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Risk-based Winterization on a North Atlantic-based Ferry Design

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The Arctic is a recent focal point of the marine and offshore industries. Winterization is required for safe and efficient operations in these harsh cold environments. A risk-based approach to winterization was recently proposed to provide a quantitative way of determining the need for winterization and its appropriate level. To further validate and enhance this approach, it has been applied to a new ice-class passenger ferry design, which will operate in a particular area of the North Atlantic. This location is ideal for the application with low temperatures, strong wind, and high waves. To facilitate this application and eliminate some limitations of the proposed approach, this article proposes a generic framework of risk-based winterization. Results from this article validated the effectiveness and feasibility of using risk-based winterization on vessel designs.

Keywords: winterization; risk assessment; ferry design; cold environments

1. Introduction

THE MARINE and offshore industries have been dealing with winterization for many years. Offshore rigs are winterized to allow year-round drilling in subarctic regions (Baller 1983). Potential of icing was considered to develop winterization measures for offshore drilling in cold environments (Keener & Allan 2009). Ice protection strategies for functional platform areas were proposed and reviewed (Ryerson 2011). A ship's thermal responses were modeled for proper selection of construction materials of hull and equipment exposed to low-temperature effects (Gospic et al. 2011). Torheim and Gudmestad (2011) proposed some requirements for the secure launch of lifeboats in cold climate. However, winterization is still a challenging subject that causes grief to many who wish to venture into the harsh cold environments for hydrocarbon resources or shorter navigation routes. Most guidelines developed by classification societies provide prescriptive requirements for winterization, e.g., Guide for Vessels Operating in Low Temperature Environments (LTE Guide) developed by the American Bureau of Shipping (ABS). These requirements may not be applicable to many situations considering the varieties of vessel systems and arrangements, environmental conditions, and operational profiles. Systems on modern vessels and offshore operation units are complex and these systems will continue to see a novel concept used to take on new operational challenges in harsh cold environments. Therefore, it becomes almost impossible to provide a complete guideline or rule set for winterizing an installation. Considering this challenge, a risk-based approach to winterization was proposed (Yang et al. 2013). This quantitative approach is intended to provide a way of determining the need for winterization and its level on a case-by-case basis. Risk assessment is nothing new for the marine and offshore industries. Classification societies have published general guidance notes on risk assessment and its applications to vessel design and operations (e.g., ABS 2000, 2003). These guidelines have laid a good foundation for the acceptance and application of the risk-based approach by the marine and offshore industries.

The proposed risk-based winterization approach needs to be further validated and enhanced for ease of practical applications. This article proposes a holistic framework of risk-based winterization to support its implementation. The foundations of this risk-based approach are historical data, operational experience, experts' knowledge and judgments, and analytical risk analysis methods (either

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quantitative or qualitative). Winterization is defined in this article as the adaption of conventional vessels, installation designs, and their operations to mitigate the effects of icing in low-temperature environments for safe operations. This study primarily focuses on winterization of the systems on board the vessel (especially those systems that are exposed to atmospheric air because they may more likely have icing problems). Ice conditions and material properties in low-temperature environments are beyond the scope of this study. This study applied the risk-based approach to a new ice-classed passenger ferry design that is known to be winterized for year-round operation in the North Atlantic. This particular location is ideal for the application with temperature as low as –25°C combined with strong winds and high waves often resulting in potentially extreme ice accretion conditions. The new ferry design is known to have incorporated decades of experience operating in this region and therefore it can be considered with some confidence that the winterization plans applied to the design will be more than adequate for the region of operation. This design sets an acceptable benchmark to evaluate the new risk-based approach.

The proposed risk-based winterization framework aims to provide a supplementary tool to handle the winterization issues that are not addressed by the recognized ice class rules (e.g., the ABS Guide for Building and Classing Vessels Intended for Navigation in Polar Waters) and the cases where the ABS LTE Guide are not applicable. In this article, the ice class requirements have not been associated with the environmental attributes used in risk calculations, e.g., operating envelope and maximum allowable temperature difference between the operating envelope and the environmental load. Vessel operators need to specify these values in the proposed approach.

The rest of this article is structured as follows. Section 2 discusses factors that need to be considered in environmental load modeling. Section 3 proposes a complete framework for winterization analysis on vessel design using the risk-based approach. In Section 4, following the proposed framework, the new ferry design is assessed and optimized for the purpose of winterization. Part of the results and findings of the analysis is summarized in this section. Additionally, case study examples are provided to demonstrate how these results were achieved through the application of the risk-based approach highlighting the major steps in the proposed framework. Finally, Section 5 provides conclusions and some recommendations for future work.

2. Environmental load modeling

2.1. Temperature

Temperature appears to be a simple attribute of environmental loading but defining it is no simple task. There has been some debate about it lately. The ABS LTE Guide defines three temperatures as (ABS 2010):

(1) Design Internal Temperature: The design internal temperature, also denoted as T_{DIT}, is applicable for machinery located in closed, unheated spaces. It is determined from the Design Service Temperature plus 20°C (36°F) ($T_{DIT} = T_{DST} + 20$). In no case is the design internal temperature to be greater than 0°C (32°F).

(2) Design Service Temperature: The design service temperature, also denoted by T_{DST}, is to be taken as the lowest mean daily average air temperature (LMDAT) in the area of operation where:

- Mean: Statistical mean over observation period (at least 20 years).
- Average: Average during 1 day and night.
- Lowest: Lowest during the year.

(3) Minimum Anticipated Temperature: The minimum anticipated temperature, also denoted as T_{MAT}, can be specified by the designer, owner, or builder. In the absence of temperature data for the trading area, the minimum anticipated temperature can be determined as the Design Service Temperature minus 20°C (36°F) ($T_{MAT} = T_{DST} - 20$) for exposed machinery. An alternative T_{MAT} definition was recently presented: the minimum temperature in the ship operation area taking into account the period of navigation. This temperature should not be greater than LMDAT – 2 σ, where σ is the standard deviation of LMDAT.

The ferry design under consideration will operate in a particular area of the North Atlantic. Climate statistics of North Atlantic are sufficient. Surface climate of the North Atlantic, which includes sea surface temperature, air temperature, wind, and sea level pressure, has been studied in depth (Deser & Blackmon 1993; Kushnir 1994; Saenger et al. 2009). Historical air temperature data were collected from climatology stations located in the area where the ferry will be operating. The mentioned temperatures are graphically shown in Fig. 1. However, no probability can be attached to these values. To characterize the environmental loading within the proposed risk-based approach, a probabilistic representation of the temperature over various durations of exposure is required. In this article, this was done by taking historical hourly temperatures for 20 years, calculating average temperatures over specified durations, identifying minimum temperature for each year, and then determining the probability of exceedance of the minimum temperatures for the specific durations by fitting a probability distribution. The result is what Sulistiyono et al. (2014) called the Temperature–Duration–Frequency plot shown in Fig. 2 for the location of interest.

2.2. Other aspects of environmental loading

2.2.1. Wind. Wind is another important attribute of the environmental loading. Although wind will not cool an object to any temperature below the ambient temperature, it will increase the rate of heat loss from a relatively hot object. The concept of wind chill is a measure of the combined effect of low temperature and wind (Steadman 1971). Wind chill-equivalent temperature presents the cooling power of the wind that would be felt on exposed flesh (Osczevski 1995). Therefore, wind chill is only applicable to an animate object. To include the effects of wind on vessel systems (i.e., inanimate object), convective heat transfer formulas developed by McAdams (1954) were used to calculate the convective heat transfer coefficient in heat loss calculations in this article:

$$h_c = 4.3v + 6.2v \le 5 \text{m/s} \tag{1}$$

$$h_c = 7.6v^{0.78}v > 5 \text{m/s} \tag{2}$$

where h_c is convective heat transfer coefficient (W/m^2·K), and v is the wind speed (m/s).

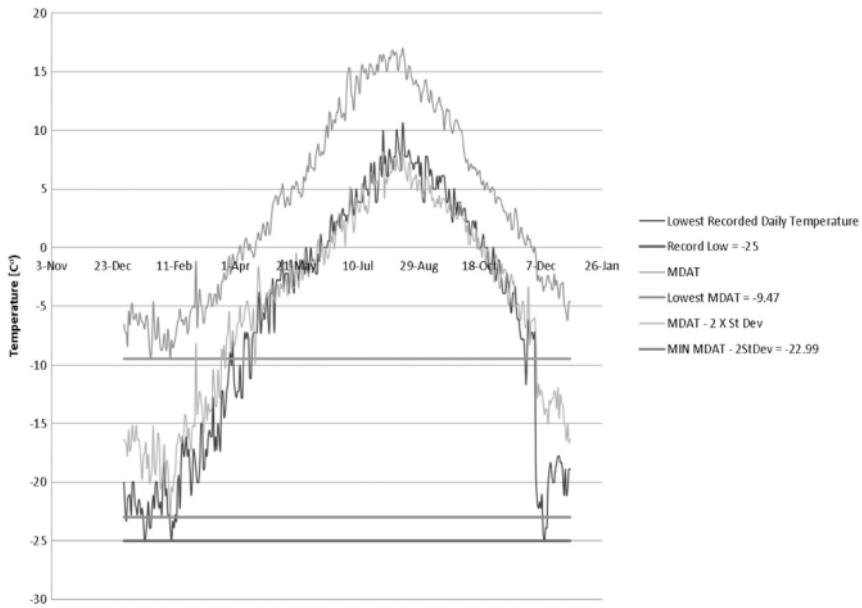

Fig. 1 Plots of MDAT of the area of operation

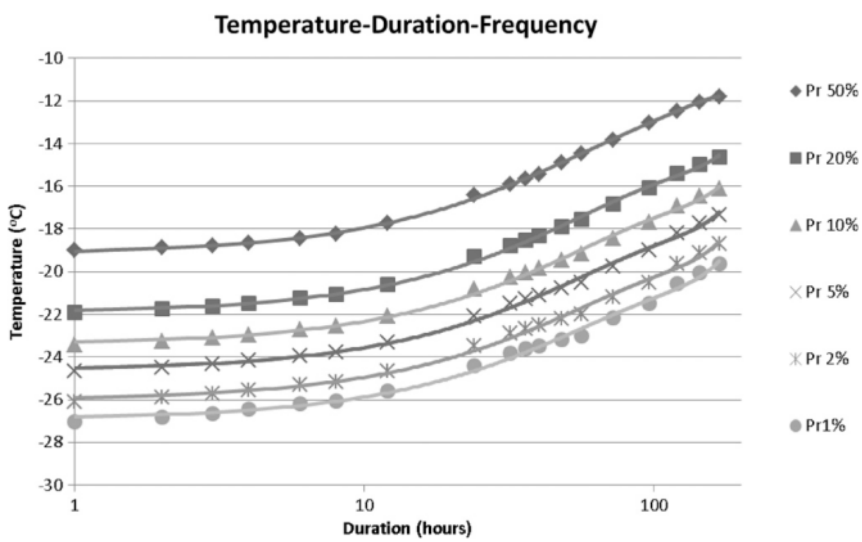

Fig. 2 The Temperature–Duration–Frequency (TDF) plot at the area of operation

The convective heat transfer coefficient was used to calculate the overall heat transfer coefficient using the formula proposed by Earle (1983):

$$\frac{1}{U} = \frac{1}{h_{c1}} + \frac{1}{(k_1/x_1)} + \frac{1}{(k_2/x_2)} + \cdots \frac{1}{(k_n/x_n)} + \frac{1}{h_{c2}} \qquad (3)$$

where U is the overall heat transfer coefficient, h_{c1} and h_{c2} are the convective coefficients of surfaces 1 and 2, k_i is the conductivity factor of material i, and x_i is the thickness of material i (i = 1, 2, . . ., n).

The wind applied to these calculations can be taken as the mean wind speed in the area of operation plus two standard deviations. For the area of operation, this wind speed value is 15 m/s.

2.2.2. Moisture. There has to be moisture/water for icing to occur. Sea spray is the major source of moisture/water to vessel systems. Spray icing has been an important research subject for many years. Makkonen (1987) studied the salinity and growth rate of spray ice. A model for generating the spray resulting from ship–wave collisions was used by Zakrzewski et al. (1988) to determine the maximum height of the spray source above the ship deck. Ryerson (1995) summarized the results of spray and ice measurements made by U.S. Army Cold Region Research and Engineering Laboratory on a large ship, which might be useful for modelers of superstructure icing. Blackmore and Lozowski (1998) developed an approach for modeling freshwater spongy spray icing. Ryerson (2011) assessed the threat of icing to structural and operational areas of offshore platforms by using a crosstabulation matrix. It is known that sea spray icing causes very rapid heat losses, sudden temperature drops, and rapid ice accretion. However, there is lack of understanding on the mechanism of this effect and its impacts on assets. In addition to sea spray, the moisture/water may also come from freezing rain and ice pellets in cold regions. The occurrence of freezing rain and ice pellets may be rare but hazardous to surface infrastructures (Roberts & Stewart 2007). In this study, moisture/water has not been included in the environmental load modeling. However, this is a potential improvement area of the environmental load model.

3. The proposed framework of risk-based winterization

The proposed framework (Fig. 3) consists of three major steps, which include:

(1) Identification of vessel systems with potential problems;
(2) Assessment of need for winterization; and
(3) Determination of winterization options and levels.

These three steps are discussed in detail in the following sections.

3.1. Step 1—identification of vessel systems with potential problems

Vessel systems with potential problems can be identified through a thorough review of vessel drawings in accordance with winterization guidelines. Examples of available guidelines include:

(1) ABS LTE Guide;
(2) RMRS' (Russian Classification Society) Requirements for Ship Equipment to Ensure Long-term Operation at Low Temperature;
(3) DNV (Norwegian Classification Society) Ice Class Rules–Sections 6 and 7, Winterization and Design Ambient Temperature (DAT); and
(4) ISO 19906: Petroleum and natural gas industries—Arctic offshore structures.

This review aims to identify areas where requirements are not met. For example, the ABS LTE Guide requires alternate bridge windows be provided with heaters and wipers. If drawings show only wipers will be installed, the bridge window becomes one system that needs further assessment. In some cases, drawings do not provide sufficient information to determine whether requirements have been met. For example, escapes routes are required to be prevented from ice and snow accumulation and readily functional. Drawings may not clearly indicate what arrangement will be made to keep escape routes ice-free. Then escape routes also become a candidate for further analysis. A list of systems with potential problems can be achieved through this step. This list sets the scope of winterization assessment.

3.2. Step 2—assessment of need for winterization

One system is taken from the list achieved through Step 1 for assessment of need for winterization. Either quantitative or qualitative assessment methods can be used to answer the question: "how likely is it that a vessel system design may fail in low temperature environments?" The decision on whether to apply further winterization is made based on results of these methods. The following paragraphs explain how and when these two methods can be applied.

(1) The quantitative method proposed by Yang et al. (2013) requires historical weather data for environmental load modeling, operating envelope (i.e., the temperature to be maintained for normal operation of a system), and maximum allowable temperature difference between the load and operating envelope of a system without winterization. With availability of such information, a probabilistic risk analysis can be conducted to estimate risk level of the system without winterization. If risk exceeds acceptable level, winterization is necessary. Otherwise, the system is "safe" and does not need winterization. "Safe" is defined as the opposite of "unsafe/failure." In this study, failure does not mean the actual failure of a system (i.e., a not-working state). Failure is defined here as the state or condition of a system not meeting its desirable or intended function as a result of icing problems. For example, the failure of navigation lights does not mean navigation lights fail to work. It is defined as the status at which ice/snow begins to accumulate on the lens and make navigation lights invisible within a regulated distance. However, quantitative assessment will not be used in the following situations.

(a) Information is not available for quantitative assessment. For instance, it is hard to determine the operating envelope and maximum allowable temperature difference for escape routes, because many factors need to be considered to determine these two values. They include factors causing or affecting icing problems in escape routes, e.g., deck height, vessel speed, wave height, whether escape routes are enclosed or exposed, etc.
(b) Only a preliminary assessment is required at the initial phase of a winterization project. To conduct quantitative assessment, environmental load modeling is necessary. It requires analyses of a large amount of weather data, which can be a very time- and effort-consuming task. Operators may not wish to do such analyses in some cases. For instance, they only need to have a rough idea about what systems and number of systems need winterization. This will provide useful information for budgeting.

(2) Qualitative assessment is proposed to handle situations in which the quantitative method is not applicable or required. The assessment qualitatively determines the likelihood of failure of a new design in low-temperature environments based on the historical icing problems of an existing design operating in the same or similar environments. The following describes the process of the proposed qualitative assessment.

(a) Collection of information about icing problems during operation of similar systems under the same or close environmental conditions. For example, to assess escape routes in a new

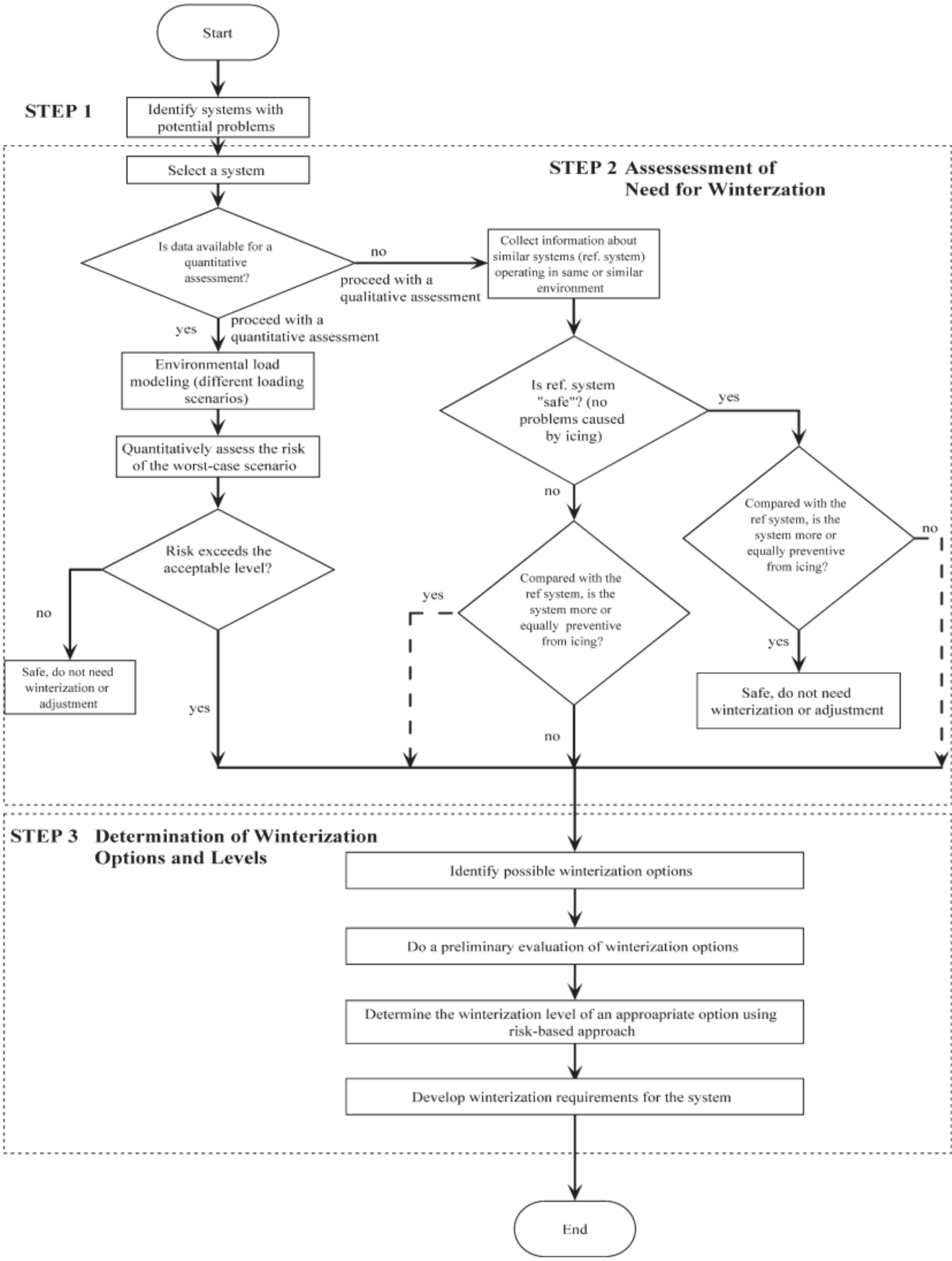

Fig. 3 The proposed framework of risk-based winterization

ferry design for need of winterization, information about ice/snow accumulation on escape routes of a ferry that has been serviced on the same route for a few years should be collected. The information may include frequency of ice buildup on the horizontal surface of escape routes and its thickness. To collect relevant information, questionnaires need to be distributed to experienced operators, e.g., ship captain. Feedback from the questionnaires will indicate if the system encounters any problem caused by icing. This system is used as a reference against which a new design is compared. It is named reference system hereafter.

(b) Comparison of a new design against the reference system. This step aims to determine whether the new design is equally or more preventive from icing. Still using the escape routes example, factors including deck height, vessel speed, and route barriers should be compared. For instance, if a new vessel has a higher deck height and lower vessel speed, it is considered to be more preventive from sea spray icing.

(c) Determination of need for winterization. There are four combinations of results from the previous assessment. They are:

- The reference system is "safe" and the new design is more preventive, which indicates winterization is unnecessary.
- The reference system is not "safe" and the new design is less preventive, which indicates winterization is necessary.
- The reference system is "safe" and the new design is less preventive, which indicates winterization may be necessary.
- The reference system is not "safe" and the new design is more preventive, which indicates winterization may be necessary.

A safe state is defined as the state of a system fulfilling its desirable or intended function in low-temperature environments. For situations where results indicate winterization may be necessary, operators can determine whether to winterize a system based on its criticality. Following the previous example of escape routes, winterization should still be applied because it is a safety-critical system, because ice/snow accumulation on the routes may result in slipping hazards during evacuation and consequently lead to serious injuries or even death. For systems that are not safety-critical, e.g., a refrigerator in a vessel's galley, additional risk assessment will be necessary to confirm need for winterization.

3.3. Step 3—determination of winterization options and levels

This step aims to identify a proper winterization option with an appropriate winterization level, a level at which a system is neither over- nor underwinterized under specified environmental loadings. The risk-based winterization approach also provides the opportunity to determine such winterization levels. The process is presented as follows.

(1) Identification of winterization options. A preliminary review is required to identify varieties of options available to winterize a vessel system. A team of experts should be set up to perform such review.

(2) Evaluation of identified winterization options. A set of criteria needs to be defined for evaluation purposes. They may include ice prevention effectiveness, installation cost, operation and maintenance cost, system reliability, etc. Evaluation can be made based on experts' judgments. The measurement scale for each criterion needs to be explicitly defined, which eases prioritization for experts. It is preferable to make the evaluation by a small group of experts. In this way, experts will be able to reach agreement on their judgments. This will avoid the problem of inconsistent experts' judgments. Additionally, because sometimes experts are not explicit in their preference, they may tend to provide interval values to indicate their judgments. This is another type of uncertainty in this evaluation process. Fuzzy sets (Zadeh 1965) or rough sets (Pawlak 1982) can be used to handle uncertain information in the evaluation process. Lots of work relevant to this topic has been published, e.g., Van Laarhoven and Pedrycz (1983), Zhai et al. (2009), and Yang et al. (2011). The topic is beyond the scope of this article, so it is not necessary to discuss it in detail here.

(3) Determination of winterization level. Once the best option is identified, the risk-based approach can be applied to determine the winterization level, e.g., heating requirement and insulation thickness. Heating requirements can be obtained by setting the risk after winterization equal to an acceptable level. Because environmental load modeling produces probability distributions of the lowest annual average temperature over various durations, results of this step will be winterization levels (e.g., heating requirements) for various durations of exposure.

(4) Development of winterization requirements. To ensure a system is "safe," winterization requirements should be developed based on the worst-case scenario (i.e., winterization level for the shortest duration of exposure), because the lowest mean temperature will be achieved for the probability distribution of the lowest annual average temperature over the shortest duration. Consequently, it leads to the highest winterization level. A few factors can be determined at this stage, which may include design capacity, energy requirement, and additional fuel consumption.

4. Case studies—winterization of the ferry design

Following the proposed framework, a new ferry design that will be operating in a particular area of the North Atlantic was analyzed for winterization. The following sections present a few case studies to demonstrate the application of the proposed framework.

4.1. Identification of ferry systems with potential problems

Drawings of the new ferry design were reviewed in accordance with the ABS LTE Guide. A list of systems with potential problems was identified and presented in Table 1. These systems were assessed using the risk-based approach.

4.2. Assessment of need for winterization

To assess the need for winterization, both quantitative and qualitative assessments were applied to the identified systems. Table 2 gives part of the results of the assessments. The following two examples are used to demonstrate how assessments were performed to evaluate the need for winterization.

4.2.1. Quantitative assessment on water pipelines. The method discussed in Section 2.1 was applied to analyze the lowest annual average temperature over various durations of exposure for the area

Table 1 Ferry systems with potential problems

System	LTE Guide Reference	Drawing No.	Potential Problems
Bridge window	3/3.2	400081-120-0001B, 400,081-120-3006	The ship will install electric heaters and wipers to clean some of the bridge window for deicing purposes; however, alternate bridge windows will not be provided with heaters and wipers
Escape route	3/3.2	400081-120-3011	It is not clear how escape routes will be kept from snow and ice and readily functional
Exterior stairs	3/3.3	400081-120-3017A	The exterior stairs are noted as being steeper than the 35°C required by the LTE Guide and the stair material is not indicated as being grating as required by the LTE Guide
Lubricating oil	4/2.4	N/A	It is necessary to confirm all main propulsion and auxiliary prime movers are provided with lubricating oil maintained at the proper minimum temperature in accordance with manufacturer's recommendations
Anchor windlass	4/4.2 (ii)	400081-120-3008	It is not clear how anchor-releasing arrangements are provided to reduce the effect of icing
Bow door and stern ramps	4/4.6.2 and 5.1.2	400081-120-1005, 400,081-120-1006A	The bow door and stern ramps are noted as hydraulically operated; it is not clear whether these systems are suitable for operations at the MAT (–25°C); it is also uncertain that the seals used for the bow door will remain pliant at the MAT
Water pipelines	4/5.1	400081-120-5,007, 400,081-120-1010, 400,081-120-5011B	It is not clear how sanitary waterlines will be protected from freezing on deck 3 (car deck); it is noted that the ships fire and wash water lines pass through deck 3 (car deck), and drawing no. 400081-120-5011 indicates that pipes are exposed to open air
Valves	4/5.1.3	400081-120-1005, 400,081-120-1003, 400,081-120-1006	It is noted that the ramps and bow doors are hydraulically operated and the control valves are located on deck 3, which is exposed to ambient temperatures; it is not clear how they will be protected from freezing
Air vent	4/5.1.5	400081-120-5006B	It is not clear how the vents will be kept ice-free
Emergency generator room	4/5.1.8 (v)	400081-120-7,017, 400,081-120-1010	It is not clear whether the heating arrangements will be sufficient to heat the emergency generator room on deck 3 to 10°C at the MAT
Ventilators for HVAC system	4/5.1.8 (vii)	400081-120-7002	It is not clear how the ventilators for the HVAC systems will be kept ice- and snow-free; they are to be protected from snow and ice accumulation that may interfere with effective operation of the closures and recirculation of exhaust gases
Emergency power supply	4/7.1.2 (a)	400081-120-8002E, 400,081-120-5011B	The LTE Guide requires that the auxiliary boiler and its controls be operable on the emergency source of power; it is not clear whether emergency heating will be provided to the space where passengers will stay during black out; drawing number 400081-120-5010B indicates that any exposed pipes are to be insulated and heat traced, but 400081-120-8002E does not indicate any heat tracing
Engine room	4/8.1	400081-120-6001A	The LTE Guide requires that if any of the engines are to be on standby in low temperatures that the automation system includes a low-temperature alarm to notify the operator that the temperature is too low to start the machinery; not clear whether a low-temperature alarm will be included for the engine rooms
Lifeboat engine	5/4.	N/A	It is not clear whether the lifeboat engine will be able to perform its function at the design service temperature or −30°C
Lifeboat capacity	5/4.1(i) and 5/4.4	400081-120-3010	The LTE Guide required lifeboats be sized at 125% to accommodate bulky cold weather clothing; it is noted that the POB is to be 210 and each lifeboat has a capacity of 120, which is approximately 114% sized
Navigational equipment	5/3	N/A	Please confirm that the navigational equipment is capable of operating in conditions the vessel is expected to operate in at the design service temperature

HVAC, heating, ventilating, and air conditioning; POB, passenger on board; N/A, not applicable.

where the new ferry will operate. Considering the worst-case scenario, probability distribution for 1-hour duration with a 100-year return period was used as the environmental load. It follows a normal distribution with mean temperature as –27.00°C and standard error of 1.49.

For illustration purposes, assume that:

(1) Operating an envelope of a water pipeline follows a normal distribution with mean temperature to be maintained at 0°C with a possible variation of 1°C (The freezing point of sea water can vary mainly depending on salt-to-water ratio. The fresh sea water may freeze at –2°C or lower; therefore, it may still remain in the liquid form from 0 to –2°C); and
(2) Maximum allowable temperature difference between the operating envelope and the load is 0°C.

Because $|\Delta T_{Actual}| = |L - T_{op}|$ (i.e., the difference between the load [L] and operating temperature), then $|\Delta T_{Actual}|$ may follow a normal distribution with $\mu = |-27 - 0| = 27$ and $\sigma = \left[(1.49)^2 + (1)^2\right]^{0.5} = 1.79$

$$\mathrm{PoF} = \Pr(|\Delta T_{Actual}| > k) = \int_k^{\infty} f_{\Delta T_a}(\Delta T_a)\, d\Delta T_a = 1 - \Phi\left(\frac{k-\mu}{\sigma}\right) = 1 - \Phi\left(\frac{0-27}{1.79}\right) = 1.0$$

where PoF is the probability of failure and k is the maximum allowable temperature difference between the load and operating envelop of a system without winterization.

Table 2 Results of the assessment of need for winterization

System	Does It Need Winterization?	Justifications
Bridge window	Yes	Ice/snow accretion often occurred on bridge windows on the existing ferry; considering same bridge window arrangement, winterization is necessary; the new ferry will have wipers and heaters for deicing purpose; heating requirements need to be identified; additionally, the new design does not have alternate heated windows, which is not in compliance with the LTE Guide; we need to consider the risk of reduced visibility when the unheated windows are blocked
Escape route	No	Escape routes on the existing ferry is "safe" and that of new ferry is more icing-preventive
Exterior stairs	Yes	Ice/snow accretion often occurred on exterior stairs on the existing ferry; the stair slopes of the old and new designs are the same; stairs on both ferries are exposed to a cold environment
Lubricating oil	Yes	The questionnaire feedback showed that at approximately 20°C the captain needed the lubricating oil to run the engine; risk exceeded the acceptable level
Anchor windlass	Yes	Ice/snow accretion often occurred on the forecastle deck of the existing ferry, including anchor windlass/mooring equipment; however, the thickness is less than 1 inch; this ice buildup on the anchor windlass could adversely affect the drop the anchor in an emergency
Bow door and stern ramps	No	Bow/stern ramps' hydraulic systems on the existing ferry never have had any operation problem as a result of low temperature; considering the same arrangements on the new ferry, hydraulic systems do not to be winterized; however, there will be heaters in the ramps' hydraulic systems of the new ferry; seals for bow doors will remain pliant assuming nitrile rubber is used; although the result showed that it may not be necessary to winterize the bow and stern ramps' hydraulic systems, they should always be well maintained for a cold environment, e.g., changing filters, check hoses and fittings
Water pipelines	Yes	Risk exceeded the acceptable level
Valves	No	It is noted that the ramps and bow doors are hydraulically operated and the control valves are located on deck 3, which is exposed to ambient temperatures; all hydraulic systems are inside; therefore, there should not be any icing problem; they will be functional regardless of hydraulic oil viscosity; the only noted hazard could be possible damage of valves caused by manual ice removal by mallets or hammers
Air vent	Yes	The existing ferry never have had tank air pipes freeze or clog in low temperature either as a result of ice accretion or freezing of the ball to seal the vent pipe; the vent pipes of the existing ferry are fully enclosed; the new ferry has air vent pipes exposed and this needs winterization
Emergency generator room	Yes	On the existing ferry, the emergency generator compartment is heated and never has difficulty to start the generator as a result of cold temperatures; the same arrangement should be made to the new ferry; winterization requirements need to be determined
Ventilators for HVAC system	No	On the existing ferry, the ventilation inlets have been clogged but never prevented the closing of the vents; the new design is safer than the old design with a higher intake position; it is facing inside, which makes it more preventive from spray; there is an option to circulate engine room air to provide heating to make it safer; additionally, the heat loss calculation showed that 3121 kw is needed to maintain the engine room temperature at 10°C; it is greater than the available propulsion machinery output (3040 kw)
Engine room	Yes	The engine room needs to be heated to main its room temperature at 10°C
Lifeboat engine	Yes	Captain of the existing ferry has experienced difficulties starting the lifeboat engine as a result of low temperature
Navigational equipment	Yes	No information regarding navigation equipment on the new ferry was provided; assumptions were made for risk assessment; risk exceeded the acceptable level

HVAC, heating, ventilating, and air conditioning.

The severity value was assigned as 2; the risk was considered high according to the risk matrix (Fig. 4). The evaluation scale of the risk matrix can be customized as per the operators' criterion. Operators need to define the acceptable level and customize the risk matrix. In this example, acceptable risk level is assumed to be low and obviously the risk exceeds the level. It indicates that winterization is necessary.

4.2.2. Qualitative assessment on escape routes. Questionnaires were distributed to collect information about icing problems of an existing ferry that has been servicing on the same route for many years. Feedback was received from the captain of the ferry. The results showed that ice buildup rarely occurred on the horizontal surface of the escape routes and the thickness of ice buildup in the worst case was less than 1 inch. This indicates that icing is not a problem and escape routes on this ferry should be considered "safe." The following compares the existing ferry's arrangements with that of the new ferry design.

(1) Environmental load: The ferry will operate on the same route and year round as the existing ferry does; therefore, equal environmental load is expected.
(2) Vessel bow shape: The new ferry will have an ice-breaking bow, which is not optimized for seakeeping and therefore spray will likely be high when the vessel encounters waves

CONSEQUENCE

PROBABILITY	Insignificant (0-2)	Marginal (2-4)	Moderate (4-6)	Critical (6-8)	Catastrophic (8-10)
Definitely (0.1-1)	High	High	Very High	Very High	Very High
Likely (10^{-2}-10^{-1})	Medium	High	High	Very High	Very High
Occasional (10^{-3}-10^{-2})	Low	Medium	High	Very High	Very High
Seldom (10^{-4}-10^{-3})	Low	Low	Medium	High	Very High
Unlikely (<10^{-4})	Low	Low	Medium	High	High

Fig. 4 Risk matrix

in open water. The existing ferry does not have the same ice class bow and its hull is also not optimized for waves. It creates considerable spray in an oncoming sea.

(3) Protection of the escape routes: The deck height above the deepest waterline of the new ferry is considerably higher than that of the existing ferry. The existing ferry's escape routes are located on either side in a breezeway-type passage that is open to the bow. The new ferry has a forward superstructure that protects the entire aft end of the vessel. The exterior escape routes are located entirely aft of the superstructure. Additionally, the bulk of passengers will be evacuated through enclosed escape routes. Therefore, spray and atmosphere icing should be a lesser problem.

In summary, escape routes on the new ferry are more icing-preventive than that of the existing ferry. Because escape routes on the existing ferry are "safe," escape routes on the new ferry should not need further winterization.

4.3. Determination of winterization options

Winterization options were proposed for the systems that need to be winterized. They were evaluated by a group of experts. Assumptions were made to simplify the evaluation process:

(1) Experts can reach agreements on their judgments and assign consistent evaluation scores; and

Table 3 The evaluation scheme

For Criterion Relevant to Cost	For Criterion Relevant to Performance	Score
Very high	Very bad	1
High	Bad	3
Medium	Moderate	5
Low	Good	7
Very low	Very good	9

Table 4 Probability distribution of the environmental load (100-year return period)

Duration	Distribution Type	Mean	Standard Deviation
1 hour	Normal	−27.0	1.49
12 hours	Normal	−25.6	1.45

(2) Experts are explicit in their preference, i.e., they will not assign interval scores.

A simple 9-point scale (Table 3) was used as the evaluation scheme. The winterization levels of the best options were determined using the risk-based approach. Table 4 gives the probability distributions of the load. For the purpose of brevity, only two case studies are presented to demonstrate the process.

4.3.1. Bridge windows.

Three winterization options were identified. They are:

(1) Wiper only;
(2) Wiper and heater; and
(3) Ice/water repellent coating or material.

Table 5 gives the evaluation results. It shows that the application of a wiper and heater together is the best option. The new design has electric heaters on 12 of 24 bridge windows, whose dimensions are given in Table 6. The LTE Guide requires that alternate bridge windows should be provided with heaters and wipers. However, the drawings indicate that this requirement has not been met. To assess the arrangement of heated bridge windows in the new design, Regulation 22 (Navigation Bridge Visibility) in Chapter V Safety and Navigation of 2009 SOLAS could be considered. It requires that the horizontal field of vision shall extend over an arc from right ahead to at least 60° on each side of the ship from the primary steering position. Therefore, 60° can be used as the acceptable horizontal vision angle in the assessment. The bridge window W-7S is used as an example to illustrate how heating requirement can be determined using the risk-based approach.

4.3.1.1. Step 1: Define the acceptable risk level and PoF. Ice or snow accretion on bridge windows may significantly degrade visibility of the captain and consequently leads to improper judgments and collision. Severity value of the consequence was assigned as 4. According to the risk matrix, the maximum allowable PoF value should be 0.001 to achieve an acceptable low risk level.

4.3.1.2. Step 2: Determine the efficacy (E) based on the PoF. Efficacy is defined as the capacity of a winterization option to reduce the temperature difference between the load and operating envelope. To maintain the window ice-free, the following parameters were set for the risk-based approach:

(a) Operating envelope (T_{op}) follows a normal distribution with mean temperature to be maintained at 1°C with a possible variation of 0.5°C; and
(b) Maximum allowable temperature difference between the operating envelope and the load is 0°C.

Determination of winterization levels requires defined boundaries. These parameters can be viewed as a boundary condition, which is

Table 5 Evaluation results of winterization options for bridge window

	Window Visibility (0.25 as weight)	System Reliability (0.25)	Installation Cost (0.25)	Maintenance Cost (0.25)	Total Score
Wiper	5	5	5	5	5
Wiper and heater	7	7	3	5	5.5
Ice/water-repellent coating or material	1	5	5	1	3

Table 6 Dimensions of bridge windows with heaters

Type	Position	Clear Opening H × B (mm)
W-7P, W-7S	Deck 7 (bridge)	1434 × 1298
W-8P, W-8S	Deck 7 (bridge)	1434 × 1677
W-12P, W-12S	Deck 7 (bridge)	1876 × 1845
W-13P, W-13S	Deck 7 (bridge)	1787 × 1591
W-14P, W-14S	Deck 7 (bridge)	1787 × 1282

H × B, height × side.

set by the operator. For example, operators may set the mean temperature of the operating envelope to 0°C to have minimum heating requirements of the bridge window.

The distribution for 1-hour duration was used for heating requirement calculation. Since Because $|\Delta T_{Actual}| = |L - T_{op}|$, then $|\Delta T_{Actual}|$ may follow a normal distribution with $\mu = |-27 - 1| = 28$ and $\sigma = \left[(1.49)^2 + (0.5)^2\right]^{0.5} = 1.57$

$$\text{PoF} = 1 - \Phi\left(\frac{k - (\mu - E)}{\sigma}\right) = 1 - \Phi\left(\frac{0 - (28 - E)}{1.57}\right)$$

$$= 0.001, \text{ then } \frac{0 - (28 - E)}{1.57} = 3.09,$$

$$E = \Delta T = 32.9^\circ C$$

4.3.1.3. Step 3: Estimate the average heating requirements. The average wind speed is 15 m/s, then $h_c = 7.6v^{0.78} = 62.8$ (W)/(m^2)(°C). Let thickness of glass be 8 mm. The overall U is:

$$U = \frac{1}{\frac{1}{h_c} + \frac{x_{glass}}{k_{glass}}} = 42.5(W)/\left(m^2\right)(^\circ C)$$

The heat transfer area (A) is 1.4 × 1.3 = 1.8 m^2.
The estimated heating requirement is Q = UAΔT = 2541 watt.

The longest daily operation duration of the ferry may be 12 hours. The design capacity of the heater is 2541 watt × 12 hours = 30 kWh. Assume that fuel consumption is 160 g/kWh and density of fuel is 832 kg/m^3. Additional fuel consumption can also be estimated. The results show that average heating requirement for a 12-hour duration is 2424 watt. Then, average energy requirement becomes 2424 watt × 12 hours = 29 kWh. Additional fuel consumption is 29 kWh × 160 g/kWh/832 kg/m^3 = 0.01 m^3/hour. Table 7 provides a summary of proposed winterization requirements for bridge windows.

4.3.2. Anchor windlass. Three options were identified to winterize the anchor windlass. They are:

(1) Electric heat tracing;
(2) Water/ice-resistant cover; and
(3) Ice-repellent coatings.

Table 8 gives the evaluation results. It indicates that shielding the whole anchor windlass using a water/ice-resistant cover is the best

Table 7 Summary of winterization requirements for bridge windows

System (recommended winterization option)	Type (number of windows)	Heating Requirement (watt)	Design Capacity (kWh)	Additional Fuel Consumption (m^3/hour)	Total Additional Fuel Consumption (m^3/hour)
Bridge window (heater + wiper)	W-7P (1), W-7S (1)	2541	30	0.006	0.1
	W-8P (1), W-8S (1)	3334	40	0.007	
	W-12P (1), W-12S (1)	4775	57	0.011	
	W-13P (2), W-13S (2)	4021	48	0.009	
	W-14P (1), W-14S (1)	3267	39	0.007	

Table 8 Evaluation results of winterization options for anchor windlass

	Icing Prevention Effectiveness (0.33 as weight)	Installation Cost (0.33)	Operating and Maintenance Cost (0.33)	Score
Electric heat tracing	5	1	1	2.31
Water-resistant cover	7	7	7	6.93
Ice-repellent coatings	1	5	5	3.63

way to prevent it from icing. A heated cover is more costly and is not recommended. Manual removal of ice/snow from the cover is required on a regular basis (e.g., once every trip). Ice accretion on a flexible cover would be less than a solid surface. Under windy conditions, the cover will flap and eject small ice particles. To further winterize the chain stopper, a robust pin can be applied. In an emergency, the vessel crew may hammer the pin out to pay out the anchor. The pin can be chained to improve safety and prevent loss.

5. Conclusion

The risk-based approach proposed by Yang et al. (2013) to winterization provides a rational way to identify what vessel systems need winterization, determine what level they should be winterized, check whether existing winterization will meet the need, and under what condition they will fail. To expand on this approach, and to eliminate some limitations (e.g., lack of information for quantitative assessment), and to make it more practical, this article proposes a holistic framework of risk-based winterization, which could serve as a guideline for operators to assess and optimize winterization on vessel designs through risk assessment. This proposed framework was applied to a new passenger ferry design, which is intended to operate in a particular area of the North Atlantic. This application further validated the proposed method and the feasibility of using a risk-based winterization approach on vessel designs. The risk-based approach can assist in the assessment of the need for winterization of a vessel system and the development of site-specific winterization requirements for the system.

This work could be further extended on the following aspects:

(1) Generation of data on ice spray and ice loading;
(2) Minimization of uncertainty in the data related to efficacy of winterization methods and weather load;
(3) Consideration of economic model in the decision-making framework; and
(4) Development of simplified tools and guidelines that could be used by practitioners.

Disclaimer

The views expressed herein are those of the authors and are not to be construed as official views of the ABS.

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11