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To cite this article: S R Jacobsen *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **700** 012043

IOP Conf. Series: Materials Science and Engineering **700** (2019) 012043 doi:10.1088/1757-899X/700/1/012043

Development of a method for evaluation of measures used for winterization of offshore facilities and units

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Abstract. The environmental conditions in the Barents Sea include low temperatures, wind, snow and precipitation influencing safety, working environment, operations and equipment functionality. The conditions are not extreme compared to other Arctic areas, however they do necessitate protection and winterization of the facility. A study performed for the Petroleum Safety Authority (PSA) in 2016 identified known measures for winterization of facilities in the Barents Sea. The study found uncertainties related to the effect the measures have on winterization when considering environmental conditions. Further work was recommended to evaluate the effect of measures when considering performance influencing factors. A new study was initiated by PSA to develop a method to evaluate the efficiency of measures and a means to document the results. The method considers how well a measure achieves a specific safety and winterization goal, effect of the measure on energy consumption, effect of the measure on investment cost and operating cost, and vulnerability of the measure, including operational and organizational factors. In order to refine and test the method, it was applied to case studies considering a year-round production facility, a light well intervention vessel and a drilling facility used in the winter season in the Barents Sea. The paper is not intended to be a research paper but is a presentation of a method that has been developed to perform an initial evaluation of the effectiveness of winterization methods.

1. Introduction

Based on previous work including a study [1] and a paper [2] related to commonly used winterization measures, the Petroleum Safety Authority (PSA). initiated further work in 2017 and 2018 to follow up identified recommendations. These included developing a method to evaluate the efficiency of measures used for winterization and testing of the method by applying it to selected operational cases. There is currently no common approach to evaluating needs and effects of winterization measures. The work is documented in a report issued in December 2018 [3] and is the basis for this paper.

The southern part of the Barents Sea is of particular interest regarding winterization requirements for petroleum activity. The meteorological and oceanographic conditions of the area have provided the basis for selection of measures, climatic, meteorological and oceanographic conditions considered in the work covered by this paper.

IOP Conf. Series: Materials Science and Engineering **700** (2019) 012043 doi:10.1088/1757-899X/700/1/012043

1.1. Definitions and abbreviations

For clarity and to avoid misunderstanding, we have chosen to use the following definitions and abbreviations in this paper:

Issue: used generically to describe "something that poses a challenge" to operation in a cold climate

Measure: used generically to describe an action, solution or measure put in place to mitigate the effects of an issue. The purpose of a measure in this context is to enable safe and prudent operation under winter conditions including low temperature, wind and precipitation.

Metocean: abbreviation for meteorological and oceanographic conditions

MTO: man, technology, organization, the effects and consequences of human (man), technology and organizational influence on the performance of a given measure

One-pager: collation of the various elements of the assessment documenting and visualizing the results

Performance influencing factor: any factor that may affect the performance of a measure, normally in a negative way.

Wind chill: the combined effect of low temperature and wind leading to a lower effective temperature and greater cooling effect

Winterization: the combined mitigating measures that are put in place on facilities to enable safe and prudent operation in winter conditions.

1.2. Context

We regard it as necessary to describe the metocean conditions relevant for the area considered. The Barents Sea covers a large area and presents considerable variations in temperature and ice coverage. The southern part of the Barents Sea (south of 74,5°N) opened by Norway for oil and gas activity covers approximately 313 000km^2 [4]. The conditions in this area are not considered extreme. However, low temperatures (Figure 1), wind, precipitation, including accumulation of snow and icing on structures and equipment, do affect operations and equipment functionality unless countermeasures are implemented.

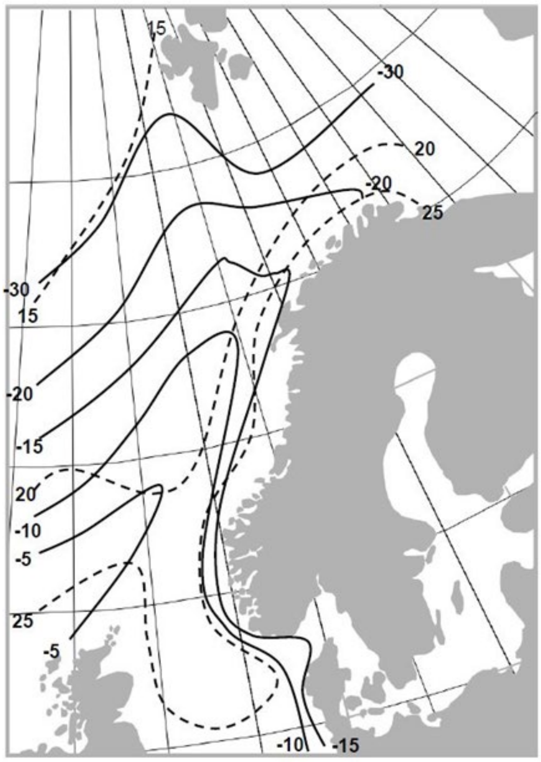


Figure 1. Highest and lowest air temperature with an annual probability of exceedance of 10-2 (the temperatures are given in °C) [5].

1.3. Metocean conditions
The metocean conditions for the Norwegian Continental Shelf are documented in NORSOK N-003 [5]. This standard contains a division of the opened area into five sub-areas having relatively uniform conditions and distinguishable from neighbouring areas. Recent studies performed by a collaboration of oil and gas operators in Norway have developed a comprehensive metocean report specifically addressing the relevant areas of the Barents Sea [6].

Ocean currents have a major influence on temperature and sea ice coverage in the Barents Sea. Warm Atlantic water from the south influences the climate in the Barents Sea. The Atlantic water keeps the southern part of the Barents Sea primarily ice-free during winter [6].

Intervals for temperature, wind and precipitation used in this work are based on metocean documents [5 & 6] and hindcast data from the Norwegian Meteorological Institute's NORA10 database [7]. The selection of the actual intervals for temperature, wind and precipitation are representative and do not include extremes.

Polar lows leading to relatively sudden increases in wind speed, changes in wind direction and heavy snowfall [8], represent a complicating issue that needs to be considered in winterization design.

Understanding the metocean conditions at a specific location is essential to assess the need for, and criticality of, different winterization measures. In order to perform a study for a given location and facility, the metocean data intervals should be adjusted to fit the specific conditions.

Air and seawater temperatures in the area affect the wind chill temperature and the potential for icing, both atmospheric and marine. Wind chill and icing are operational issues that are important to consider when operating in the Barents Sea.

1.4. Facilities and vessels in the Barents Sea
Currently there is only one permanent floating production facility, Goliat, in the Norwegian Area of the Barents Sea. There is a subsea facility for the Snøhvit field, which requires rig or vessel intervention. Exploration is performed using semi-submersible mobile offshore drilling units due to water depth. In addition, there are various types of vessels supporting the activities including emergency preparedness, transport of goods and equipment, well intervention, maintenance, construction and seismic surveys.

2. Methods and materials
The objective of the work has been to develop an assessment method and tool, "one pager", to evaluate the efficiency of a winterization measure. An experience-based approach is utilized in developing and testing the method. This has been found an acceptable approach based on previous work [1] and access to a broad experience base. Total involvement in the project has included persons from authorities, operating companies, drilling entrepreneurs, academia, risk management consultants, facility designers and suppliers of winterisation equipment. The work was divided into two stages.

Stage 1 - Development of method and tool:
- Develop a method to evaluate and analyse the effect of a winterization solution and measure,
- Include the performance influencing factors, which may strengthen or weaken the measure,
- Mature and refine the evaluation tool by performing a limited number of trials.

Stage 2 - Case tests utilizing method and tool:
- Test and refine the method by applying it to defined cases involving various types of facilities, locations and relevant measures.
- Evaluate optimal combinations of measures for varying weather conditions and locations.

The test of the method and the tool, one pager, was performed in a series of workshops. The participants in the workshops were supplemented with persons having operational experience with winterization of production facilities and exploration drilling, mainly from the Barents Sea.

2.1. Assumptions and limitations
Winterization measures are assessed individually. Combinations of measures are not included in the method but are discussed. Safety issues when designing winterization, are always of prime importance.

The winter season is not defined as any given months as this varies depending upon location. The geographical area is limited to the southern part of the Norwegian Continental Shelf in the Barents Sea opened for petroleum activities.

The effects of sea ice, icebergs, bergy bits, other forms of ice as well as fog have not been included as these are outside the project definition of winterization and are covered in other projects executed on behalf of the PSA. Polar lows have not been dealt with as a specific issue as they are a combination of low temperature, wind and precipitation and are thus inherently covered in the evaluation tool.

Climate data for temperature, wind and precipitation including snow was extracted from the NORA10 Hindcast database [7]. When using hindcast data for operational purposes, due conservatism should be applied as well as correcting for known biases.

The case studies have considered a selection of measures identified in the SINTEF report [1]. The selection has been made on the following criteria:

- All sub-issues must be represented by measures
- Similar measures are considered once rather than being duplicated.
- A balance between technical, operational and organizational measures is sought. Similarly, a balance is sought between measures that are suitable for modifications of existing facilities and measures that are only relevant to new builds.

2.2. Uncertainties and sources of error
As with all methods based on assessments made in a workgroup, one depends on the participants having both theoretical knowledge and practical experience. There is a degree of subjectivity when assessing the effect of a measure under different circumstances. There will be a considerable degree of subjectivity when distinguishing between "good effect" and "very good effect". Thus, the assessment may differ from person to person and between groups considering the same measures. This is a property, which the method shares with qualitative methods used for hazard and risk assessment, e.g. ISO 17776:2016 [9].

The estimates for investment costs (CAPEX) and energy consumption, operation and maintenance costs (OPEX), are generalized when considering what has a high or low impact. These assessments should be used with due consideration and be made specifically for a given facility when developing a winterization strategy.

2.3. Case studies – refinement and test of the method
The method was applied to three cases studies to retest, refine and confirm the viability and appropriateness of the method.

2.3.1. Case 1, Year-round production using a new build permanent production facility located in the Barents Sea area around the 73rd latitude towards the west. This case was selected to explore the flexibility that is available when taking the needs for winterization into account already in the design phase. The case allows for optimization of layout and design maximizing the effect of the selected measures. It also allows optimization of the electric generation systems required to power the winterization measures e.g. heating systems. A year-round operation case requires comprehensive measures to eliminate or minimise disruptions to activities.

2.3.2. Case 2, Winter drilling operation using an existing mobile offshore drilling unit located north of the 73rd latitude towards the east. This case was selected to explore the constraints on the choice of measures available when an existing unit is winterized by modification. This case illustrates the balance between what is desired and what possible, selection of measures, efficiency of measures, available electric power, CAPEX and OPEX. The case also provides an insight of what can be achieved when modifying an existing facility and the tailoring of measures employed on a new build facility, case 1.

2.3.3. Case 3, Well intervention using an existing light well intervention vessel in the same location as case 2. This case was selected to explore the constraints of modification of an existing unit (case 2) and the flexibility available when an operation can be planned with regard to weather and the possibility of suspending the activity if the environmental conditions exceed the design criteria. The expectation is that less stringent measures can be put in place compared to case 1 and case 2. This could reduce electric power requirements and costs, CAPEX and OPEX, while achieving an acceptable efficiency of the winterization measures. The operational window and up-time for the vessel will be lower than the facilities considered in the previous cases.

3. Results

The result of the work has been the development of a method and the "one-pager" providing a systematic approach to the assessment, documentation and visualization of the results [3]. An illustration of the process 'Figure 2' and the one-pager 'Figure 11' have been included to provide clarity.

The method was tested by application to three case studies considering a year-round production facility, a light well intervention vessel and a drilling facility utilized in the winter season in the Barents Sea. A workgroup including personnel with relevant competence and experience participated in the case studies.

The aim of the case studies has been to refine, test and confirm that it is possible and proper to use the method that has been developed. The actual results of the case studies as such are of less importance than confirmation of the viability and appropriateness of the method.

3.1. Evaluation method

The method is designed to evaluate an individual solution or measure. It is also possible to perform a case study assessing several measures for an installation of facility. The actual steps in the process are described below.

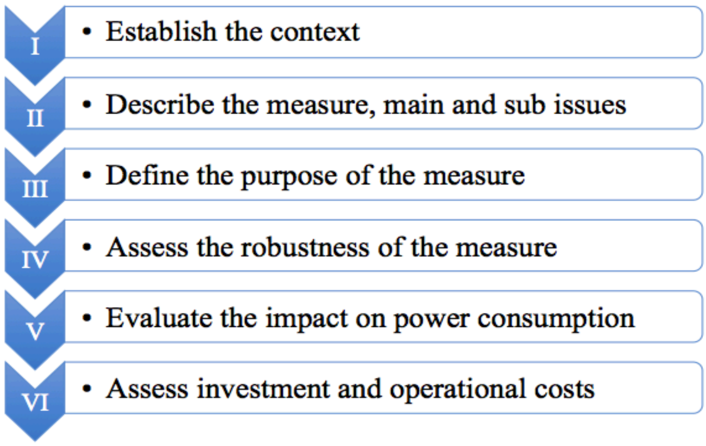


Figure 2. Method process chart.

3.1.1. Establish the context (I): The process is similar to that of a risk management process [10 & 11] and the purpose is to ensure that basic parameters and assumptions are defined, documented and agreed for the assessment.

The context has been established by identifying climatic conditions, such as minimum temperatures and their return periods, wind, precipitation, atmospheric icing etc. for the case studies used to test the method. The design assumptions and intended operations are established based on climate data for the specific locations with regard to operation, regularity requirements, barrier strategy including need for winterization of safety critical functions and design limits for the equipment. If the methodology is to be used to develop a concept for a specific project, it is natural that the level of detail needs to be increased.

3.1.2. Describe the measure, main and sub issues (II): Step II provides a short description of the measure and identifies the main and sub issues to be mitigated 'Figure 3'. The robustness of a measure is evaluated relative to the issue it is to mitigate and affect. For example, the cooling effect on a helicopter deck is greater than for a walkway, which is partially protected against the weather and wind by other structures.

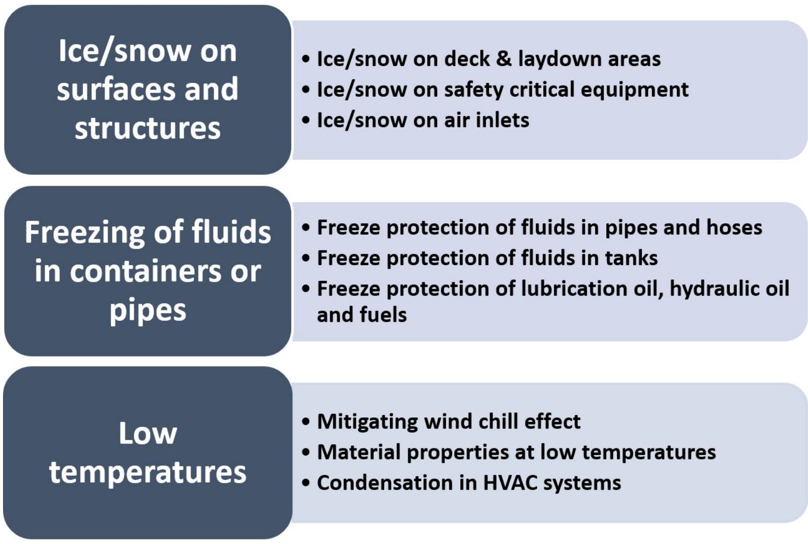


Figure 3. Main and sub-issues (examples).

3.1.3. Define the purpose of the measure (III): The purpose of a measure is to enable safe and prudent operations under winter conditions. Step III identifies the purpose of the measure, i.e. maintain normal operations or provide a safety critical function, i.e. prevent and limit the impact of unwanted events. Individual measures may take care of several issues. The most critical issue, in a barrier context, will define the performance requirement for robustness, capacity, reliability, efficiency, integrity etc. [12].

3.1.4. Assess the robustness of the measure (IV): Step IV is the core of the assessment taking into consideration performance influencing factors. The method uses the concept of robustness to describe how a measure is affected by conditions such as temperature, wind, precipitation and MTO factors. The opposite of robustness is vulnerability, and the terms are interchanged where appropriate. A robust measure will have the same or almost equivalent effect at a broad range of temperatures, winds and precipitation, as well as combinations of these.

Rather than assessing impact and robustness separately, we have chosen to assess robustness by looking at how well the measure performs under increasing severity of influence of temperature, wind, precipitation, and MTO factors. The effect of the measure describes how well it mitigates an issue. There is a significant element of subjectivity, especially in distinguishing between the three highest categories. The effect of the measure is shown in 'Figure 4'.

1	None or very little effect
2	Some effect, but insufficient
3	Useful effect, possibly sufficient
4	Good effect, sufficient
5	Very good effect

Figure 4. Effect of a measure.

The performance influencing factors, temperature, wind and precipitation are considered most relevant in a general context. When assessing measures for a given facility it will be necessary to make specific analyses for all performance influencing factors. This method does not limit the number of influencing factors that can be incorporated if appropriate and necessary. The following intervals have been chosen for temperature, wind and precipitation 'Figure 5'.

Interval	Temperature (°C)	Wind (m/s)	Precipitation (mm/day)
1	5 to 0	0	0
2	0 to -5	0 to 5	0 to 5
3	-5 to -10	5 to10	5 to 10
4	-10 to -20	10 to 20	10 to 20
5	< - 20	> 20	> 20

Figure 5. Intervals for temperature, wind and precipitation.

The intervals can occur in different combinations of wind, temperature and precipitation. Under real circumstances, some combinations are more likely than others e.g. the lowest temperatures usually occur in the case of clear weather and light wind.

The influence of wind and temperature is related to the cooling effect or wind chill. At any given temperature, an increase in wind velocity will increase both heat loss and energy consumption to achieve the same effect e.g. use of electric heating.

It is important to consider the robustness of a measure taking into account combinations of wind and temperature. Precipitation may also contribute to the cooling effect. For active and energy-intensive measures, the energy requirement will also be driven by the amount of energy required to melt or evaporate precipitation.

The dominant factor in terms of winterization is temperature. Most often, there will be a need to consider temperature in relation to wind to assess actual heat loss. Nevertheless, there may be issues and corresponding measures where it is the combination of temperature and rainfall that is of interest. In those cases, it is easy to exchange wind with precipitation on the y-axis using precipitation as the variable factor.

The method assesses the effect of the measure as a function of temperature (x-axis) and wind (y-axis) in a two-dimensional matrix as illustrated in 'Figure 6'. The example in the matrix illustrates that the measure is vulnerable to decreasing temperature and increasing wind. The coloured fields in the matrix categorize the vulnerability and robustness of the measure when combining temperature and wind.

Wind m/s							
> 20 m/s	5	Useful	Useful	Some	None/little	None/little
10 - 20	4	Good	Useful	Some	Some	None/little
5 - 10	3	Good	Good	Useful	Some	Some
0 - 5	2	Very good	Good	Good	Useful	Some
0	1	Very good	Very good	Good	Useful	Useful
		0 - 5	0 - (-5)	(-5) - (-10)	(-10) - (-20)	< (-20)
		1	2	3	4	5
		Temperature °C				

Figure 6. Robustness as a function of wind and temperature.

Precipitation is assessed independently of temperature and wind as shown in 'Figure 7'. This was done to avoid the complex presentation of a three-dimensional matrix.

None/little	>20 mm/day	5
Some	10 - 20	4
Useful	5 - 10	3
Good	0 - 5	2
Very good	0	1
	Precipitation	

Figure 7. Robustness as a function of precipitation.

An assessment of the effect of human (M), technology (T) and organizational (O) factors has been included. MTO factors influence the performance and the ability of personnel to act as required. It is used as a coarse assessment of vulnerability for issues like:

- Fatigue, inattention, habit, e.g. oversight of signs and warnings
- Resource requirements (persons) for the measure, e.g. manual removal of ice and snow
- Physical working environment factors, e.g. keeping personnel warm, adequate lighting, etc.

Human performance is affected by cold, including wind chill and rainfall [13]. This is assessed in the same way as vulnerability to temperature, wind and precipitation. An example is manual removal of snow and ice, which requires a lot of personnel resulting in a poor MTO score. Manual removal of snow and ice is also vulnerable to temperature, wind and precipitation requiring special protective clothing and limited exposure time for each person. In total one would not consider manual removal of ice and snow as robust.

The scale of the MTO factors 'Figure 8' is not divided into intervals and differs from the assessment of other physical factors, which affect a measure.

1	Little or no sensitivity to MTO factors
2	Some sensitivity to MTO factors
3	Moderate sensitivity to MTO factors
4	Sensitive to MTO factors
5	Highly sensitive to MTO factors

Figure 8. Categorisation of MTO vulnerability.

For categories 3, 4 and 5, it is necessary to identify compensating measures to reduce the vulnerability of the measure by MTO factors. The grading is coarse and includes many types of assessments. However, it is considered sufficient to highlight vulnerability of a measure to factors that affect human performance.

3.1.5. Evaluate the impact on power requirements (V): It is relevant to study the impact of the measures on energy consumption e.g. electric heating cables, may require significant amounts of power. This may be challenging for existing facilities and for new installations if the required energy consumption is not given sufficient consideration in the design phase.

A five-category scale without intervals was used for assessment of energy consumption 'Figure 9'. Although using a generic approach, it is easy to adapt the categories to suit a specific project.

1	No effect on energy consumption
2	Some effect on energy consumption
3	Moderate effect on energy consumption
4	High effect on energy consumption
5	Very high effect on energy consumption

Figure 9. Categorization of energy consumption.

In almost all cases, energy consumption will be linked to compensating for the effect of cooling caused by the combined effect of wind and temperature in 'Figure 6' and robustness in 'Figure 7'.

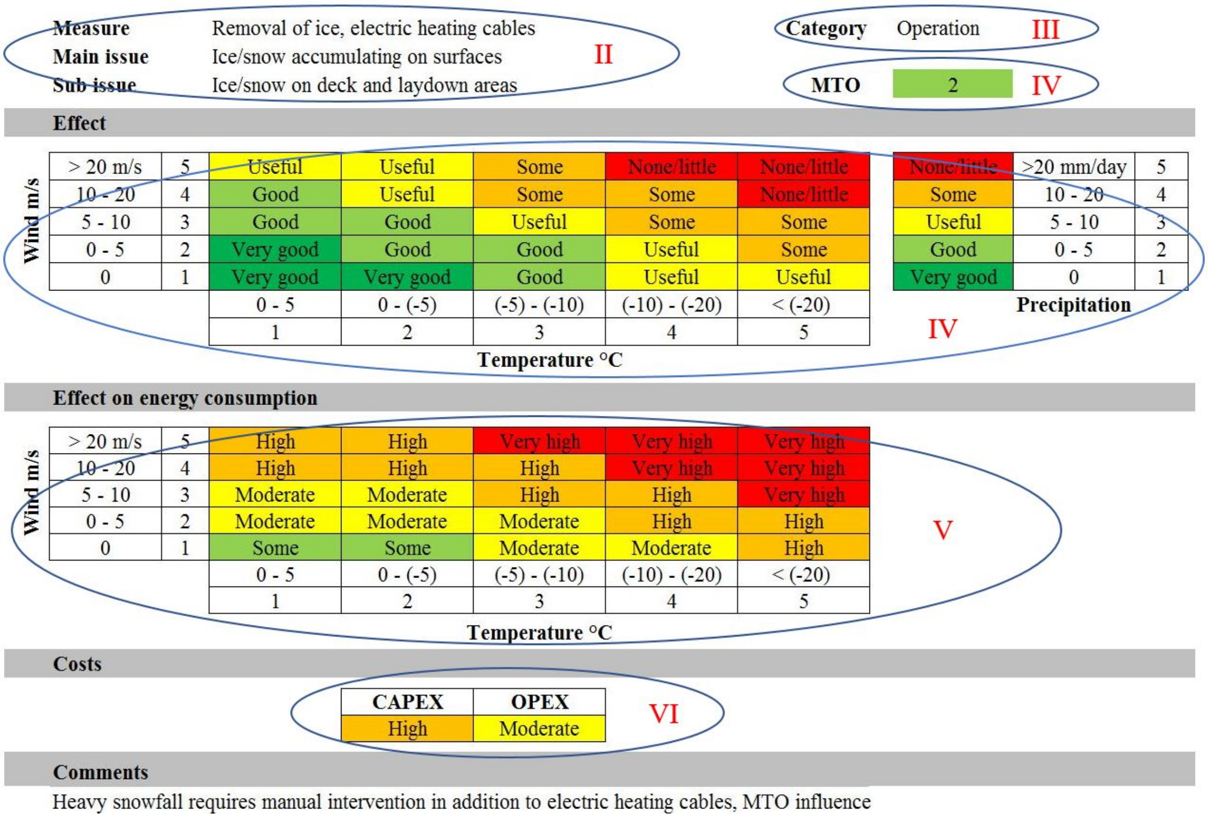
3.1.6. Assessing investment and operational costs (VI): The cost of implementing a measure has been included in the method. The assessment of cost impact is coarse but sufficient for the purpose of developing and testing a method. In operational use, it would be necessary to refine the basis and intervals for costs.

Costs may be a limiting factor and it is assumed that the winterization measures would be subject to a cost/benefit analysis. One would aim to achieve adequate and robust solutions with efficient investment and operational costs. Investment cost (CAPEX) and operating cost (OPEX) have been included in the method as shown in 'Figure 10'.

	CAPEX	OPEX
Very low	< 1 MNOK	0 – 0,5 MNOK
Low	1 – 5 MNOK	0,5 – 1 MNOK
Moderate	5 – 50 MNOK	1 – 5 MNOK
High	50 – 100 MNOK	5 – 10 MNOK
Very high	>100 MNOK	>10 MNOK

Figure 10. Categorisation of costs CAPEX and OPEX.

3.1.7. Evaluation tool, one-pager: Based on the method described above, a “one-pager” was developed to guide one through the process, facilitate documentation and visualization of the assessment results illustrated in Figure 11.



Measure	Removal of ice, electric heating cables	Category	Operation
Main issue	Ice/snow accumulating on surfaces	MTO	2
Sub issue	Ice/snow on deck and laydown areas		

Effect

Wind m/s		1	2	3	4	5		Precipitation	
> 20 m/s	5	Useful	Useful	Some	None/little	None/little	None/little	>20 mm/day	5
10 - 20	4	Good	Useful	Some	Some	None/little	Some	10 - 20	4
5 - 10	3	Good	Good	Useful	Some	Some	Useful	5 - 10	3
0 - 5	2	Very good	Good	Good	Useful	Some	Good	0 - 5	2
0	1	Very good	Very good	Good	Useful	Useful	Very good	0	1
Temperature °C		0 - 5	0 - (-5)	(-5) - (-10)	(-10) - (-20)	< (-20)			

Effect on energy consumption

Wind m/s		1	2	3	4	5
> 20 m/s	5	High	High	Very high	Very high	Very high
10 - 20	4	High	High	High	Very high	Very high
5 - 10	3	Moderate	Moderate	High	High	Very high
0 - 5	2	Moderate	Moderate	Moderate	High	High
0	1	Some	Some	Moderate	Moderate	High
Temperature °C		0 - 5	0 - (-5)	(-5) - (-10)	(-10) - (-20)	< (-20)

Costs

CAPEX	OPEX
High	Moderate

Comments

Heavy snowfall requires manual intervention in addition to electric heating cables, MTO influence

Figure 11. One-pager with method process steps.

3.2. Observations and discussion

The following observations are the main results and findings of the study:

- The method is practical, effective and replicable for evaluating individual measures.
- The use of a one-pager is suitable for documenting, visualizing and communicating results.
- The method has no built-in approach to handle combinations of measures.

As identified previously, the method is based on assessing measures individually. In practice, several measures will overlap and work together while others may have a negative interaction with each other. The method was found to be a useful tool for a coarse selection of measures and assessing their effect given a set of climatic conditions. In a real case, there is a need to assess the individual and combined effect of the measures comprising a winterization package. At present, a qualitative assessment for each specific unit or installation and the operating location needs to be performed in addition to the method.

Using case studies, albeit generally defined, demonstrated that the method could identify potentially useful measures and eliminate those with insufficient effect. Further selection of measures will then have to be done qualitatively based on the unit, location specific metocean conditions and combined effect of other measures.

The selected temperature and wind intervals worked and there has been no need to adjust these in the test. One can argue that the method has not been tested at temperatures below -20°C. Extremely low temperatures provide additional challenges, especially in terms of material quality and keeping fluids at the correct viscosity. On the other hand, the most demanding conditions for winterization tend to be associated with moderate cold in combination with strong winds and heavy precipitation e.g. during a polar low. It is demanding to have a defined method that captures absolutely every conceivable relationship within the same framework.

An important observation is the need to fully describe a measure. The better a measure is described; the better and more accurate assessments can be made. The commentary field proved more important than was envisaged when the method was developed. It was necessary to describe the context, important assumptions and consequences of the measure in addition to a schematic assessment of the effect of the measure under different circumstances. It is emphasized that an assessment of a measure should not be done purely according to a template. However, the method is well suited for a coarse or first pass selection of measures for further assessment as part of developing a winterisation strategy.

The method has primarily assessed the effect of the measure for a combination of temperature and wind. This is justified, as most often the cooling effect of temperature and wind is the main issue. However, it may be natural to evaluate the combination of temperature and precipitation and assess wind separately for certain measures and conditions. No such case was identified during the test of the method. Temperature appears to always be a key factor in evaluating winterization.

The use of measures requiring manual intervention seems widespread. According to the experience of the workgroup, it has been found that the consequences may not be sufficiently addressed in conjunction with other operational and emergency tasks. It is necessary to evaluate this more comprehensively than this MTO assessment is designed for.

Review of winterization manuals reveals that measures relying on manual intervention are used in response to issues associated with operation under winter conditions. These measures involving the use of personnel can include:

- Removal of ice with sledgehammers and bats
- Use of steam lances for ice removal
- Removal of snow by shovelling and sweeping
- Use of tarpaulins on helicopter decks and other structures or equipment.

The wind chill affects mobility and performance of personnel thereby reducing the efficiency of manual operational measures. Restrictions on exposure of personnel to cold also reduce available time for the persons to work in these conditions [13]. It is uncertain whether there is any correlation between use of these measures and the number of personnel in the organization on a facility.

4. Recommendations

The method is designed to assess individual measures and, based on experience, select optimal combinations of measures that also consider:

- health, safety and environmental impact
- measures that may counteract each other
- overlapping or similar measures
- issues that are insufficiently covered by existing and available measures

The method could and should be developed to include a systematic approach to assessing the totality and optimal combinations of measures regarding sufficient robustness to remedy the issues encountered in winter operations. Further development of the method should consider performance requirements related to winterization measures as part of a comprehensive barrier strategy [12]. The winterization strategy should not be detached from the barrier strategy and overall design strategy.

It is recommended to pay attention to equipment that is defined as safety-critical and/or has a barrier function e.g. emergency shutdown, ballast, riser or mooring systems. It is necessary to ensure that these functions are maintained under the environmental conditions with the selected winterization measure. This is required in order to reveal important issues that may be inadequately handled or not identified by an overall assessment.

5. Conclusions

The method has shown encouraging results for assessing individual winterization measures when used under prevailing environmental conditions in the Barents Sea. However, the method does not provide the optimal combinations of winterization measures. It is possible that several combinations of measures could provide a robust winterization package. It is anticipated that robust combinations with low energy requirements and negligible effects on health, safety and the environment would be preferred.

It is imperative to collect location specific climate data e.g. hindcast data and evaluate these against the design of the facility and planned operations. Several measures may provide the required effect within the climate conditions. After applying the method to specific facilities and operations, one sees that passive measures e.g. custom designs and enclosures, are in general, more robust than active measures.

There is sufficient flexibility in the method allowing it to be used for any type of facility and location. The method provides a good basis for evaluating, selecting and combining winterization measures required for an operational envelope in a cold climate environment. The method also lends itself to use in areas other than the Barents Sea. To do this, relevant metocean data is required for the area or location where a facilities winterization needs will be analysed.

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