, K., 2009. Statistics of Ice Loads Measured on MT Uikku in the Baltic. Proceedings of POAC 2009.

Lindqvist, G., 1989. A straightforward method for calculation of ice resistance of ships. In: Proceedings of 10th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Lulea, Sweden, 12e16 June 1989, pp. 722e735.

Rahman, M., Taylor, R., Kennedy, A., Simões Ré, A., and Veitch, B., 2015, "Probabilistic Analysis of Local Ice Loads on a Lifeboat Measured in Full-Scale Field Trials", Journal of Offshore Mechanics and Arctic Engineering, 137(4), p. 041501.

Riska, K., Wilhelmson, M., Englund, K., Leiviskä, T., 1997. Performance of Merchant Vessels in the Baltic. Research report no 52. Helsinki university of technology, ship laboratory, Winter Navigation Research Board, Espoo.

Rules.dnvgl.com. (2018). Allowable thickness diminution for hull structure of offshore ships. [online] Available at: https://rules.dnvgl.com /docs/pdf/DNV/codes/docs/2007-04/RP-C101.pdf [Accessed 11 Jan. 2018].

Sihn, W., Pascher, H., Ott, K., Stein, S., Schumacher, A. and Mascolo, G. (2015). A Green and Economic Future of Inland Waterway Shipping. Procedia CIRP, 29, pp.317-322.

SMHI. (2018). smhi.se. [online] Available at: http://smhi.se [Acessed 11 Jan. 2018].

Svensson, T., Sandström J., 2014. Load/Strength analysis of wave energy components. SP Rapport 2014:80. URL http://publikationer.extweb.sp.se/user/default.aspx?RapportId=20469

Taylor, R., Jordaan, I., Li, C. and Sudom, D. (2010). Local Design Pressures for Structures in Ice: Analysis of Full-Scale Data. Journal of Offshore Mechanics and Arctic Engineering, 132(3), p.031502.

Tõns T., Freeman R., Ehlers S., Jordaan I.J., 2015. Probabilistic design load method for the Northen Sea Route. ASME 2015. In: Proceedings of the 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2015), May 31–June 5, 2015, St. John's, Newfoundland, Canada.

Trafi.fi. (2018). FSICR Ice Class Rules. [online] Available at: https://www.trafi.fi/filebank/a/1510737568/021da3a49321139231df02 7d50ff5b13/28389-TRAFI_494_131_03_04_01_00_2016_EN_ Jaaluokkamaarays_2017 .pdf [Accessed 11 Jan. 2018].

Wiegmans, B., Witte, P. and Spit, T. (2015). Characteristics of European inland ports: A statistical analysis of inland waterway port development in Dutch municipalities. Transportation Research Part A: Policy and Practice, 78, pp.566-577.