NTNU
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS

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Analysis of the ballast system of WindFlip	16th June, 2010
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Abstract:

The thesis firstly includes a study of the structure and requirements of a general ballast system. Based on this knowledge a ballast system suiting the needs of the WindFlip concept was designed through using the risk-based design methodology (RBD).

The presented ballast system has one sub-system for ballasting during rotation of WindFlip from horizontal to vertical position and back again (called main ballast system). Another sub-system (called the secondary ballast system) is used during transit without payload and during onloading of payload (one Hywind floating offshore wind turbine). The latter system is connected to an eductor circuit for stripping the ballast tanks.

The main ballast system ballasts by flooding the ballast tanks. The tank is ventilated so it can flood freely, ventilation is closed when the tank is completely full. As WindFlip does not have a pressure hull, pressure is increased in empty ballast tanks when being submerged to compensate for increased hydrostatic pressure. During deballasting ventilation is used to relieve pressure gradually. Water in the ballast tanks is purged out by compressed air. The main ballast system has two main pipelines which are branched into feeder lines going into each tank. There are two valves connected to the feeder line leading into each tank; a butterfly valve and a pressure reduction valve (PRV). The butterfly valve is used for ventilation and the PRV for the compressed air. The function of the two main lines may be switched (from vent to compressed air and vice versa), and there is an interconnection between the two also securing redundancy. The main ballast system reaches out to 102 ballast tanks.

The secondary ballast system reaches out to 27 ballast tanks. The layout of this system is quite similar to common ballast systems. The main difference is that it only has one ballast pump, which is allowed for unmanned barges according to DNV. An eductor system is included in the secondary ballast system for stripping the ballast tanks. This system may however not be mandatory, this should be discussed further with the classing society. A ballast treatment plant is not included in the design as WindFlip mostly will operate locally. There is however a possibility for conducting ballast exchange with the sequential method during continental travel.

A Fault Tree Analysis (FTA) was performed in order to find the unreliability of the system. The most interesting result was that a failure during rotation is expected once every third year. The FTA was compared to the use of Bayesian networks (BN). The report shows that BN can replace the FTA and that BN is a more flexible method.

Keyword:

Ballast system, risk-based design,

fault tree analysis, bayesian network

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Preface

This is my master thesis in my last semester at NTNU. It consists of two parts; first a thorough study of ballast systems and its structure, and secondly design and analysis of a system suiting the WindFlip concept. I have chosen to focus on exploring the design space and using this knowledge to design a reliable and effective ballast system. A fault tree analysis has also been performed on the system and has been compared with a similar model based on the Bayesian network.

Designing an entire ballast system is an extensive task. There are many aspects to consider and to optimize in order to get the best result. I have tried to include many of the important aspects and gone deeper into the ones I felt were most important for WindFlip. The workload has been large, but it has also rewarded me greatly in terms of new acquired knowledge. The work has hopefully also rewarded WindFlip AS. I have had great benefit from many of the skills I have obtained through the years at Marine Technology, as they really proved their value when analyzing the different tasks.

I have put a lot of effort into research in order to create a good fundament for creating the ballast system of WindFlip. Especially DNV has provided valuable resources for designing the ballast systems. I have also had great benefit from contacts aiding me during designing, like Captain William Gaines who has firsthand knowledge about the most similar vessel to WindFlip, R/P FLIP. WindFlip AS has, along with several students with thesis' about WindFlip, has given me the framework to base my design on.

We would like to give special thanks to Professor Bjørn Egil Asbjørnslett, Professor Svein Kristiansen, Professor Maurice F. White, Technical Trainee Hallvard T. Uglane at DNV and Captain William Gaines of Scripps Institute for all help given.

Trondheim, 16th of June 2010.

Atle Alvheim

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1 Introduction

1.1 The Concept of WindFlip

Floating offshore wind turbines has lately been promoted as a green energy source with a huge potential. The size and shape of floating offshore wind turbines has been and still is an issue which needs to be resolved in order to enable offshore wind production. Suggested solutions have been to tow the turbine standing with two or three tugs or to assemble large pre-made blocks at the offshore site by the use of a semi-sub. Both solutions are slow, expensive and largely dependent on good weather.

Illustration 1 - Hywind illustration (Statoil, 2010)

5 MW Hywind		
Total length	190	[m]
Draft	110	[m]
Height above WL (top of nacelle)	80	[m]
Propeller diameter	120	[m]
Total weight	6500	[mt]

Table 1 - 5 MW Hywind data (Statoil, 2010)

WindFlip is a barge specially designed for transporting and partly installing floating offshore wind turbines. The concept provides a solution for transporting these immensely huge wind turbines to a designated site. The barge is fully capable of working in significant wave height pushing two meters. The barge is towed to an offshore site while carrying one turbine horizontally on deck. At the site 102 ballast tanks in the aft part of the vessel will be filled with about 29 000 tons of sea water, as a result the barge will rotate to vertical position. In this position the turbine will be towed from the barge by a tug. Further on the turbine will be anchored to the seabed. WindFlip empties the ballast tanks and rotates back to horizontal and starts its journey back to the wind turbine production site.

Vessel specifications:

Vessel type		Unmanned barge	
L_{pp}	Length between perpendiculars	137.2	[m]
L_{oa}	Length overall	140.0	[m]
B	Maximum breadth	27.8	[m]
D_{0^o}	Draft at 0^o trim	5.6	[m]
D_{85^o}	Draft at 85^o trim	120.0	[m]
LWT	Light ship weight	10 331	[mt]
DWT	Weight of payload, fuel and stores.	6 612	[mt] (112[mt] from stores)
∇_{0^o}	Displacement at 0^o trim	10 443	[mt]
∇_{85^o}	Displacement at 85^o trim	28 472	[mt]
Towing speed		5	[knots]
$H_{s,max}$	Maximum significant wave height	2	[m]

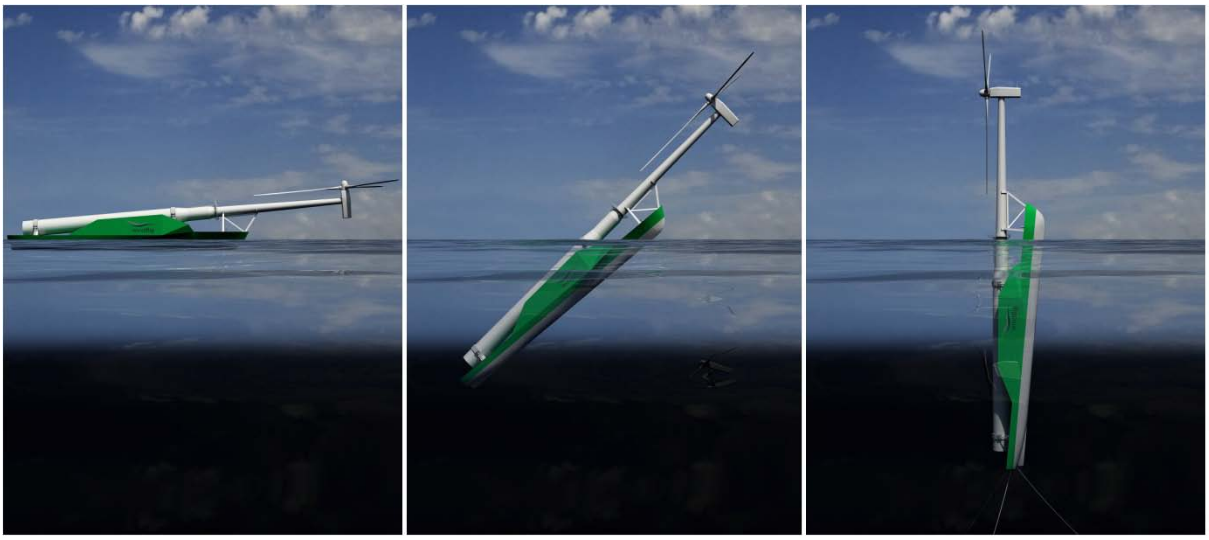


Illustration 2 - The Concept of WindFlip (WindFlip AS, 2010)

The hull is uniquely designed to be able to perform this operation. Most of the volume is located in the aft, this provides the displacement needed to support the heavy turbine. The turbine has to be lowered into the hull as far as possible to secure a low center of gravity. Another feature is the wing tanks amid ship, these provide extra waterline area and thereby extra stability in the rotational phase. They are also filled with water to lower GM while the barge is in transit without turbine, a too high GM gives unfavorable motion. The waterline area for a vertical WindFlip is also specially designed. This section is designed with an aim on achieving similar heave motions as the wind turbine which is essential during release of the turbine.

The wind turbine is fastened to deck with a five degree angle between the turbine's stem and the waterline at zero degrees of trim. This is a design feature which improves stability and increases the distance between the turbines rotors and the sea water during transit. The top part of the turbine is elevated compared to the lower part. This means that the vessel only has to trim to 85 degrees for the turbine to stand in vertical position (90^0). The filling sequence is therefore completed at 85 degrees of trim angle.

1.2 Thesis outline

I wrote a project thesis about WindFlip in the fall of 2009. The project's aim was split in two; a stability analysis and a risk analysis were to be performed of the rotational operation and the release of the turbine. In the risk analysis a FMEA was performed to discover failure modes of major components of WindFlip's operation. Bayesian Networks were also studied and used to create a model picturing risk of an operational phase. A model testing of scaled version of WindFlip took place in February earlier this year. A four meter long WindFlip model and a wind turbine was built and tested. The stability calculations of my project thesis were important for a model test of WindFlip and proved to correspond well with the scaled model, though smaller deviations could be observed.

The master thesis will in some degree be an extension of this work.

The main tasks of this master thesis can be seen on the next page, this has been excerpted from the thesis description. The description can be viewed in full in Appendix A – Thesis outline.

1. *Gather requirements, information and experience concerning ballast systems in the industry.*
2. *Describe WindFlip's operation and the ballast system's requirements for fulfilling the operation.*
3. *Make a detailed overview of components available for the ballast system and construct a possible system design for the ballast system onboard WindFlip.*
4. *Develop a basis for a risk and reliability analysis on component and system level to assess improvement potential from a safety risk point of view. Failure probabilities from existing data have to be found.*
5. *Use the structure of the system and failure probabilities to create two models, a FTA model and a Bayesian Network model. Describe the two methods.*
6. *Compare the results from each model and elaborate on the comparative performance of the models (pros and cons, possible improvements of the models etc.).*
7. *Assess design improvements in the ballast system design and do a cost-benefit analysis on the alternatives.*
8. *Present a fully functional ballast system that meets the requirements for efficiency and safety.*

My master thesis will go further into the ballasting process by designing a ballast system by the use of the Risk-Based Design methodology. The detail level of the design will be to component level, regarding tanks, pipelines, valves, vents and pumps. The master thesis will therefore focus on a much more detailed level than the project thesis which focused on the whole operation. Thorough work with background information about ballast systems in general is the basis for designing the new system. This includes looking into classing and regulations. Risk-based design will also have to be studied in order to be applied properly in the design process. The study of Bayesian networks in my previous work will provide a fundament for applying the method in the risk analysis. The method will be compared to the use of FTAs.

Note that task seven has been left out due to the high work load of the other tasks.

2 WindFlip Operation

2.1 The operation

Note that some of the text in the following description is excerpted from my project thesis.

Before launching the operation weather reports have to state fairly good conditions for the duration of the transportation, rotation, release of turbine and rotation back. During the installation phase significant wave height cannot exceed two meters. It is expected that wind speed should not go above 5 m/s while currents should stay below 2 knots. If either of these restrictions are compromised the operation has to be paused or aborted. If the conditions are within limits, the operation can start and the barge can be towed by a tug from the production site to the offshore field, e.g. The North Sea. WindFlip will be connected to an umbilical from a tug providing WindFlip with electricity, in and outgoing control signals, pressurized air and perhaps hydraulics.

At the offshore site WindFlip will be anchored to the seabed by using a configuration as in the below figure. The anchoring will in a minor sense maintain WindFlip's position while rotating. The anchoring system's real intention is to be a counter weight during the release of the wind turbine.

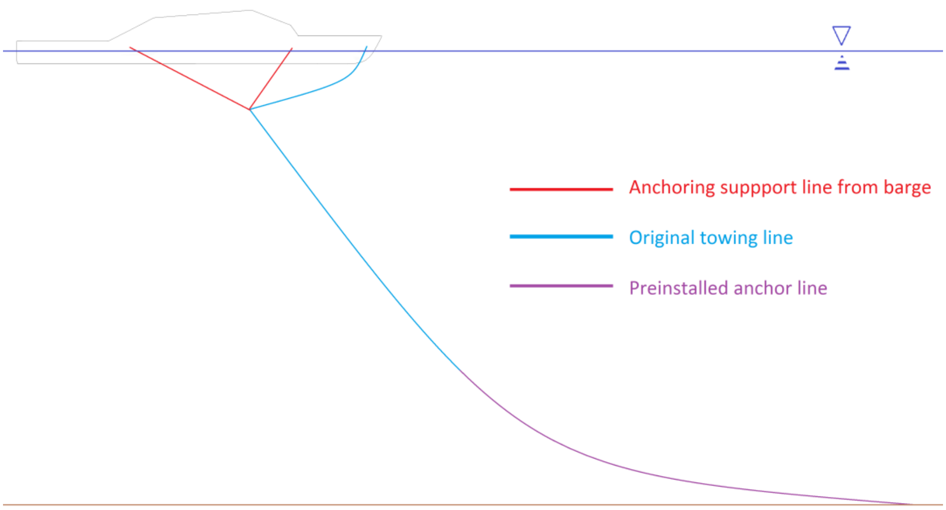


Illustration 3 - Anchoring of WindFlip

The blue line is the original towing line which is fastened to the preinstalled anchor line. The red lines are the lines which will be in tension while anchored.

At this point ballasting of WindFlip may commence. All important systems will be monitored and send information through the umbilical to a control room monitoring and operating WindFlip remotely. The system monitoring the ballast system receives input from all valves, vents, and instruments measuring the pressure and filling/emptying. If the monitoring system picks up errors/inconsistencies or loose signal, the operation has to be stopped. Errors in the system can damage the whole operation. An unfilled tank will affect the trimming, give a roll angle and it can cave in due to hydrostatic pressure. A partly filled tank will give the free surface effect. The rotation has to be reversed either controlled remotely or perhaps manually by an ROV.

Signals will be sent to the many valves onboard WindFlip and the ballast tanks will be flooded according to a preset program. A computer program will handle this automatically, but with an option of manual over steering. An automated process is preferred as human error could be critical to the stability of WindFlip.

Ballasting rotates the barge from zero degrees to 85 degrees of trim angle. Six hours is assumed to be sufficient time for one way rotation.

The ballast tanks are numbered in the following manor. A more detailed numbering of the tanks can be found in Appendix B – Tank numbering.

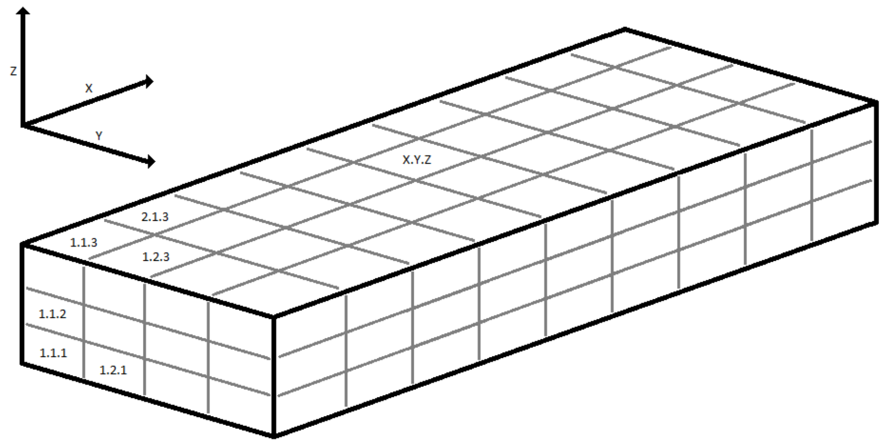


Illustration 4 - Numbering of ballast tanks

Rotation to vertical position will proceed as in the table below. The notation states that two or four tanks being filled at the same time, in reality one tank will be filled at the time. If tank x.1.x is filled, then x.4.x is to be filled next, if x.2.x is filled then x.3.x will be filled next. Filling this way will give a roll angle. The option is to fill two tanks at the time, this would reduce stability due to an increase in free surface moment compared to only one tank being filled.

Loadcase	Filling	Comments
LC0		No ballast.
LC1	5.(1&4).3, 6.(1&4).3, 7.(1&4).3 30%	Transit mode, tanks are filled to lower GM. These tanks are emptied before starting the rotation.
LC2	1, 2, 2.(1&4).1, 3.(1&4).1, 4.(1-4).1, 5.(1-4).1, 6.(1-4).1, 6.(1-4).2, 7.(1-4).1, 7.(1-4).2, 8.(1-4).1, 8.(1-4).2, 9.(2-3).1, 9.(1-4).2, 10.(2-3).1, 10.(2-3).2, 11.(2-3).1, 11.(2-3).2	Ballasting to a larger draft (parallel submersion) in order to make use of stability provided by the wing tanks when the vessel starts to rotate.
LC3	5.(1-4).2, 7.(2-3).3, 8.(2-3).3	Rotation starts. These tanks are filled in addition to the ones in LC2.
LC4	4.(1-4).2	Tanks filled in addition to LC2 and LC3, the next LCs are denoted in the same manor.
LC5	2.(2-3).1, 3.(2-3).1	
LC6	1.(2-3).1	
LC7	1.(1&4).1, 1.(2-3).2	
LC8	1.(1&4).2	
LC9	2.(1&4).2	
LC10	2.(2-3).2	
LC11	3.(1-4).2	
LC12	5.(1&4).3, 6.(1&4).3	
LC13	7.(1&4).3, 8.(1&4).3, 11.(2-3).1 0%, 9.(2-3).3 30%	WindFlip has reached 85 degrees and is ready to launch.

Table 2 - Loadcases for WindFlip with payload

The following GM-values, displacement and trim angle have been attained for the different loadcases.

Loadcase [-]	Trim Angle [º]	Trim change [º]	Displacement [m^3]	Disp. change [m^3]	$GM_{transverse}$ [m]	$GM_{longitudinal}$ [m]
LC1	0.02	-	11561	-	1.79	248.16
LC2	-0.55	-0.57	23990	12429	1.57	33.82
LC3	1.45	2.00	26007	2017	1.15	44.05
LC4	3.11	1.66	27063	1056	1.25	55.53
LC5	10.32	7.21	28741	1678	1.38	15.69
LC6	18.99	8.67	29221	480	1.19	5.20
LC7	31.91	12.92	29461	240	1.16	1.94
LC8	48.35	16.44	29665	204	1.36	1.46
LC9	60.36	12.01	29908	243	1.77	1.78
LC10	69.95	9.59	30307	399	2.67	2.70
LC11	76.76	6.81	31136	829	4.46	4.56
LC12	80.54	3.78	32163	1027	5.84	6.01
LC13	85.03	4.49	33950	1787	8.03	8.17

Table 3 - Data concerning rotation of WindFlip with payload

When loadcase 13 has been reached the ballast system will freeze until the wind turbine has been released and is at a safe distance away from WindFlip.

An interesting fact that can be derived from the previous two tables is that the change in trim angle is the largest in loadcases seven to nine. The change in displacement, the addition in ballast volume, is on the other hand the least. There is a connection to stability, both longitudinal and transverse GM is quite low compared to the other loadcases. This study reveals that an error in ballasting is most critical in these three load conditions. It is therefore very important that the ballast tanks remain at their filling levels and that the current procedure is followed through.

A deballasting sequence has also been developed for the rotation back to horizontal and is denoted below. Note that the loadcases are still noted from horizontal and not from vertical.

Loadcase	Filling	Comments
LC0		No ballast.
LC1	1, 2, 1.(2-3).1 70%, 1.(1-4).2, 2.(1-4).2, 3.(1-4).2, 4.(1-4).2, 5.(1&4).3, 6.(1&4).3, 7.(1&4).3, 8.(1&4).3	Transit mode. GM lowered compared to LC0 and draft increased to reduce slamming.
LC2	7.(1-4).1, 8.(1-4).1, 9.(2-3).1, 1.(1-4).1, 6.(1-4).1, 5.(1-4).1, 7.(1-4).2, 8.(1-4).2, 2.(1-4).1, 9.(1-4).2, 10.(2-3).1	Tanks filled in addition to LC1, same notation follows.
LC3	10.(2-3).2, 3.(1-4).1	
LC4	4.(1-4).1	
LC5	11.(2-3).1, 11.(2-3).2, 5.(1-4).2	
LC6	6.(2-3).3	
LC7	6.(1&4).3	
LC8	7.(2-3).3, 8.(2-3).3	
LC9	9.(1&4).3 50%	WindFlip at 74 degrees

Table 4 - Loadcases for WindFlip without payload

Note that loadcases have only been calculated to about 74 degrees, this has to do with limits in the software (Maxsurf's Hydromax Pro) used to produce these results.

Loadcase [-]	Trim Angle [º]	Trim change [º]	Displacement [m^3]	Disp. change [m^3]	$GM_{transverse}$ [m]	$GM_{longitudinal}$ [m]
LC0	-2.04	-	3831	-	9.73	457.74
LC1	0.00	2.04	9480	5649	5.82	286.85
LC2	-0.82	-0.82	19928	10448	6.18	132.47
LC3	0.68	1.50	21936	2008	3.54	48.70
LC4	4.94	4.26	23092	1156	2.81	24.00
LC5	11.77	6.84	25139	2047	2.16	10.25
LC6	41.05	29.28	26241	1102	1.40	1.36
LC7	56.07	15.01	26595	354	1.55	1.43
LC8	70.87	14.80	27318	723	2.12	2.08
LC9	73.69	2.82	27691	373	2.25	2.24

Table 5 - Data concerning rotation of WindFlip without payload

This study shows that unloading of ballast is most critical at loadcase six and seven. Stability is however a lot better overall.

A conclusion can be drawn from the last few tables; the rotation with and without payload is most critical at trim angles around 45 degrees.

There is one more load condition which has not been presented above. During on loading of the wind turbine trim will be changed from LC1 (WindFlip without payload). The turbine is to be skidded onboard WindFlip. The cargo deck is inclined by 5 degrees as mentioned earlier, this needs to be leveled out in order to skid the turbine onboard. Forward tanks of WindFlip have to be filled in order trim forward and make the cargo deck reach zero degrees.

2.2 Other considerations

There are 102 ballast tanks which have to be available during rotation. 27 ballast tanks are assumed to be used during ballasting for transit and during onloading of payload.

Sizing of the ballast tanks should be revised, my project thesis discovered that this has to be done to improve damage stability. The tanks in the two middle rows (x.2.x and x.3.x) are too large. Proper sizing will be derived by an iteration process, but this is not within the scope of this thesis.

3 Ballast systems

3.1 Ballast Systems in General

A ballast system has several tasks, one of the main ones is to achieve enough displacement when a vessel is cruising with little or no cargo. This ensures that propeller and rudder are sufficiently submerged so the propeller can operate at design draft and the rudder has enough submerged area for maneuvering. Another important matter is seaworthiness. The cargo is normally placed deep as this lowers center of gravity and increases stability. Without cargo, the center of gravity would be a lot higher due to the superstructure, highly placed equipment, etc. Taking in ballast water in low compartments would improve stability by lowering KG and increasing KB, as well as increasing the waterline component in BM.

Ballast could also aid during freight in severe weathers. Changing trim may reduce the impact of waves and the overall strain on the vessels structure. Ballasting can also be used to change the air draft due to overhead cranes in port or other height limitations like bridges. Another area of use is to balance a vessel with an asymmetric load distribution (both longitudinally and transverse). (DNV, 2010)[1]

For regular bulk carriers or tankers it is common to have segregated ballast tanks, but using the cargo tanks for ballast is also done.

WindFlip's use of the ballast system:

- The main task of WindFlip's ballast system is to shift the center of gravity in order to rotate the barge and then safely release the wind turbine.
- Ballast is also used to lower GM during transit without cargo. The stability of WindFlip is actually "too good" in this condition, the high restoring moment gives swift restabilization of roll which could strain the hull. GM is lowered (KG increased) by filling the highly placed ballast tanks.
- Ballasting is also important during onloading of the wind turbine. The Wind turbine is supposed to be skidded onboard and as WindFlip's deck is inclined by five degrees, the barge needs to level.

3.2 Environment

In the last few decades more and more focus has been directed to environmental effects of ballast water. There has been a problem that the ballast system in some cases can be influenced by the bilge system[2] due to common operation areas or faulty valves. This means that the ballast water could contain oil or other harmful substances. Unloading ballast to sea could therefore result in polluted waters and damage the local ecosystem.

Pollution is however not the only problem, ballast water may also contain plankton, plants, bacteria, etc. Ballast water with such may be transported a long distance and released into new environment. Studies have shown that it is fully possible for the organisms and species to remain viable even

[1] DNV - an abbreviation for the Det Norske Veritas. The society was founded in 1864 and has its headquarters in Høvik, Norway (DNV, 2010).
[2] Bilge system – picks up and stores water, oil, particles, chemicals, etc. from leaks or spills onboard a vessel.

though being transported for several weeks in the rough environment of a ballast system. When released into a new environment colonies may grow which could be harmful and create an imbalance in the local ecologic system. (DNV, 2010)

Shipping transports 3-5 billion ton of ballast water internationally per year. (IMO, 2010)[3]

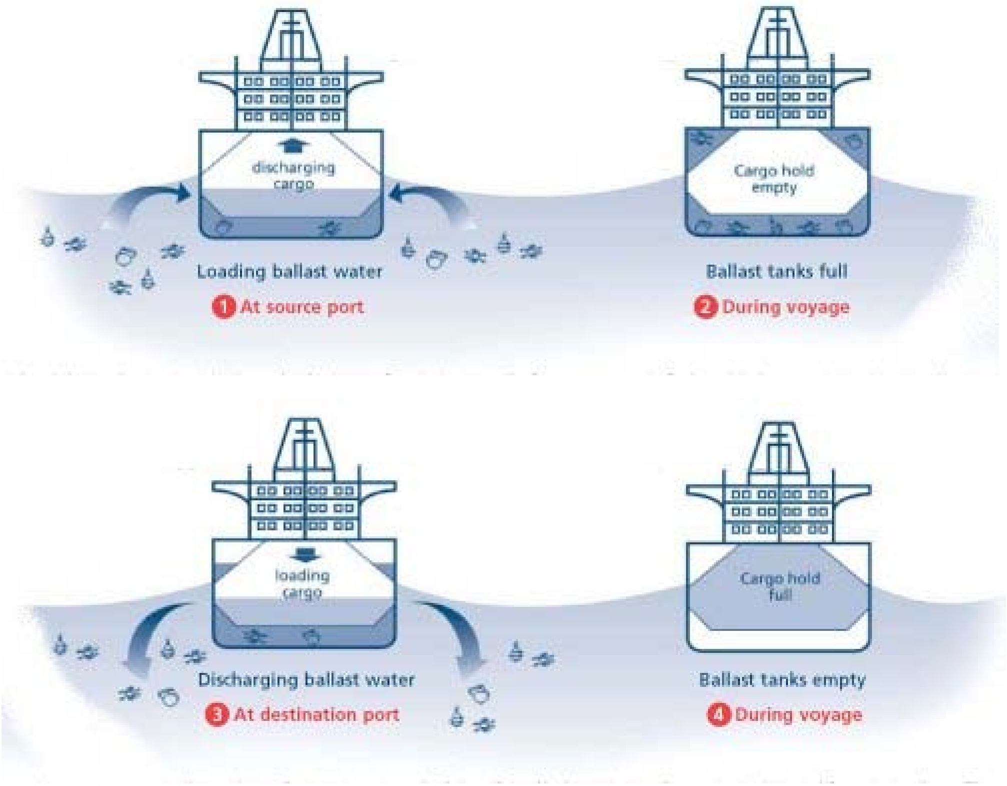


Illustration 5 - Cross sections of ships showing ballast tank and ballast water cycle (IMO, 2010)

The WHO[4] has expressed concern about the danger connected to ballast water. They have done several studies of the effect of ballast water discharge and have also found cases (cholera instance in southern parts of the US) where contaminated substance has been transported through ballast. (WHO, 2010)

Guidelines for handling ballast water have been published by IMO in resolution A.774(18) and A.868(20). A new annex to IMO's convention of preventing pollution from ships, Marpol 73/78, is also being considered. (IMO, 2010)

In the guidelines of A.868(20), paragraph 7.1.1 states "Every ship that carries ballast water should be provided with a ballast water management plan to assist in the minimization of transfer of harmful aquatic organisms and pathogens." The plan is to be specific for each ship. Vessels should record and report treatment of ballast water to port state authority.

The increased focus on this subject also led IMO into developing a convention concerning control and management of ships ballast water end sediments in 2004. The convention requires about 30

[3] IMO – The international maritime organization (Est. 1959), works for ensuring safety at sea. (IMO, 2010)
[4] WHO – World Health Organization (Est. 1948), responsible for health governance within the United Nations. (WHO, 2010)

voluntary states to comply with the directives denoted in the convention. According to (DNV, 2010) 23 percent of the world's tonnage has currently ratified the convention.

Some countries have, awaiting the convention to take effect, created national regulations to control ballast handling. This includes performing surveys and inspections upon a vessels arrival. The inspection will check certificates and the ballast water record book and may also take a sample of the ballast water. The vessel in question may not discharge ballast until the discharge is regarded as safe. Ballast water may, where available, also be unloaded into portside treatment plant to clean the water from harmful content.

Ballast water exchange is also an option, the procedure is to change ballast water coming from a coastal zone with sea water from the open sea. It is expected that the organisms will not survive when released at open sea."Regulation B-4 Ballast Water Exchange" of IMO states that the exchange should happen at least 50 nautical miles from port and at a water depth of at least 200 meters. If this is not possible designated areas may be available for making exchange.

DNV states the following recommendations for newbuildings based on the convention:

- Implement the use of a Ballast Water Record Book
- Implement approved Ballast Water Management Plan
- Minimize the use of ballast water (BW)
- Ensure the most effective flushing using Ballast Water Exchange
- Minimize the uptake of sediments
- Facilitate removal of sediments from ballast water tanks
- Prepare for possible delivery of ballast water to reception facilities
- Prepare for possible installations of a Ballast Water Treatment system at a later stage

WindFlip will be attached to one specific location at the time. The distance from production site to installation site is expected to be around 300 nautical miles. Loading and unloading of ballast water is not seen as a threat to the environment during such an operation. However, WindFlip may travel between continents for new projects. During such transit WindFlip will carry ballast water which needs to be handled safely. The environmental aspect of the ballast system design is therefore relevant. The requirements denoted above actually concern tankers and bulk carriers, but are not, in any way, irrelevant for a barge with a ballast system.

3.3 Corrosion

Corrosion is a huge problem in ballast systems. As a very large share of WindFlip is part of the ballast system, the design is therefore very prone to suffering damage from corrosion. There are two ways of coping with corrosion; preventing corrosion of happening and performing maintenance when it has occurred.

There is a wide range of preventive measures, most common is the use of chemical inhibitors, anodes, cathodic protection and the use of coating.

3.3.1 Chemical inhibitors

Inhibitors is most commonly used in the oil extraction and processing industries. A corrosion inhibitor is a chemical substance which effectively reduces corrosion rate when a small concentration is added to the environment. The chemical either reacts with the surface of the material and creates a protective film or reacts with the environment at the location. The inhibitor may be solid or liquid, liquid inhibitors are most regular for application in ballast tanks. An inhibitor will (Roberge, 2000);

- Increase anodic or cathodic polarization behavior
- Reduce movement or diffusion of ions to the metallic surface
- Increase electrical resistance to the surface

Inhibitors could definitely be applied to WindFlip, but an issue is that there will be large amounts of water going in and out of the ballast system so a vast amount of chemicals may have to be used. Another issue is that for an inhibitor to work sufficiently the chemical will need to work well in a wide range of pressures (from one to twelve bars) and temperature. This means that different inhibitors may have to be applied. The inhibitor has a quite experimental nature, meaning that a lot of thorough testing will have to be done in order to find a suitable inhibitor. There are indications of inhibitors being expensive if applied to WindFlip, a study would have to be performed to see if the benefits balances costs and if this method is better than others.

3.3.2 Anodes

The use anodes are very common in marine industry. The anode is a metal which is intended to be dissolved before other metal structures. The method works as follows; the metal used as protection has to be more anodic than the structure in need of protection. The structure will become a cathode as electrons are released from the anode and start to protect the structure. The anode is sacrificed until it is fully corroded, then the next most anodic substance will start to corrode, the ballast tank.

Illustration 6 - A typical anode (Silent Run Ltd., 2010)

Anodes could be placed in every ballast tank and checked periodically. Deterioration could be noted and an average corrosion rate could be found. When the anode is close to be fully corroded, the anode is substituted. Accessibility to the tanks would of course be needed.

After contacting the manager of the R/P FLIP[5] program, Captain William Gaines, I was informed that R/P FLIP has applied anodes to every ballast tank.

3.3.3 Cathodic Protection

Cathodic protection (CP) is based introducing an electrical current running from cathode to anode. In essence it works in the same way as just using anodes, but by using an electrical current corrosion rate can be controlled. The stronger electric current used, the slower corrosion rate of the protected

[5] R/P FLIP – the only other vessel with a rotating ability, a research vessel made in 1962, operated by Scripps Institution of Oceanography in San Diego, USA.

structure, while the anode will dissolve faster. A weak current could result in excessive corrosion and a too strong current can damage the coating. (Roberge, 2000)

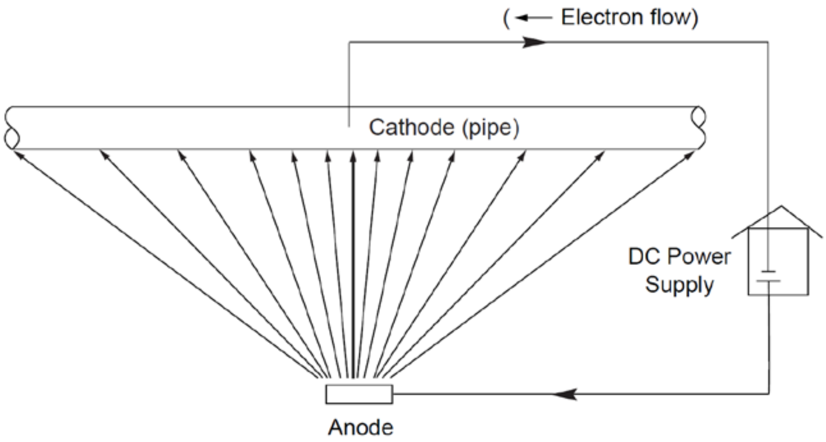


Illustration 7 - The principle of cathodic protection (Roberge, 2000)

CP works well in combination with coating. The protection will occur at areas where the coating is at its weakest.

3.3.4 Coating

The use of coating for controlling corrosion is also a very common. The coating is a barrier between the metal structure and the corrosive environment. The coating needs to have very strong properties against growth of organisms. Such growth will slowly wear down the coating and leave the metal underneath unprotected. A major drawback of coating is that if a patch is left unprotected, all corrosion will be centered at this point. If a larger area is unprotected, corrosion will be “distributed” evenly and thereby not be as critical. Regular coating may be only meant for protection, but metallic coating can also have a load-bearing capability.

R/P FLIP have recently started using an epoxy coating made by Sherwin-Williams. The coating was originally designed for the US navy for saving tank preservation time and therefore shipyard time. The coating is reported to have a very positive impact on the fight against corrosion when combined with the use of anodes.

3.4 Structure of the System

A regular ballast system consists of the following components according to (Rowen, et al., 2005):

- Suction pipes/pressure pipes
- Various valves: butterfly valve, globe valve, gate valve, ball valve , etc.
- Seawater intakes
- Ballast pumps
- Overboard piping and pump system
- Connection to bilge system
- Control equipment
- Filters

A typical ballast system can be viewed below.

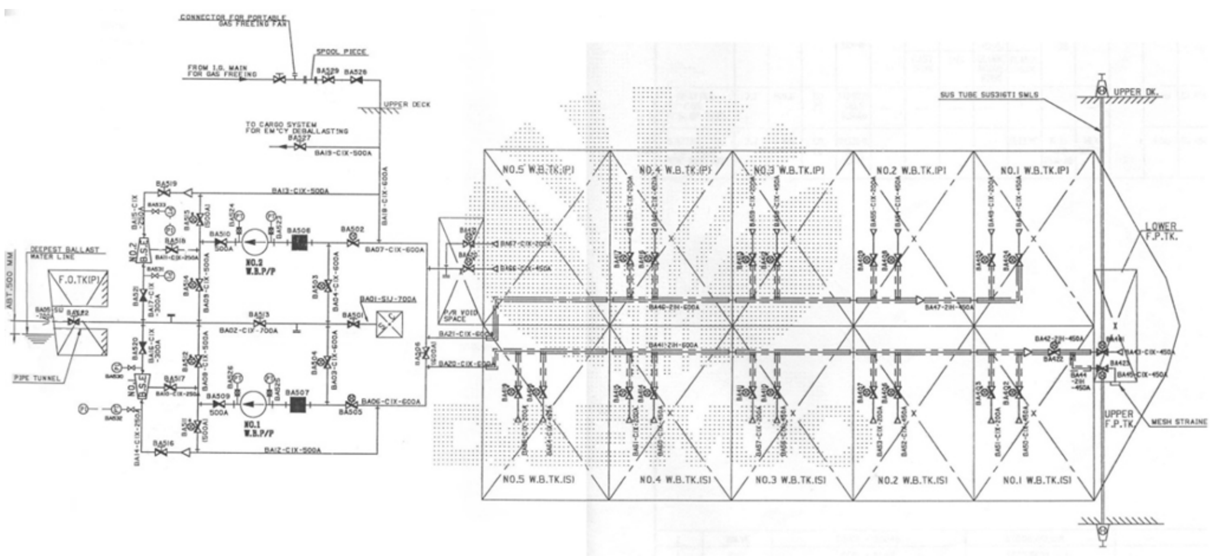


Illustration 8 - Ballast system layout of M/T BW ULAN

The ballast system layout above shows BW's tanker M/T BW ULAN's[6] ballast arrangement. The arrangement drawings has been obtained with consent from BW through a fellow student, Vishal Sharma. The ballast system's main features are:

- One sea chest letting in ballast water
- Two filters
- Two pumps ensures desired flow in the system
- Two educators for stripping tanks
- Two lines controlling ballast levels on starboard and port side of the vessel

In the following three of the main functions of the system are described in order to get a better understanding of how this system works as an example of how other common ballast systems work.

[6] M/T BW ULAN particulars – L/B/D 332/58/22 meters, GT/DWT 158 000/300 000, service speed 15.5 knots. (IHS Fairplay, 2010)

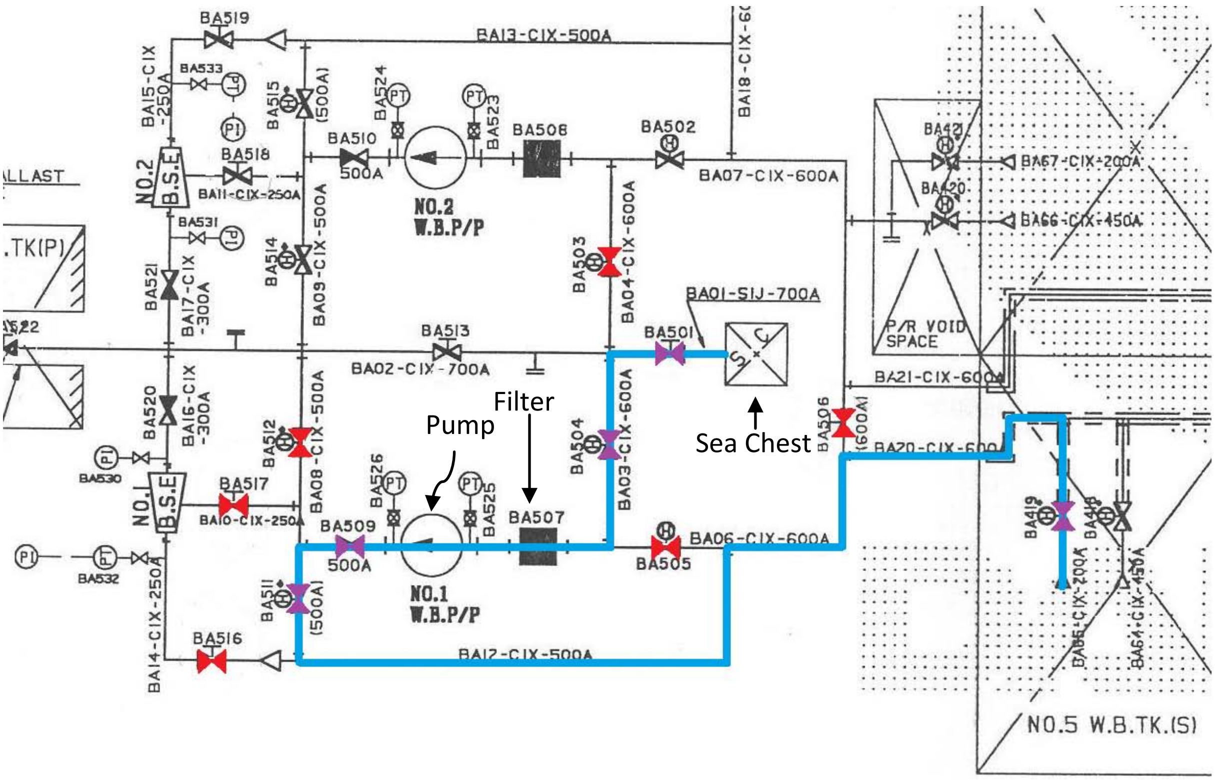


Illustration 9 - The ballasting function

The ballasting process of a single tank can be seen above. The blue line illustrates the flow of water, the purple valves are open while red ones are closed. The ballasting process occurs as follows. The sea chest lets in sea water to the suction side of the pump. Before the pump is activated it is primed as the pump needs to be filled with water in order to start working. With the pump online the water is lead through the filter and onwards to the discharge side of the pump and then to the ballast tank. Note that the same tank could be filled by combining use the top pump and filter, the tank could also be filled by using the top pump and filter alone.

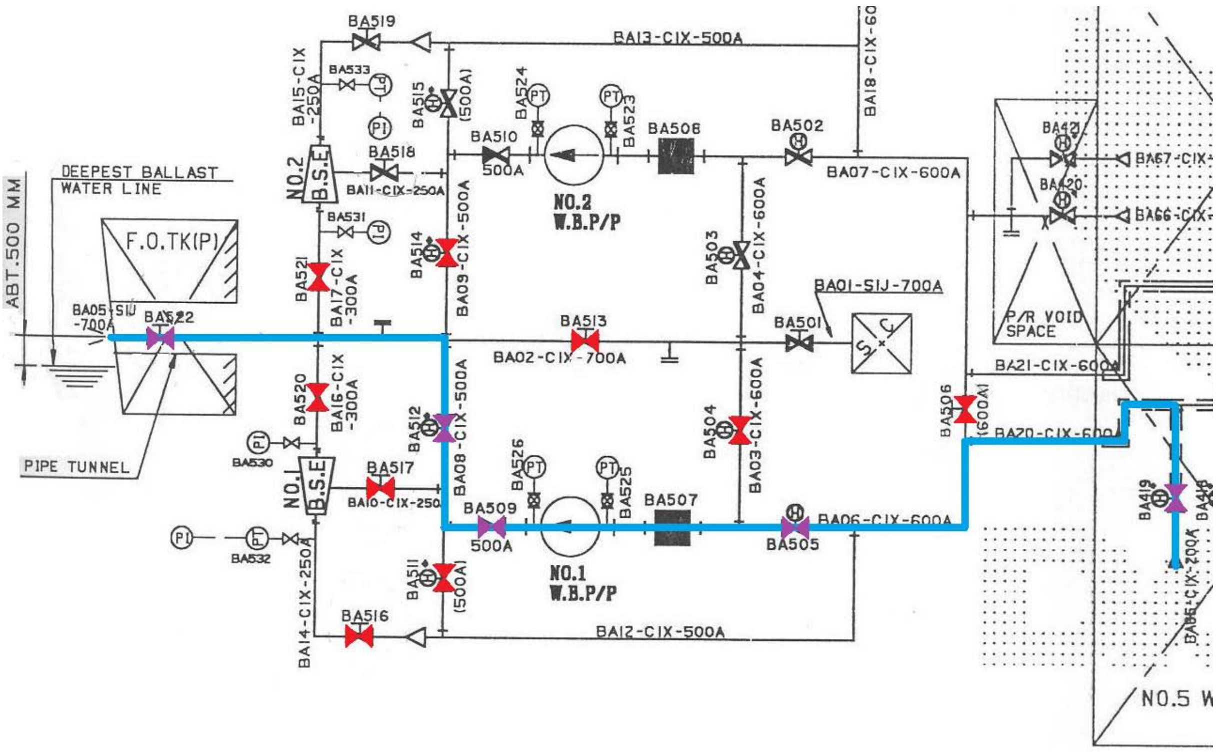


Illustration 10 - The de-ballasting function

In the de-ballasting process the lower line (BAIZ-CIX-500A) and the line leading to the sea chest is shut down, placing the ballast on the suction side of the pump. The water goes through the pump and is discharged. Again both pumps could be used separately or together.

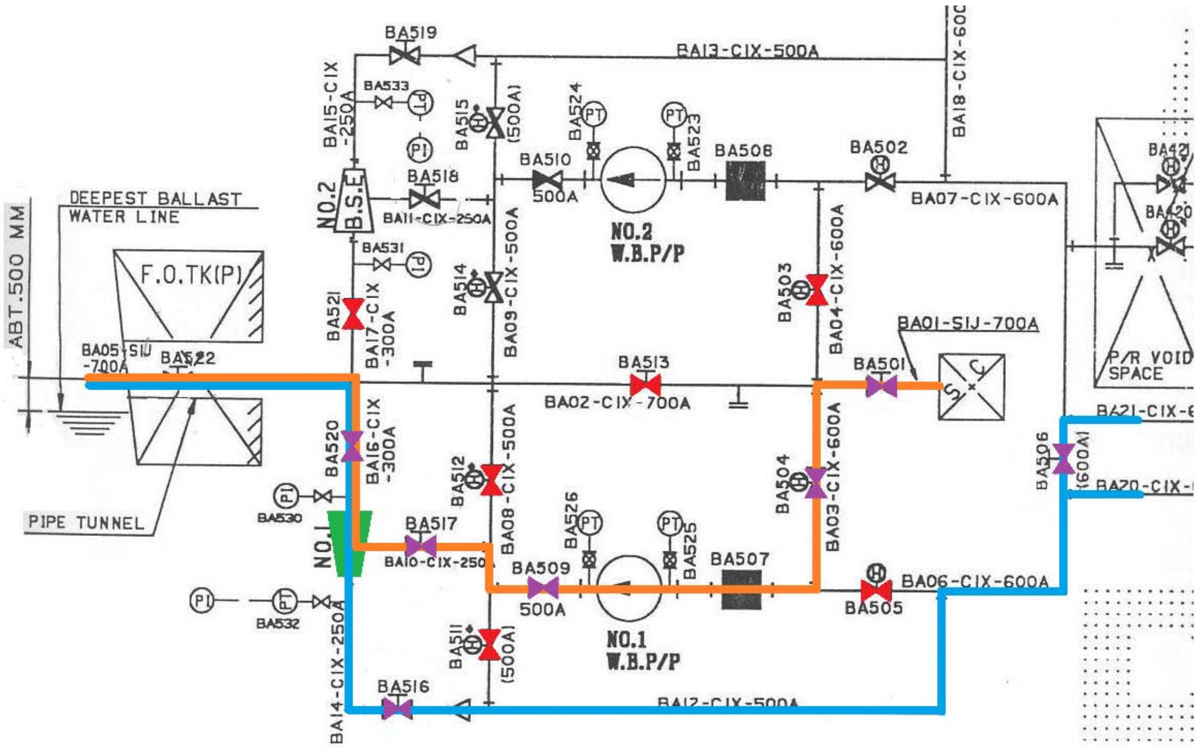


Illustration 11 - Stripping of ballast tanks

The last function concerns stripping of the ballast tanks. Normal de-ballasting will not completely empty the ballast tanks, the emptying of the ballast tank in Illustration 11 will cease when the filling level is low. At this point lesser and lesser water will go through the pump and the pump will therefore stop. Stripping empties the tanks further by the use of an eductor, illustrated as a green trapeze in Illustration 12. The educator is basically a nozzle which uses high speed water supplied from the pump to create a vacuum.

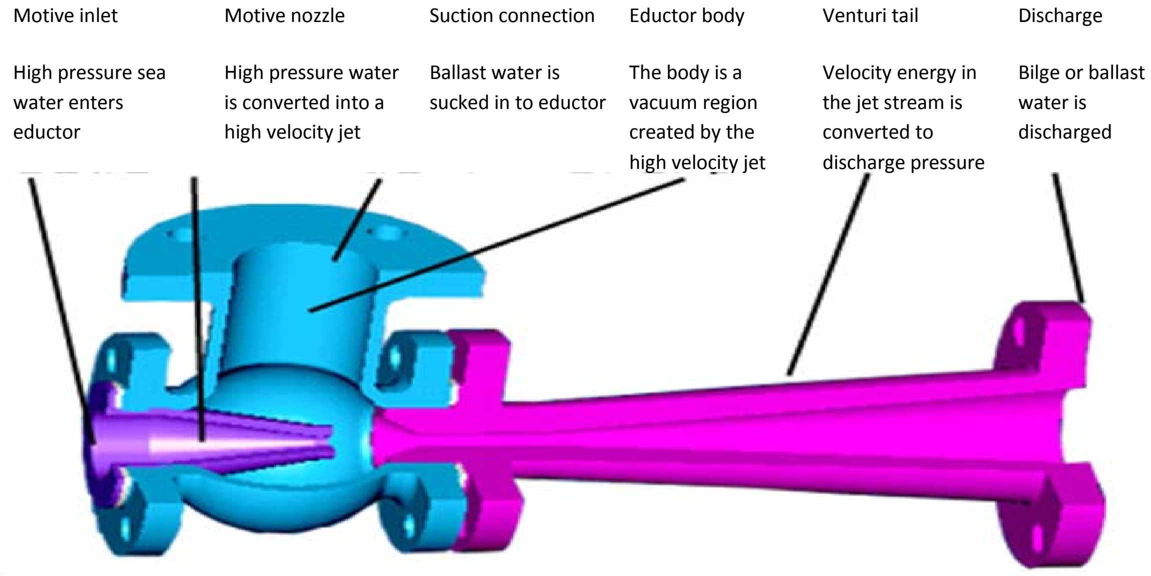


Illustration 12 - The principle of an eductor (Primetech, 2010)

The orange line Illustration 11 is water pumped from the sea chest, through the eductor and discharged from the vessel. The blue line is the stripping line which empties the last drops of ballast by the created vacuum. The system is redundant so either eductor could strip through either ballast lines. They could also be operating simultaneously, stripping both starboard and port side.

All functions described above could be performed in several ways and ensures flexibility to the system. The redundancy also makes it possible for the vessel to operate even if one or more components have failed. The components can be isolated by closing surrounding valves and repaired or replaced.

3.4.1 Piping

Ballast pipes may be made of GFRP, steel or other materials with matching properties. GFRP is short for Glass Fiber Reinforced Plastic which is a strong composite and lightweight material. GFRP is not subject to corrosion like steel, but may sustain severe damage from impact loads or cyclic stresses. An impact may cause delamination where the holistic strength of the material is weakened because of the inside layers being separated (Ashby, et al., 2006). GFRP is also easier to repair and replace than steel components.

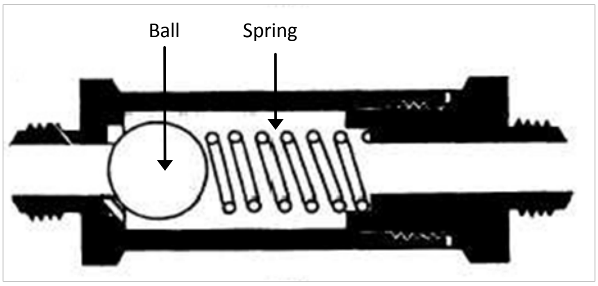
Grey cast iron may be used, but not for pipes going through fuel tanks or in the double bottom because of being vulnerable to impacts (DNV, 2010). WindFlip will need strong steel types in order to cope with the high pressure the pipes will be exposed to. A con with using steel is that both installation and maintenance cost will be relatively high. A lot of maintenance will probably be needed due to corrosion and the tough operating conditions the pipes will be exposed to.

3.4.2 Valves

In this chapter a few different types of valves will be presented.

The on-off valves do as the name indicates, they start or stop a flow. They are usually hand operated in vessels. This category includes a large number of valves as most valves have the ability to stop or allow flow. Typical on-off valves are; gate, plug, ball and pressure relief valves. This is especially common in safety management systems. Pressure relief valves can be meant for handling overpressure from water or gas, these valves are called relief valves and safety valves, respectively. Under normal operation such a valve may be closed, if there is a pressure build-up the valve will open. (Skousen, 2004)

Another type of valves is the non-return valves, these are designed to disallow backflow of fluid. Backflow is mechanically resisted. Non-return valves are also called check valves. A non-return valve which also has the on-off ability is called a stop-check valve. The figure below displays two types of non-return valves, a higher pressure on the left side than on the right allows flow. (Skousen, 2004)



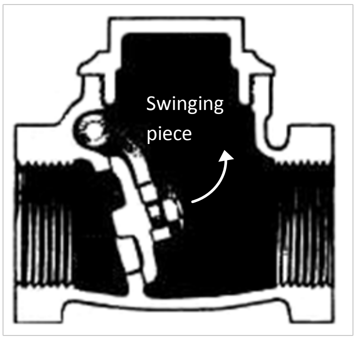
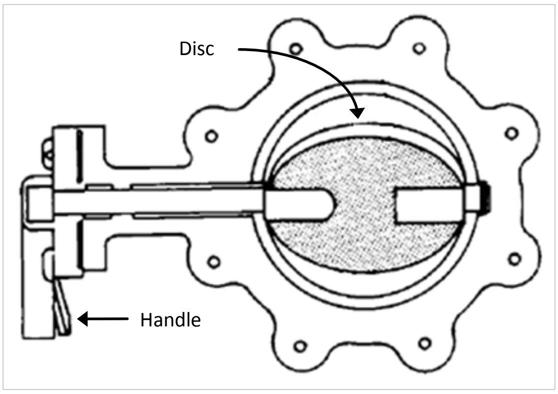


Illustration 13 – A ball check valve (left) and a spring-loaded check valve (right) (Integrated Publishing, 2010)

Valves controlling flow, temperature or pressure are in general called throttling valves. A butterfly valve is a typical valve for adjusting a flow rate. A disc in the valve's body rotates to adjust flow. Another throttling valve is the pressure regulator, or pressure reducing valve (PRV) which secures constant pressure downstream. (Skousen, 2004)



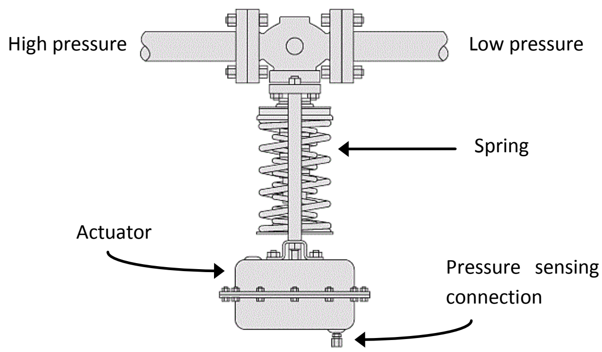


Illustration 14 - A butterfly valve (left) and a PRV (right) (Answers.com, 2010) (Spirax-Sarco, 2010)

The most common valve to use in normal ballast systems is the butterfly valve. The valve can be used as both a gate valve and flow regulator. The body is made of cast steel and flow is regulated by turning an inside disc which is tread onto a bar. The valve has a relatively low pressure drop compared to other valves (Song, et al., 2009). DNV recommends a wafer-style valve with insides covered in tar epoxy. The wafer-style valve has a high quality seal meant for bi-directional pressure differentials and prevents backflow. The tar epoxy is a coating which is very resistive to corrosion, chemicals and abrasion protecting the valve against jamming.

The butterfly valve is more light weight and a simpler design than other valves, and is also likely to need less maintenance than other valves. A drawback with butterfly valves is that in a system with high-pressure drops cavitation and choked flow can occur. Another disadvantage is that a flow can generate substantial side load when meeting a tilted disc.

As mentioned earlier, the ballast system of WindFlip will be exposed to fairly highly pressure, but this pressure is actually quite low compared to other installations. Valves used are required to have good pressure margins, there will also be installed pressure relief valves which will relieve the system in case of a pressure build-up.

All valves onboard WindFlip will be remote controlled, the control is redundant by having an extra signal circuit. There will also be a structure enabling manual steering by the use of ROVs. DNV requires means of observing the valve position for manual steered valves.

3.4.3 Ballast pumps

(DNV, 2010) states that all ballast tanks may be ballasted or de-ballasted by two separate pumps. Ballast pumps are usually used for both ballasting and deballasting of a vessel. During ballasting water is lead into the suction side of the pumps through a low or high suction head, pressure is increased through the pump and water is lead to spaces with lower pressure, into the ballast tanks. Deballasting of ballast water is performed by using the same pumps. However the system for ballasting is closed down and the suction side of the pump extracts ballast water from the tanks, as seen in the examples given in chapter 3.4. The water is lead through the pump and onwards to the discharge line and outlet valve. Alternatively, the ballast could be directed to another tank. This process is usual during loading and unloading of cargo in order to maintain pitch and roll angle.

The ballast tanks of WindFlip are meant to be filled through free flooding with minimum use of pumps. Use of pressurized air is set to be the main way of discharging ballast, the water is blown out of the tanks. Completely emptying the tanks is however difficult, the ballast pumps may be used for this matter. There will be pumps as a part of the ballast system, but these are mainly meant for filling the wing tanks during transit without cargo. The pumps will have to be powered by an electric engine supplied by power from an assisting vessel through an umbilical. A problem with electric engines is that a quick stop of the engine may cause a phenomenon called water hammer. Water hammer occurs when a moving water flow abrupt comes to halt, at this point the kinetic energy is converted to pressure wave which may damage the surrounding structure (Bartolini, et al., 2004). This could be resolved by a “soft start” system (DNV, 2010).

Centrifugal pumps are commonly used in ballast systems, they are known for delivering a very high flow rate at a low pressure, this is the reason for them being very much used in ballast systems. The centrifugal pump is dependent on ejectors in order to have sufficient operating conditions. The ejector primes the pump, meaning filling the pump with liquid to be pumped.

3.4.4 Filtering and Treatment

First of all, it is expected that there is no problem in terms of extra fouling or corrosion by letting in untreated ballast water. Filtering of water during flooding is therefore not needed. This has been confirmed by R/P FLIP representatives. Particles may however pose a small threat to operation of valves, but open sea water is relatively clean and will probably not cause any problems.

The environmental issue mentioned in Chapter 3.2 on the other hand needs to be addressed. Options for ballast treatment can be summed up in the illustration below.

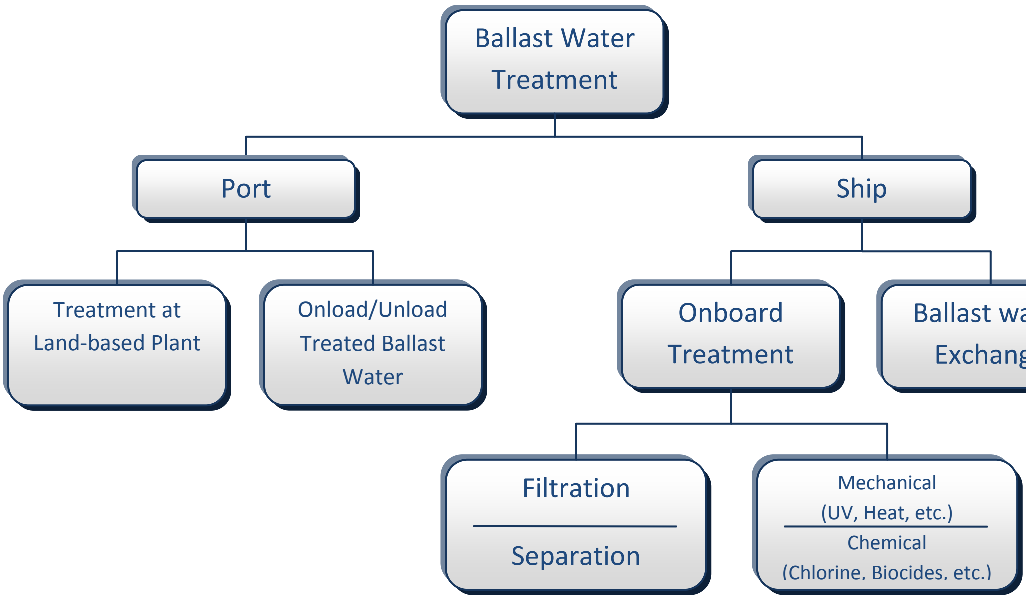


Illustration 15 - Ballast water treatment options

The two port alternatives are not common today but may be relevant in the future as ballast water management gets developed further. Thereby WindFlip only has two main choices; treat ballast onboard by various configurations or change ballast at open sea (exchange). Treatment onboard can be done relatively simple by filters or separation units or more advanced by combining several methods. A treatment plant adds costs, weight and is spacious.

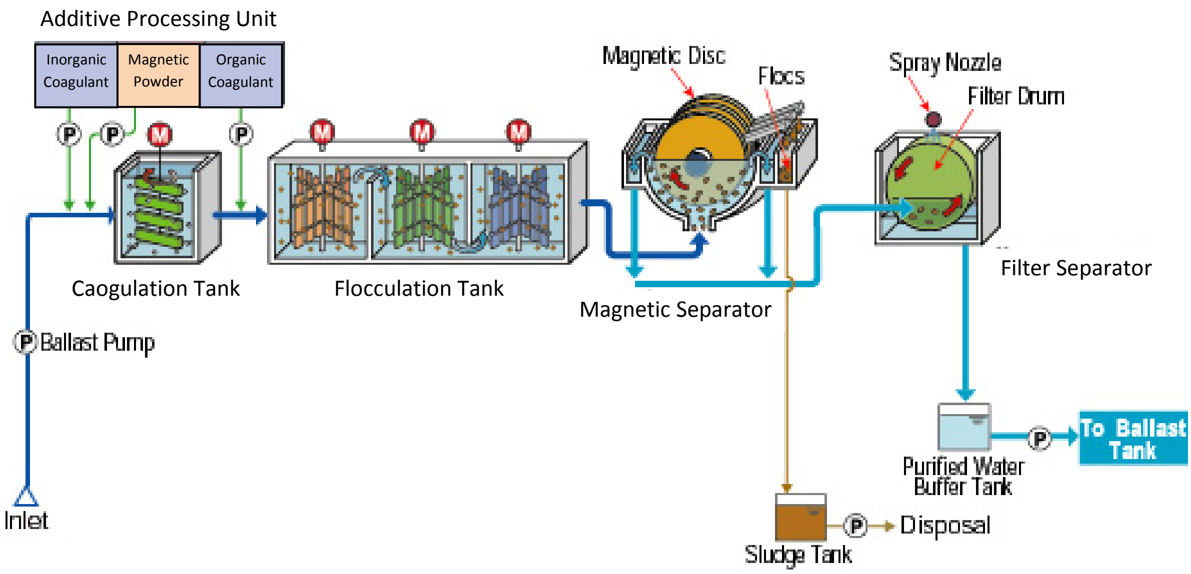


Illustration 16 - An example of a ballast treatment system by (Hitachi Plant Technologies Ltd., 2010)

A large pre-study of ballast water treatment made by IMO concluded the following:

"Exchange of ballast water is the primary and generally the most cost effective treatment method identified by IMO and countries that have some form of ballast water control in place." (IMO, 2001)

It should be noted that treatment has been improved and become more cost effective since 2001. This is however irrelevant as WindFlip will most of the time serve in local waters. A solution beyond treatment plants seems more suitable for WindFlip.

3.4.5 Control Equipment

Controlling the equipment remotely is very important for the WindFlip concept. Valves and other equipment can be operated remotely by adding an actuator. If the system is automated signals from sensors monitoring the state of the system will be sent to a controller. The controller interprets the signals and triggers the actuator to adjust the valve according to the situation. The signals from the sensors will be sent to a monitoring panel if the process is manually remote controlled. Here personnel are the ones giving valves orders.

The actuator can either be activated by hydraulics or electrically.

3.4.6 Other considerations

WindFlip contains over hundred ballast tanks. The many tanks will be exposed to high pressures and stresses, leakage is therefore an important concern for WindFlip. Testing will be performed in order to check tightness of welds. This procedure is to be done before any coating is applied on the weld connections. Tightness testing is often combined with testing of structural integrity. A common way to perform both tests is to fill one tank at the time with water of positive pressure. Possible water ingress in the surrounding tanks is monitored by adding fluorescent dye to the water and using ultraviolet light to find the leaks. The effect of stresses made by pressure and the pure weight of the water on the supporting structure is also recorded. An obvious disadvantage of performing tests with water is that water is a corrosion promoting agent which may damage uncoated steel. This danger could however be reduced by thorough drying up of areas exposed to water. (DNV, 2010)

Another way of testing is to use pressurized air instead. This test uses a soap solution in order to discover leaks. The solution is applied on all boundary welds, leaks are discovered by the observation of bubbles surrounding the leaking area. Leakage can also be revealed by spray/hose testing and vacuum testing. (DNV, 2010)

The issues mentioned above will not be addressed further.

3.5 Maintenance

Maintenance is another important aspect which needs to be considered in a design process. The system needs to be designed in a manner that reduces the life cycle cost. The extremities are to either choose expensive components which have the highest reliability and do little maintenance or to choose cheaper components and expect doing more corrective operations. The optimal solution most likely lies somewhere in-between. Different components have certain failure patterns, it is crucial to be aware of this in order to create a suiting maintenance strategy. If these match each other downtime may be prevented, corrective measure quickly executed, resulting in a reliable system which secures the income potential of WindFlip.

Considering maintenance should be a process parallel to designing the ballast system. The master thesis will however not go deeply into maintenance, instead focus will be directed into creating a system with a structure that ensures sufficient reliability. Maintenance will only be commented in the following sub chapters.

3.5.1 Failure Types

There are several recognized failure types, the most common failure is related to wear and tear over time which can be seen as aging. Some components will deteriorate over time due to corrosion, fatigue or general wear, this will degrade the components strength. The margin between strength and strain will decrease, when zero the component will fail.

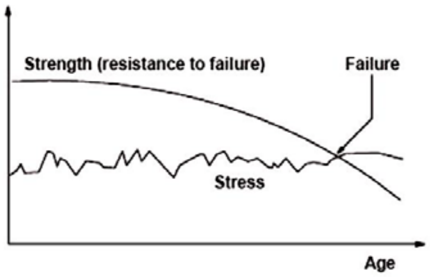


Diagram 1 - Failure due to reduction of strength (Rasmussen, 2003)

Another way of failing is that the strength of the component is relatively constant while the stress increases. This is could be a result of perhaps vibrations, e.g. a rotating piece may is affected by gravity over time which moves the center of the piece relatively to origin of rotation. This would slowly increase vibrations to a point where the stress on the piece matches its own strength and fails.

Diagram 2 - Failure due to increase of strain (Rasmussen, 2003)

A parallel in the figures above is that monitoring condition and/or stress could provide information which could be used to do preventive or corrective measures without the component failing.

Considering a large number of faults for a specific component will result in a failure distribution. The two types of failure discussed above are likely to have a failure distribution like the one showed below:

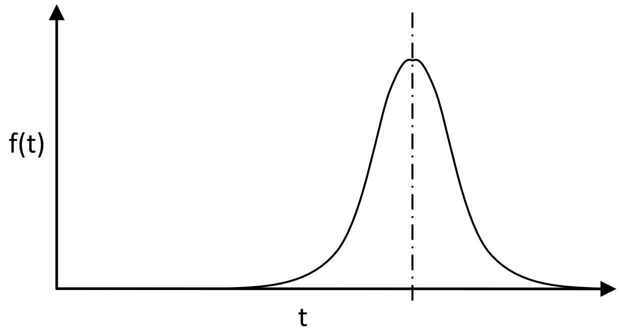


Diagram 3 - Failure distribution due to aging

The next instance of failure presented here is a failure type which often is a result of external conditions. In this case strength of the component is constant and high stresses seem to occur randomly. This means that a failure pattern is difficult to distinguish or even non-existent. Such failures are hard to resist as it is impossible to pin point possible time of possible breakdown.

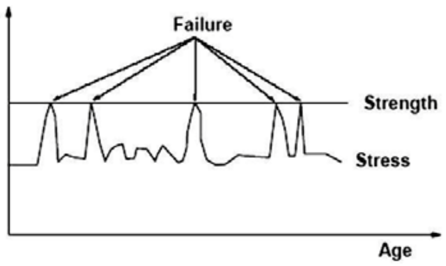


Diagram 4 - Failure due to random high stress periods (Rasmussen, 2003)

This type of failure is likely to have a failure distribution like below:

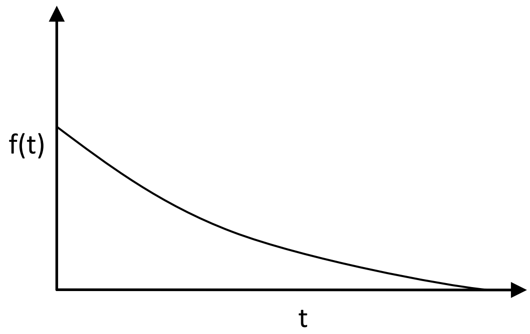


Diagram 5 - Failure distribution due to random failure

Another failure distribution concerns components troubled with running-in failures. Such components have a weakness in the design which provokes errors during production or produce inherent quality problems, the result is some components with built-in defects. The weakness will result in failure at an early age.

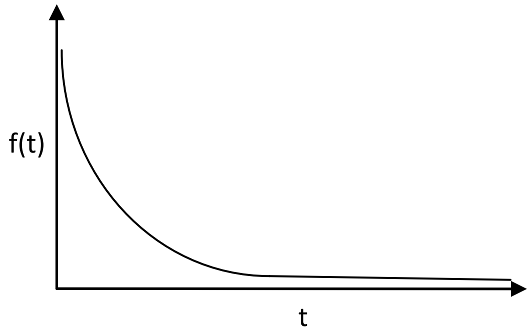


Diagram 6 - Failure distribution due to running-in failures

The failure distribution may be combined with the distributions presented above. The resulting failure distribution may have a bath-tub shape. Note that z(t) is used in the next diagram, z(t) is the failure rate function and equals:

$$z(t) = \frac{f(t)}{1 - F(t)}$$

Where F(t) is the probability if failure and equals.

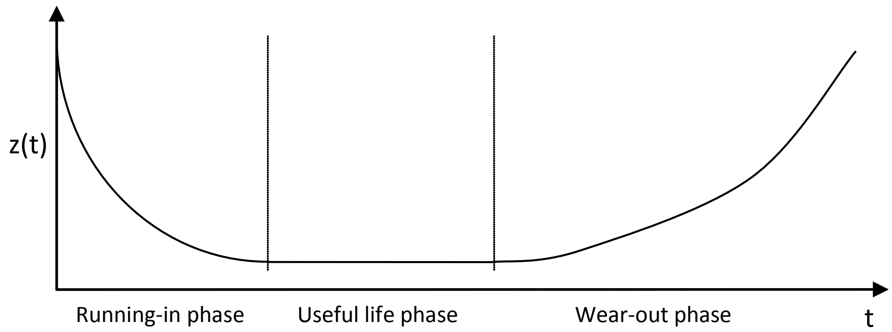


Diagram 7 - Bath-tub shaped failure rate (OREDA Participants, 2009)

Another failure type is when a component fails upon demand. This type of failure may occur in the shut-down process of a component or while it is dormant. The problem with such a failure is that there is virtually no way of knowing if the component will work when it is switched on again. A typical component with this failure type is the light bulb.

3.5.2 Performing Maintenance

The figure below is based on having selected a type of maintenance that fits the failure characteristics of a component. The figure includes cost related to performing preventive and corrective maintenance, as well as costs connected to the downtime performing operations. The figure is a good illustration of how there is a balance between the amount of preventive and corrective maintenance. In order to minimize costs an optimal composition of preventive and corrective maintenance needs to be found.

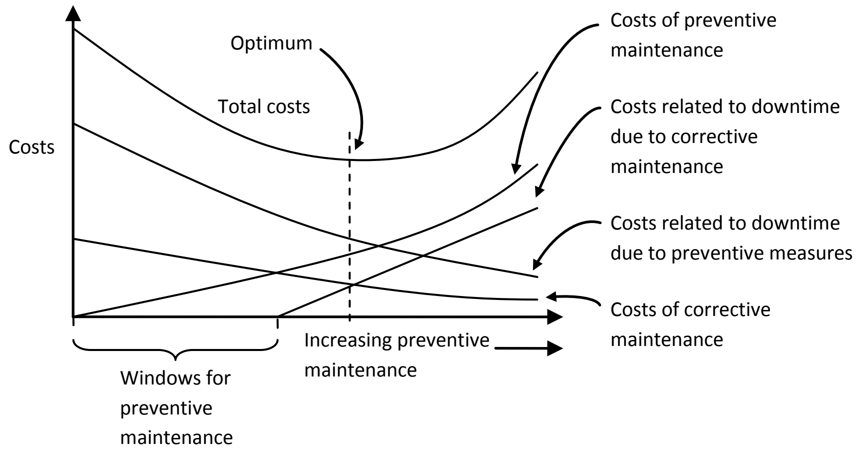


Diagram 8 - Costs of maintenance (Rasmussen, 2003)

A maintenance strategy is usually proposed by the manufacturer of the component, but sometimes reliability behavior varies and the strategy may be adjusted to match the first hand experience. Another variable is that a combination of different components from different manufacturers could have a different joint reliability profile.

One strategy of preventive maintenance is to perform periodical maintenance. Maintenance is set to occur sometime before the large peak of failures shown in Diagram 3. Determining a time period is more difficult if the peak is stretched over a larger time period. During typical periodic maintenance a checklist of things to control and/or replace will be followed.

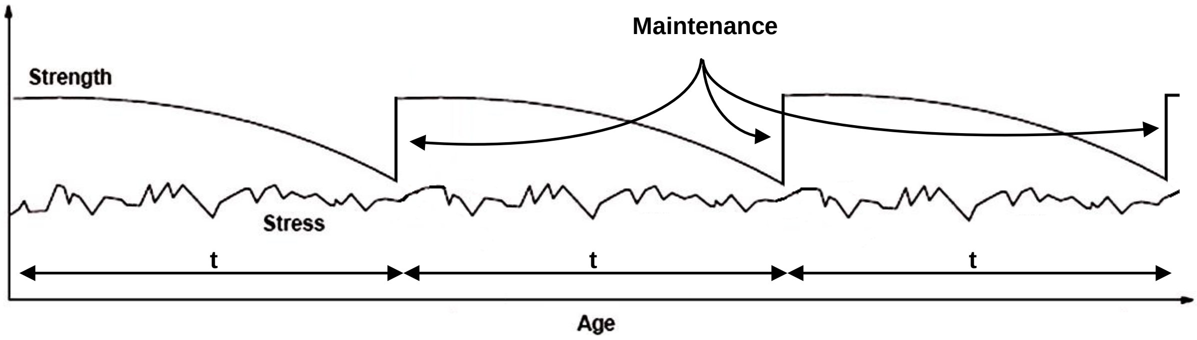


Diagram 9 - Periodical maintenance

Throughout the lifetime of a component there are many conditions or instances that may occur which could change the degradation of operability. As an example more heat generation in the components environment would degrade operability, while the use of better spare parts in maintenance could enhance operability. In the first case a failure could occur at an earlier point than anticipated, whilst in the latter operation could proceed longer than before. A strategy called condition-based maintenance can be used to optimize maintenance work. This strategy is however dependant components showing signs from wear and aging, the strategy will therefore not work well if applied to the dormant light bulb mentioned earlier. Another prerequisite is that the time from observed signs of nearby failure till the actual failure occurs have to be long enough in order to be able to respond to the situation.

Monitoring the progress of the component will continuously provide information on for example how large the margin between strength and stress is. This will reduce down-time and give better flexibility in planning and execution of maintenance. Unnecessary maintenance could be avoided and thereby reduce the probability of maintenance induced problems, like damaging parts during dismounting or improper reassembly. If a failure should occur, data from monitoring could be used to find the location of the problem.

The economic aspect also shows a good potential. Reducing probability of failure will reduce loss of income and expenses connected to the failure, reduced number of routine maintenance will also reduce costs. However this has to be weighed against the extra cost in purchase of monitoring equipment and expenses connected to operating the equipment.

Condition-based maintenance relies on one or more instruments measuring parameters which will be influenced by internal or external factors of a component. Monitoring pressure, temperature and vibrations are very common ways of checking the condition of a component.

Typically there will be some key parameters that will be most important for establishing the condition of a component. Additional parameters are often used to support the analysis identifying the components condition. The analysis constructs a trend line based on available input which defines the state of the component. The current condition is found by comparing the current value with a value produced from a new component.

Systems with a higher degree of complexity, e.g. multiple interconnections, would need monitoring of several components as a single error could create disturbances for several others. Patterns of such disturbances could indicate a specific error, thus monitoring can become a diagnostic tool.

3.5.3 Condition Monitoring of WindFlip

3.5.3.1 Monitoring of ballast level

WindFlip is highly dependent on condition monitoring during operation. The most important item to monitor is the ballast tanks. As mentioned earlier, knowing filling level of the tanks is crucial for maintaining stability during the rotational phase. By having such monitoring in place, it is possible to always ensure that the correct ballast tank is filled or emptied. The effect of erroneous action is alteration of displacement, pitch and roll angle. This will change the waterline of WindFlip and the stability criteria GM. Not knowing filling level could also result in half full tank which significantly reduces stability because of the effect of free surface moment. This effect is only negliable at a filling level above 98% (IMO, 2002).

(Hogner, 2009) concluded that a sensor system for WindFlip should include one switch sensor located at the top level of the tank and one at the bottom level, there should also be a capacitive sensor located diagonally in the tank. The switch sensors only state if they are in contact with water or not. This means that the top level switch will only tell if the tank is full or not and the bottom switch will tell if the tank is empty or not. The capacitive sensor measures the level continuously.

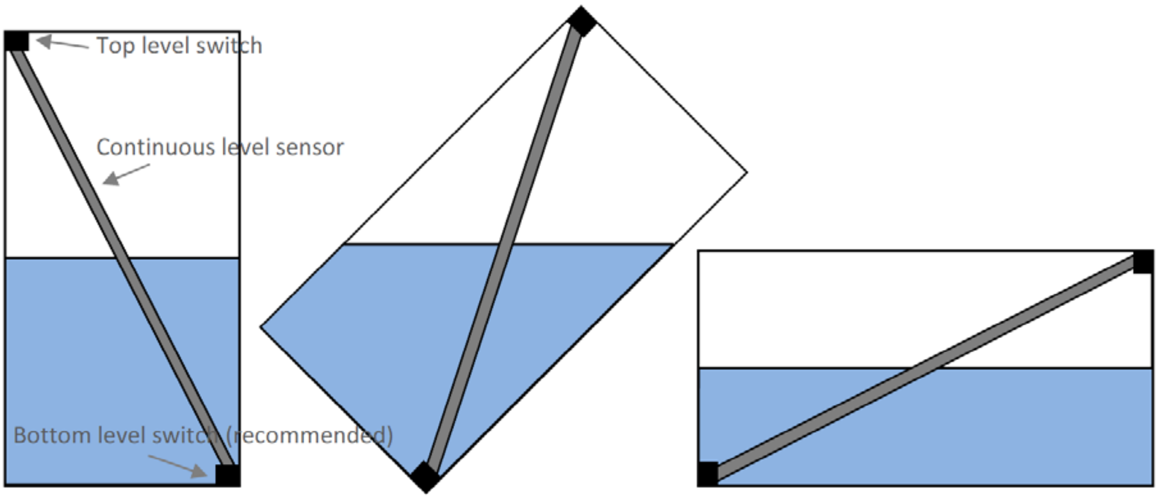


Illustration 17 - Ballast sensing system (Hogner, 2009)

The illustration above shows that the two switches will return correct information in every inclination. The capacitive sensor will return the position of the waterline within the tank, this position along with geometry of the tank and the barge's roll and pitch angles will give the right filling level with a ten percent margin of error.

Unexpected values returned from this system can indicate failure in valves, vents and pipes but could of course also indicate failures in the sensor system itself.

3.5.3.2 Monitoring of pressure

Monitoring of pressure is essential WindFlip does not have a pressure hull. This means pressure differentials are very dangerous if they become large enough. This concerns pressure in on ballast tank in relation to hydrostatic pressure, and also pressure between tanks. The pressure difference between a tank and outside of the hull may be within limits, but this does not necessarily be the case between adjacent tanks. The system for regulating pressure needs to make sure that this will not occur. Additionally, there has to be a margin to differential pressure. The hull of the vessel needs to be strong enough to handle the differential, as well as between tanks. What differential pressure will not be discussed here as it also touches upon an important matter which is not a part of this thesis; longitudinal strength of the hull. It could however be mentioned that this aspect has to be seen in context with monitoring and operation of the ballast system. A small pressure margin will impose many pressure stabilizing operations and increase use of valves and other units. This will lead to more strain on the components and will increase unreliability.

Pressure sensors may measure pressure relative to atmospheric pressure, local pressure differential or absolute pressure. An absolute pressure sensor is seen as to most applicable for WindFlip. Absolute pressure measures the pressure relative to perfect vacuum. By knowing trim, draft and pressure of all tanks the differential at all interesting points may be found. The sensor also needs to be able to handle gas (air) and corrosive liquid (sea water).

A problem with absolute pressure sensors is that in the changing environment of WindFlip will result in measurement errors. The reason is the complex relationship between density and pressure, as well as pressure and salinity of seawater. All parameters will change at different depths. (Hogner, 2009)

Selection of a suitable pressure sensor should be studied in further research in order to fully address the issue of measurement error, but also in terms of coping with a corrosive environment and submersion up to 120 meters.

3.5.3.3 Corrosion monitoring

A very large part of the barge will be exposed to corrosion as most of the barge is part of the ballast system. Corrosion in valves, vents, pipes and tanks should be monitored as damage in the pressurized system could cause extensive damage. Monitoring of corrosion is therefore crucial for WindFlip. Corrosion can be handled by using corrosion prevention systems (see Chapter 3.3) like inhibitors, coating, resistant materials, and monitoring developments in order to do maintenance. Monitoring of corrosion can be done by periodical inspection or by real-time monitoring. Inspections are usually better for finding localized corrosion while real-time monitoring works well for surveillance of uniform corrosion.

In the following a few methods used for monitoring will be presented. One way to monitor corrosion is to use corrosion coupons. The method is simple and low cost. Coupons are placed at the same location as the structure desired to monitor is. A coupon is basically a piece with a material characteristic which reflects the monitored structure. After a desired time period the coupon is retrieved and analyzed.

Use of anodes would work in a somewhat similar way as above, corrosion can be monitored by checking the piece. The difference is that they are meant for being scarified instead of the metallic structure. As mentioned earlier, noting corrosion of the anodes will however give an indication of the corrosion rate of the structure.

On-line monitoring includes Electrical Resistance probes (ER-probes), inductive resistance and several other similar variants. The concept of ER is very simple; electrical signals are sent through a piece of the same material as the surroundings called the probe. The probe will increase electrical resistance as the cross sectional area of the piece is reduced due to corrosion.

$$R = r \cdot \frac{L}{A}$$

Where R is resistance, r is specific resistance, L is element length and A is cross sectional area.

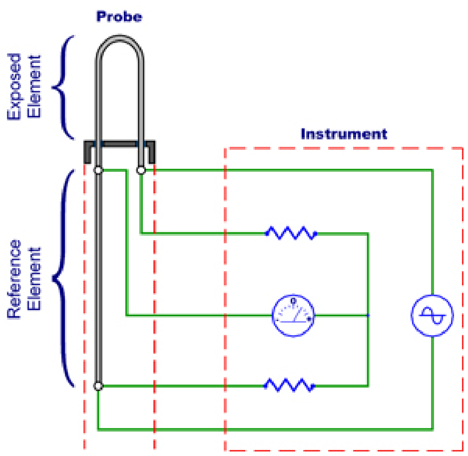


Illustration 18 - ER-probe (Alabama Specialty Products Inc., 2010)

After monitoring more thorough investigation is done through performing inspections. The inspections can use a range of different equipment and methods to reveal damage to the structure from corrosion and other sources:

- Radiography uses x-rays or gamma-rays to cross a material and see the insides. The method is efficient on “3d failures” like pores or inclusions, but is weaker in finding heat/shrink cracks and lack of fusion dependant of radiation angle. A con is that one needs access to both sides of the inspected structure.
- Ultrasound is a different method using cyclic sound pressure of high frequency. The reflection signature of the sound wave will reveal the state of structure. The method is perfect for closed structures and pipes as access is only needed from one side.
- Magnetic particle inspection is a method where a magnetic field is imposed on the structure. The structure will have to be ferromagnetic in order to enable use of this method. A structural error will be revealed as ferrous iron particles will be attracted to an area of magnetic flux leak, this leak will only occur at the location of the structural error. Use of this method should be restricted to critical locations as it would be very time consuming to cover whole of WindFlip, and is it is not optimal for uncovering inside damage.
- Penetrating oil may be used for uncovering surface errors in non-magnetic materials. The oil is either fluoridising or of strong color, this will leave stains in cracks in the surface of the material.

(Rasmussen, 2003)

3.5.3.4 Pump monitoring

The pump(s) onboard WindFlip will most likely be of a rotational type, also called centrifugal. As the pump is not totally stiff, some of the rotational forces will be transmitted to its surroundings as noise, heat and vibrations. Vibration monitoring is very important for evaluation of the state of a piece of machinery. Studies have shown that vibrations have increased in up to 90 % of failure instances. The cause of vibration is an excitation force which changes magnitude or direction. (Rasmussen, 2003)

Damage to a pump or other machinery will either increase the share of force working on the machinery or make the machinery less stiff so it will become easier to move the machinery. Both instances will result in more vibrations and worsening of the machinery’s condition.

Monitoring of vibrations can either be done by measuring movement, speed or acceleration. It is very important to place the sensor as close to the source of the vibrations. If not some frequencies may not be picked up as they may have been damped away. Piezoelectric accelerometers are very much used in the industry. (Davies, 1997)

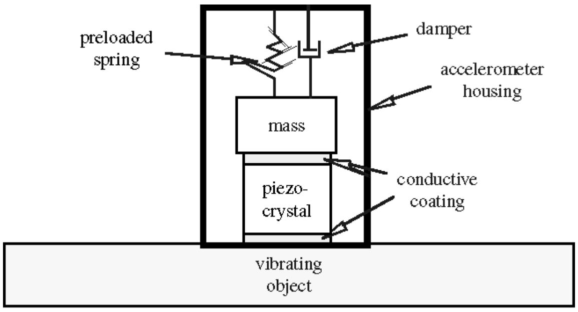


Illustration 19 - Principle of the piezoelectric accelerometer (Colerado State University, 2010)

A very useful feature with vibration monitoring is that the vibration can be used to diagnose machinery by different characteristics in terms of amplitude, frequency, phase and relative movement.

4 The Risk-Based Design Methodology

4.1 Introduction

Safety[7] may be defined as the extent of being free from danger or the level of risk one is exposed to. High safety means a low level of risk. Safety has always been a difficult topic in marine industry. The market of marine industry is in is very competitive with high possible income but also at high risk. A firm would, as any firm, push to make money. The main concern of almost any firm/project is to make money. The loss of a vessel has a great economical impact on a company in terms of lost source of income, the value of the structure itself, loss of valuable goods, clean-up costs related to environmental damage and of course injured personnel or fatalities. Having to cover such losses is something a company obviously would want to avoid. The probability of such a scenario is lowered by creating a more clever design, making the operation safer. Here, safety could merely be the consequence of a better design where economy is the main target, not safety. Another problem may be that the aim for money makes perceived risk lower then what is actually true. Handling safety with economy as the main concern, as mentioned above, have happened in the past and is clearly not optimal, but in some cases it could be said that economy has been a way of ensuring safety.

The level of safety can also be increased by creating a regulatory framework which designs have to comply with. However this approach may focus more on meeting the laws and regulations than the safety itself. Another issue is that technology advances forward in an accelerating pace which makes it difficult to make suiting and simple rules. Advanced technology means complex systems and hence intricate regulations. The number of rules one have to comply with are many and several rules have exceptions or extensions which increases the need for insight in the ruling system. However knowing how to abide them is not what is really essential, having knowledge concerning why the rules are made, how they work and of course understanding of a design and its characteristics is.

Then there is also the issue of new and innovative designs. These designs may be so far "out of the box" that there are no rules made for the designers to comply with. Safety from rulemaking is difficult in these situations. Regulations have however generally proved to be successful but the approach has several boundaries that are difficult to overcome. (Papanikolaou (ed.), 2009)

Some of the challenges in rulemaking are stated above, another important issue is that rules far too often are derived in the wake of an accident. The reason is fairly obvious, it is easier to find out what went wrong than predicting what may go wrong. Large accidents in the past have given us rules preventing similar happenings, but what happens when a thriving technology enables us to make larger and larger vessels? In 1999 the largest cruise ship in the world was the "Voyager of the seas", it had a GT[8] of 138 000 and could carry 3 100 passengers (Royal Caribbean International, 2010), only ten years later "Oasis of the seas" is able to carry 6 300 passengers at 225 000 GT (Royal Caribbean International, 2010). Can we take the risk of getting proper rules in place *after* a devastating catastrophy?

An important note is that a new way of creating and using regulations have been purposed, called Goal Based Approach. Such regulations focus on the goal rather than the road leading towards the goal. This provides the opportunity to choose many different "roads" and still reaching the set goal.

[7] "…the risk concept is a way of evaluating this [safety]" (Kristiansen, 2008)
[8] GT – Gross Tonnage, a measure of the enclosed volume of a vessel (Fuglerud (ed.), 2005)

Several of the largest companies representing the backbone of maritime industry (DNV, GL, DMA, ITF etc.) are supporting a project working with developing method for safety evaluation. The executive body of the EU, called The European Commission, has established a project named SAFEDOR[9] for this purpose. SAFEDOR directs focus to "Design for safety", in other words having safety as a design objective, like deadweight and speed, and not a constraint (SAFEDOR, 2010). This is done by performing safety assessments parallel to the design process. A risk-based regulatory framework has to be formed and integrated in the assessments. The new methodology is called Risk-Based Design (RBD) and aims at being pro-active by having a more holistic approach to safety.

RBD is meant to be implemented during design of concepts with medium or high level of innovation/complexity. Designs of a lower level are better known and are bound by well worked regulations.

WindFlip is an untraditional design which would fit the risk-based design methodology. Rules and regulations will still be checked but may in some cases not be extensive enough.

4.2 Method

4.2.1 Basis

One of the cornerstones of the new way of designing is that more exploration of the feasible design region along with risk analysis should be done in an early phase of a design.

The traditional course of designing is problematic because many important decisions about the design are made during conceptual design, this reduces freedom to explore the feasible region of the design. The decisions also include restricting the design to certain rules and regulations. Performing more studies at an early phase with fewer boundaries would enable the designer to discover innovative shifts in the design which could improve the design's abilities. The design might not comply with all rules and regulations but may still have a similar overall risk level compared to a design bound by restrictions from the beginning.

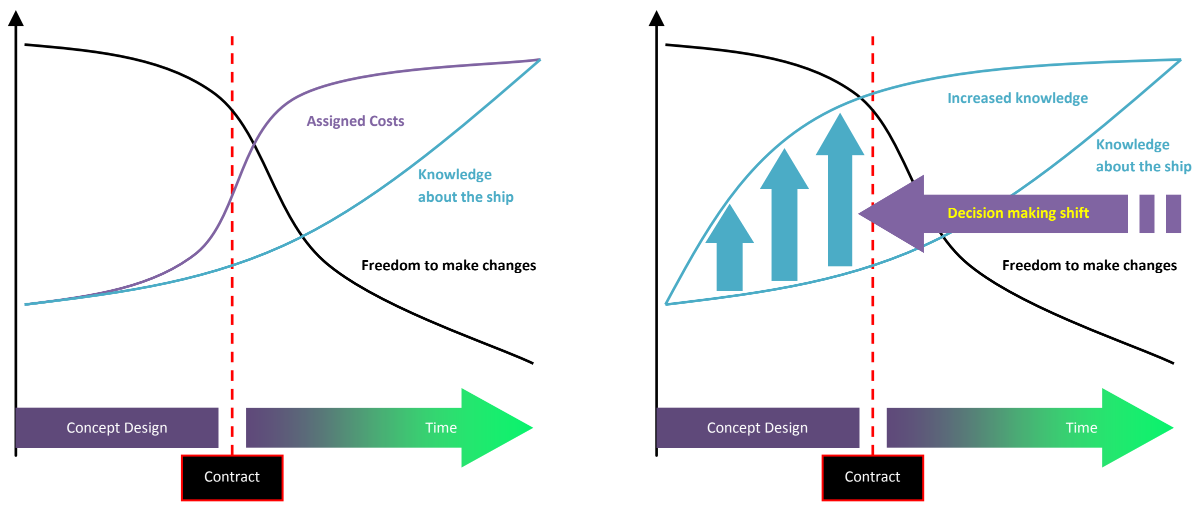


Diagram 10 - Increased knowledge of a design at an early stage (Papanikolaou (ed.), 2009)

9 SAFEDOR is translated to Design, Operation and Regulation for Safety

It is also very symptomatic in the traditional approach that really "understanding" the design, meaning learning its strengths and weaknesses, happens when one starts to see the end product, at a late stage of the design. A problem is that at this point freedom to make changes is very limited. By not making premature decisions and increasing knowledge about the design at an early phase, one would make it easier to implement improvements as nothing has been finalized yet. When it comes to risk, aspects of a design needing improvements may be identified easier if risk also is considered at an early stage. Implementing improvements would increase safety which indirectly could enhance the designs ability to handle the task it is meant for. The ability may of course also be influenced directly.

In accordance with the more holistic approach to safety through RBD, more emphasis should also be put on considering the whole life-cycle when designing.

In this study I have tried to direct focus towards increasing knowledge at an early stage and tried to have a holistic approach.

4.2.2 Procedure

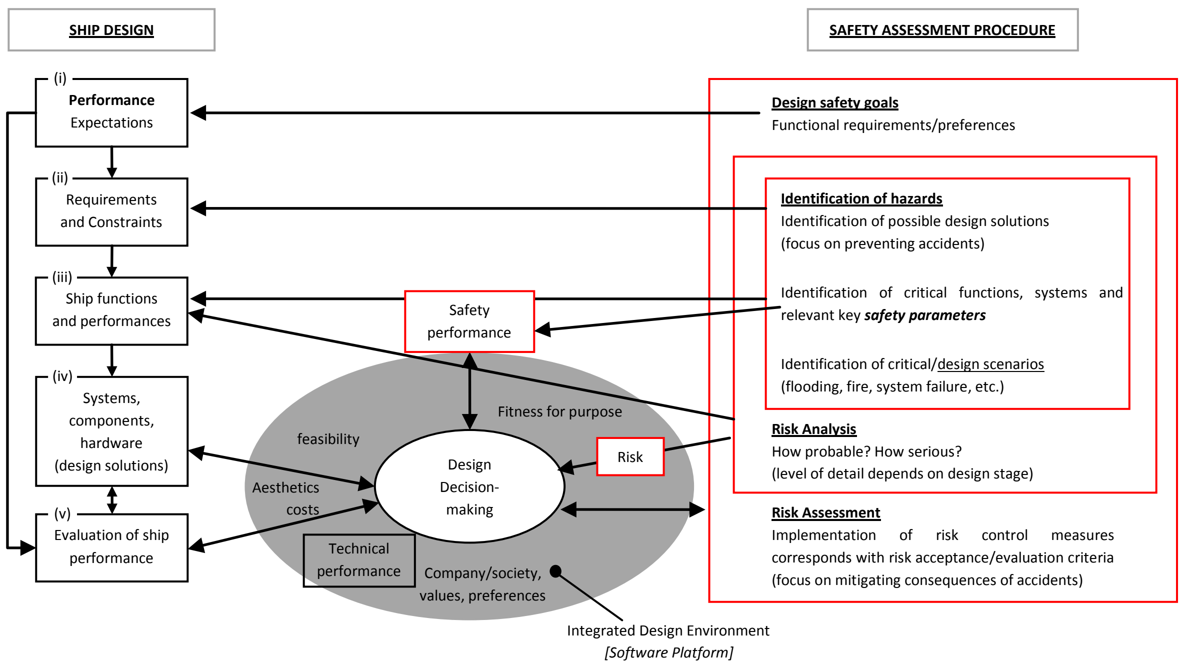


Illustration 20 - Parallel safety assessment and design process (Papanikolaou (ed.), 2009)

Illustration 17 taken from the Risk-Based Design book clearly shows how the connection between safety and design is in RBD.

The safety assessment is to be carried out parallel to the design procedure. The first phase of design would be to define what is to be achieved, definition of performance expectations. For a vessel this would be DWT, speed, load/unload time etc. At the same time the corresponding requirements will be set for safety. Top level goals could be defined as; no loss of human life, no severe environmental damage or no severe economical penalty. The top level safety criterion will be discussed further in the next chapter.

Further down the hierarchy more specific expectations can be defined like; time to evacuate, hull strong enough to withstand severe structural damage, etc. The thesis only concerns the ballast system of WindFlip, here design expectations may be fill-time of tanks or perhaps flexibility of filling, whilst safety goals may include the ability to safely handle a pressure build-up or that the tanks are to remain intact after moderate impact.

The next step is to look into requirements and constraints of the design. Typical restrictions may be rules and regulations in the extent it is available for the design. Other restrictions may be related to the framework the design is derived from. An example can be; that a lower level constraint may be the number of tanks. More tanks mean more watertight bulkheads, piping and valves which make the acquirement and maintenance cost higher. The latter is the basis of what might be a top level constraint; economy. At this stage there will also be a safety assessment for finding possible hazards to achieving the safety goals. What might prevent the system of complying? When regarding the example related to constraints, a hazard may be that instruments measuring the filling level of a tank may not function. The reason is that the instruments are very dependent on the volume and shape of the tanks in order to work properly. In the previous paragraph a pressure build-up is mentioned, this is of course also a hazard to the design. Several methods could be used to identify hazards; HAZID, FMECA, HAZOP, etc.

Further on shaping and sizing takes place. Components and systems are specified and the design is fully constructed. The safety assessment now considers the set parameters and analyzes risk of the design. A typical structure of the analysis is to make a FTA[10] and set probabilities of error. Branches of the tree with low reliability will be identified. Next the consequence of failure is studied to explore possible chain of events, ETA[11] is commonly used here. After grasping scenarios from different happenings (chain of events), the severity of such an event is quantified. The risk picture of the design is gradually constructed.

The final step is to evaluate the design's performance both in terms of performance according to design expectations and safety goals. The step will introduce possible adjustments to the design which may improve its ability to reach the design objectives. This may be to adjust the payload and speed (e.g. slower vessel taking more payload may be more profitable), or reduce probability of penetrated hull by adding a double bottom, or mitigating an accident by adding higher quality life rafts. Deciding upon an adjustment is mainly based on three key decision-making properties; performance, cost/earning and risk. The suggested design improvement is to be inputted into the models of the three properties. The outcome of these will provide information which will reveal if this is an actual improvement.

4.2.3 Top Level Safety Criterion

The overall risk is made by all risk factors relevant for the design. Risk is the product of two factors, probability and consequence. What will summarizing risk from all factors actually tell us? The top level safety criterion of RBD is a somewhat debated topic. Discussions have been going on about what is the criterion which takes all important aspects of a design into account, and how it should also be quantified in an understandable manor. The quantification should give a humanly sense of

[10] FTA – Fault Tree Analysis, hierarchy built by nodes and arcs, determines the structure of a system/operation /top event

[11] ETA – Event Tree Analysis, logic modell identifying and quantifying the outcome of an initiating event

severity, not just a number or a fraction, this provides better grounds for making rational decisions concerning risk management.

(Papanikolaou (ed.), 2009) proposes, through the work of Jasionowski and Vassalos, calculating risk according to potential of loss of life (PLL). The model starts out with selecting all relevant loss scenarios hz_j, where j is a specific loss scenario.

The most common loss scenarios are mainly based on four hazards; flooding, fire, post-accident system availability and evacuation/rescue. These subjects need to be thoroughly investigated in order to produce credible data to input the model.

Next the frequency of occurrence of each loss scenario is calculated, $fr_{hz}(hz_j)$. The probability of N fatalities given loss scenario hz_j has occurred is also found, $pr_N(N|hz_j)$. Multiplying fr with pr and summarizing for all loss scenarios gives the overall frequency of N fatalities, $fr_N(N)$.

$$fr_N(N) = \sum_{j=1}^{n_{hz}} fr_{hz}(hz_j) \cdot pr_N(N|hz_j) \tag{1.1}$$

Summing $fr_N(N)$ from N to N_{max} (the maximum number persons somehow in contact with the scenarios) provides the basis for the FN-curve.

$$F_N(N) = \sum_{i=N}^{N_{max}} fr_N(i) \tag{1.2}$$

If these values are summarized the overall risk of potential loss of life is found:

$$Risk_{PLL} = \sum_{i=1}^{N_{max}} F_N(i) \tag{1.3}$$

In the sake of decision making setting a limiting value of risk could be used to see when a design needs to be improved or not. A more common procedure is to evaluate the FN-curve, show graphically below.

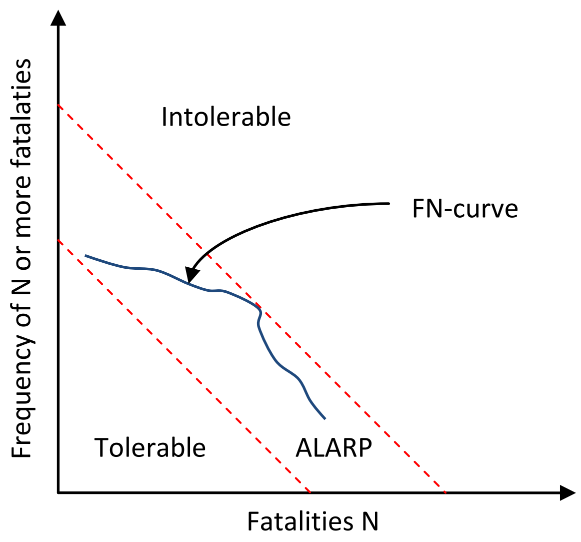


Diagram 11 - FN-diagram

The FN-curve shows the frequency of N or more fatalities occurring. The above diagram shows limits marking three regions, the tolerable-, ALARP- and intolerable region. If a point of the curve is in the intolerable region, frequency of N or more fatalities is too high and the design has to be modified. In the ALARP[12]-region the design needs to be changed so the frequency or consequence (N fatalities) is As Low As Reasonably Practicable. If points of the curve are in the tolerable region the risk is accepted.

When risk needs to be reduced potential measures are introduced. These are evaluated by reviewing the reduced risk in relation to the cost of implementing them. Commonly used criteria are the GCAF, Gross Cost of Averting Failure and NCAF, Net Cost of Averting Failure. (Skjong, et al., 2006)

$$GCAF = \frac{\Delta Cost}{\Delta Risk} \tag{1.4}$$

$$NCAF = \frac{(\Delta Costs - \Delta Economical\ Benefit)}{\Delta Risk} \tag{1.5}$$

Limiting values for these criteria have been a debated subject, IMO has lately been advised by DNV to use three million USD a limit, meaning that a risk control measure should be implemented if the GCAF/NCAF-value is below 3 million USD. Values up to 6 million can be used if risk is only just tolerable. (Skjong, 2002)

[12] ALARP - As Low As Reasonably Practicable. Risk can always be reduced but it is not desirable to do so at any cost. The ALARP-principle suggests to lower risk as low as reasonably possible when it comes to cost.

5 Executing RBD

The design process will be carried out according to the steps presented in Illustration 17. The steps are presented chronologically with separate chapters for the design and risk assessment.

Note that some steps are simplified as the scope of the master thesis does not cover all subjects listed in the steps.

As mentioned earlier, this thesis focuses more on studying the design space of ballast systems and then suggesting a possible solution that will match performance expectations and constraints. A full RBD-analysis includes all operational aspects of the complete design. The thesis will only cover a small part of the complete WindFlip design, the ballast system. The scope of the thesis determines that a FTA/BN is to be made, which is one factor in the risk picture. This means that calculating the reliability of the system will give indications of risk and safety but not fully as severity will not be further quantified. The total reliability of the system in all operational phases is however a strong indicator how well working and efficient the system is. This parameter can be compared to alternative solutions, and then studied further in terms event severity for discovering the full picture of risk in order to determine best solution. This will be suggested in further work.

5.1 Step One – Design

Performance and Expectations:

- The ballast system has to be able to rotate the barge and alter trim during transit and onloading of payload. It is expected that the ballast system will need two separate systems for handling the two tasks.
- Time spent on rotation one way: about 6 hours (Christophersen, 2010)
- Time spent on trimming for transit and onloading: set to 2 hours
- Include an environmentally friendly solution for ballast during continental voyage.
- There is not a large power supply onboard. WindFlip will be connected to an external source of power, compressed air and possibly hydraulics. Signals from monitoring systems and to control systems will also pass through the connection as the system will be controlled remotely.

5.2 Step One – Risk Assessment

In this part a basis for assessing risk and safety of the ballast system design will be suggested. The basis will act as a functional requirement of the design.

In order to use the RBD methodology when designing the ballast system of WindFlip, some adaptations have to be made. Firstly RBD is mainly meant for addressing passenger vessels, which is reflected in the top level criterion which considers potential loss of life (PLL). WindFlip is a barge and does thereby not have personnel onboard, but there will be manning on other vessels assisting the operation. The probability of personnel being directly involved in a critical WindFlip-event leading to one or more fatalities is there, but somewhat remote. In case of stability loss anchor handling/tug vessels assisting WindFlip may be influenced by forces that could lead them to capsizing. Such a scenario is however not very probable. Using PLL as a measure of risk may not be ideal for WindFlip as there are few people involved (low N_{max}) compared to passenger vessels, and the chance that fatalities may occur seems improbable. In my view analyzing WindFlip with the overall risk considered in terms of costs could be more practical and precise. Costs related to damage or loss of barge, tugs, equipment or turbine seems a lot more applicable when assessing risk of WindFlip.

In order to quantify risk in terms of cost there needs to be an underlying model. The bow-tie model can serve as such. The model consists of a causal analysis, accidental event and a consequence analysis (Rausand, et al., 2004). The causal analysis could take form as a fault tree. The fault tree is established by using the structure of the ballast system. The basic nodes are the components (valves, pump, etc.), failure(s) in at the basic level could result in a top event, which may be an accidental event. The next part is to analyze what is the consequence of such an event and how this situation can evolve, this is often done by using an event tree analysis. The events will lead to possible scenarios, the scenarios determine the severity by indicating the outcome of the past chain of events. The outcome of a certain scenario can be quantified as costs related to damage to assets, the environment and humans. The most severe scenario in terms of assets would be loss of WindFlip and payload. Quantifying this in costs would be to summarize the value of the barge and payload itself and loss of future income. A lower grade of severity could be a scenario where the hull structure of WindFlip is damaged, the value here would be related to repair costs and loss of income during the period of downtime.

To summarize; risk could be evaluated in terms of costs. The cost is found by calculating the probability of a scenario occurring and multiplying it with the cost related to this scenario. This would be a parallel to the FN-diagram, but instead of having fatalities on the x-axis costs could be used and frequency of the cost on the y-axis. The reason for using costs instead of fatalities is that there is very little personnel directly connected to WindFlip, by using model based on potential loss of life high frequencies could be accepted.

Limits marking tolerable and intolerable regions of risk in the corresponding FN-diagram should be established. This would crave extensive further study. These limitations, or risk criteria, should correspond to the same strictness in risk limitations as when considering potential loss of life.

With this framework in place, the design could be compared to the risk limits and then evaluated in relation to safety and efficiency. This will not be done in the thesis, instead qualitative functional requirements and preferences will be given:

- The ballast system needs to be safe and reliable. A goal is to minimize the unreliability of the system to a reasonable level in order to reduce downtime in important operational phases.
- Another goal is to have effective monitoring of the complex system in order to always be aware of the systems state. Monitoring important parameters will aid safe control of the system and enable routines for detection errors and handling errors before they become critical.
- The barge has to be controllable even if a failure should occur during the rotational phase. This calls for alternative solutions for ballasting, but especially deballasting in case the primary solution is disabled.

5.3 Step Two – Design

This chapter will establish functional requirements and constraints imposed by regulations.

There are two main functions that need to be in place for the ballast system to work; filling and emptying of the ballast tanks.

Ballasting is likely to be done simply by flooding the ballast tanks. This is however not possible highly placed tanks, water will have to be pumped into these.

WindFlip AS has determined that emptying of ballast tanks is to be done by using compressed air. The air will have to be lead into each ballast tank, the most likely solution is to have one or more main lines which transports the air over the full length of the barge and then having feeder lines leading into each tank.

5.3.1 Pipe diameter

The required pipe diameter is found for a single main line transporting compressed air in the following text.

One of the more important performance expectations is the time ballasting/deballasting is completed in. This is dependent on the dimensions of piping in these two phases. First the dimensioning the diameter of the pressure pipe for compressed air is done. At a later stage minimum allowable pipe wall thickness can be found based on the pipe diameter. The first step is to determine the amount of air which is needed to flow to the ballast tanks. This is actually a process of iteration as the pressure in the main pipeline going to the tanks is dependent on pipe diameter and pressure loss derived from pipe diameter. To start off, the pressure from compressor is set to be 16 bars, which is four bars more than the maximum hydrostatic pressure WindFlip will encounter.

Tank section	1	2	3	4	5	6	7	8	9	10	11	Unit
Ballast volume	1047	1602	1930	2154	2668	3099	3264	3327	3326	2549	1316	m^3
Draft	120	110	100	90	80	70	60	50	40	30	20	m
Hydrostatic pr.	12.1	11.1	10.1	9.0	8.0	7.0	6.0	5.0	4.0	3.0	2.0	bar
Air pressure	13.1	12.1	11.1	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0	bar
Air density	16.1	14.8	13.6	12.4	11.1	9.9	8.7	7.4	6.2	4.9	3.7	kg/m^3
Air weight	16.8	23.8	26.3	26.7	29.7	30.7	28.3	24.7	20.6	12.6	4.9	tons

Figure 1 - Air volume in ballast tanks

The table above shows the ballast tanks section by section. The draft is the lowest point of a tank, this is the point where hydrostatic pressure is the highest. The air pressure is set to be one bar above the hydrostatic pressure, this is needed in order to be sure of purging all ballast water out of the tank. The air densities are found for the air pressure at each section and a temperature of 10 degrees Celsius. With a density of air at 16 bars of 19.8 kg/m^3 the total amount of air needed through the main line is 12 370 m^3. Time set to empty all ballast tanks of water is set to be six hours based on preparedness time of six hours shifts in operation due to events like for example change of weather. This results in a needed air volume flow of 0.57 m^3/s. The calculations below are, as mentioned earlier, based on one main line.

The diameter is determined by considering pressure loss through the main line in relation to the diameter. A smaller diameter means a bigger loss of pressure. The pressure loss is found by calculating the equivalent head loss in the Darcy-Weisback formula (Ellenberger, 2010):

$$h_f = f \cdot \frac{L}{D} \cdot \frac{V^2}{2 \cdot g}$$

Where h_f is the head loss, f is the Moody friction factor, L is the pipe length, D is the pipe diameter, V is the speed of the fluid and g is gravity.

$$V = \frac{Q}{\pi \cdot \left(\frac{D}{2}\right)^2}$$

Where Q is the air volume flow.

The Moody friction factor is found by attaining a value from a pipe friction chart based on the Reynolds number and the relative roughness.

$$R_e = \frac{V \cdot D}{v}$$

Where R_e is the Reynolds number and v is the kinematic viscosity. The kinematic viscosity of air (independent of pressure) at 10 degrees Celsius is 14.6 mm^2/s and a diameter of 400 mm, this gives turbulent flow and a Reynolds number of about 130 000.

$$r = \frac{\varepsilon}{D}$$

Where ε is the roughness factor of the pipe material. The roughness factor for steel (slightly rusty and incrusted) is in the range of 0.02-0.040 mm (Software-Factory, 2010). The steam plant manufacturer (Spirax-Sarco, 2010) suggests 0.045 mm for commercial steel, after conferring with Professor Maurice White this value was confirmed and used in further calculations. The relative roughness is calculated to be 0.0001.

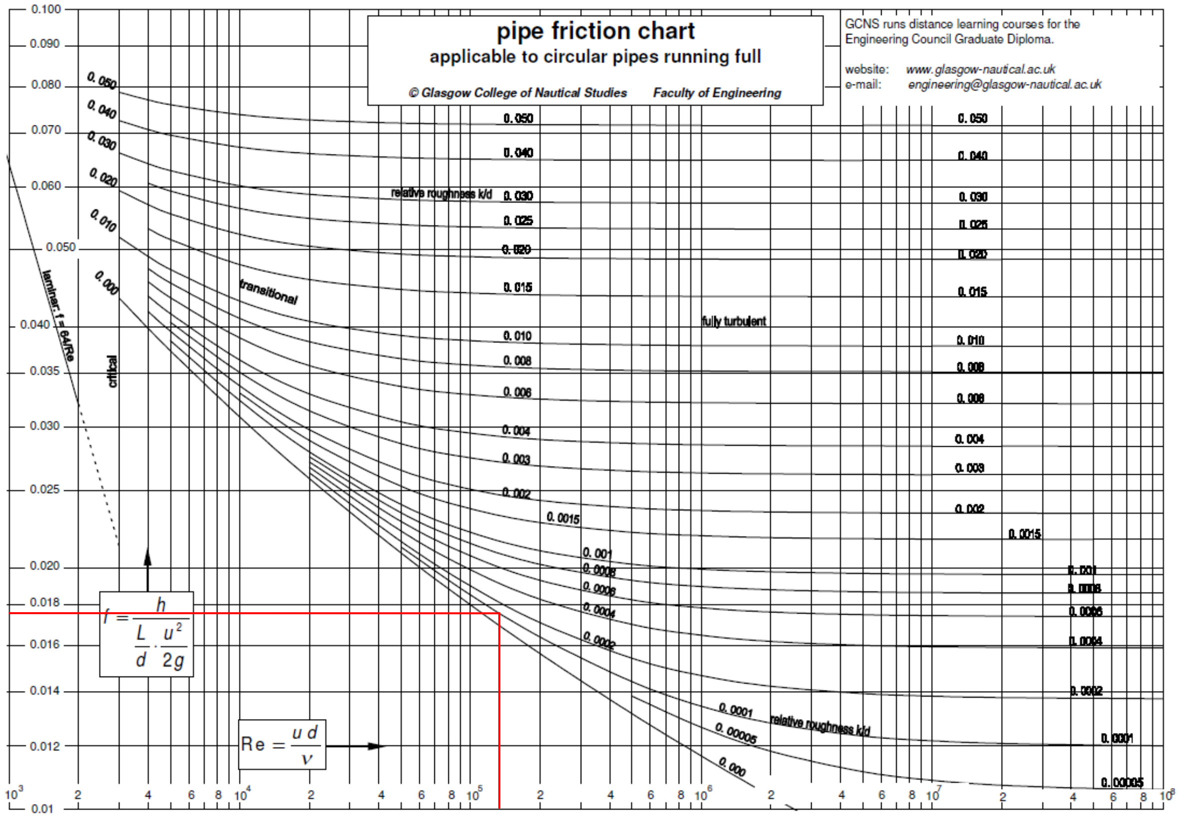


Diagram 12 - The pipe friction chart (Glasgow College of Nautical Studies, 2010)

From the plot in the pipe friction chart a friction factor of 0.0176 is found.

The length of the pipe is at 140 meters at max, this number is used in the calculations but is probably somewhat conservative.

$$h_f = f \cdot \frac{L}{D} \cdot \frac{V^2}{2 \cdot g} = 0.0176 \cdot \frac{140m}{0.4m} \cdot \frac{(4.6m/s)^2}{2 \cdot 9.81m/s^2} = 6.5m$$

The head loss is 6.5 meters which is roughly 0.7 if converted to bars.

There will probably be smaller pipelines going from the main line into each tank, these lines will be called feeder lines. There will also be sea water pipes into each ballast tank. Similar calculations as above have been done for the feeder lines and for the sea water pipe. A diameter of 300 mm was used for the feeder lines, this resulted in a pressure loss of 0.2 bars. The diameter ate the seawater inlet was set to 400 mm and gave a pressure loss of 0.2 bars.

The total pressure loss in the pressure piping (feeder line and main pressure line) amounts to about 0.9 bars. The air started with a pressure of 16 bars, the pressure at delivery to a valve leading into a ballast tank is 15.1 bars. The needed pressure at the deepest ballast tank is 13.1 bars. There is a margin of 2 bars against corrosion, loss in intersections, bends, valves and other degrading factors.

If a higher margin is wanted, large decreases in pressure loss could be obtained by using smoother steel or by a slight increase of pipe diameter.

The pipe diameter should be evaluated further in terms of costs. A larger diameter means a more steel used and an expensive pipe, but this has to be seen in relation to operational costs in terms of maintenance and of the compressor. The relationship may appear like below.

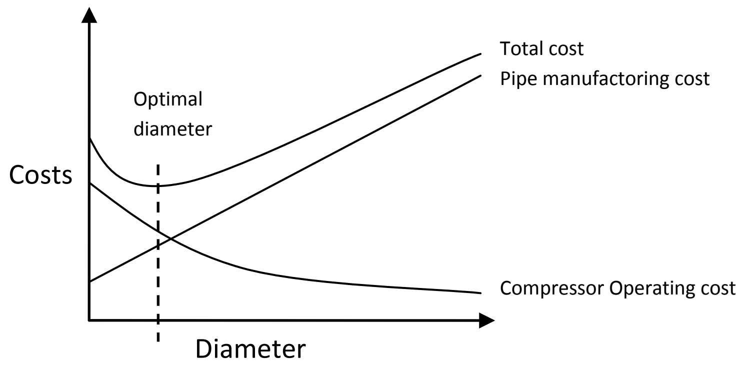


Figure 2 - Optimal pipe diameter

A trade-off study of pipe diameter will not be performed in this thesis.

5.3.2 Pump capacity

One or more pumps need to be fitted onboard WindFlip. As mentioned in Chapter 3.4.3 these are mainly meant for ballasting WindFlip into the loadcondition (LC1) for transit without cargo (the loadcase can be found in Chapter 2.1). It should be mentioned that pumps may not be needed for LC1 as the loadcases leading from vertical to horizontal may be structured so the tanks needed filled in LC1 are not emptied along the way. But the pumps will among other instances be useful when the barge is in horizontal position without cargo and ballast.

In LC1 without payload about 5700 m^3 of ballast needs to be loaded onboard WindFlip. A reasonable amount of time for completing filling is between one and an hour and a half. This means that the flow rate delivered from the pump should be around 5000 m^3/h. The pressure does not need to be high, sea water will at maximum have to be pumped 20 meters vertically, which is the height from the keel to the top of the wing tanks.

5.3.3 Regulations and Classing

Before designing the ballast system, rules and regulations needs to be reviewed in order to propose a design which may be approved by the classing society. The regulations I have chosen to study are made by DNV[13].

The regulations regarding ballast systems in DNV ruling are relatively scattered and it has been difficult to get a real overview. I contacted DNV and got thorough help with finding relevant rules for this case. I was informed that no rules are made for the special operation WindFlip performs. Regular ruling should therefore be studied along with further guidance and reviews from DNV. (Thune Uglane, 2010)

[13] DNV - an abbreviation for the Det Norske Veritas. The society was founded in 1864 and has its headquarters in Høvik, Norway (DNV, 2010).

WindFlip is designed to be an unmanned barge and will be classified accordingly. The DNV ruling is manly based on creating a set of rules which apply to regular steel vessels, other vessel types are handled with additions/exceptions gathered in separate chapters. This also applies to unmanned steel barges. When studying ballast systems the ruling concerning ships will only be considered, this is confirmed in Part.4 Ch.6 Sec.4 G203 (notated as 4/6/4-G203 in the following sections). However there are few special exceptions for barges listed in the same section such as; two ballast pumps is the minimum for ships, for barges one may be accepted. Another issue is that if emptying of ballast tanks is done with compressed air this “may be accepted upon consideration of each case”.

The thesis will not go into depth in all aspects of the ballast system. Only the most integral parts will be studied. The piping is the most important case in this respect. System components like valves, filters and pump(s) will not be studied in the same manor. The reason is that during the build process requirements will be expressed to the manufacturers of such items and they will provide approved components for use in WindFlip. When it comes to regulations regarding ballast tanks these mainly concern structural strength of the vessel. This is not a within the thesis’ scope and is not elaborated.

In any case this study is only preliminary, a full work through of the regulations relevant for the design should be done with guidance and reviewing by DNV as indicated earlier.

5.3.3.1 Piping

Pipe dimensioning – Main pipe

4/6/4-I103 states that the dimensions ballast pipe diameter at least have to be as specified for branch bilge pipes. 4/6/4-H401 concerning main bilge pipes states that the minimum internal diameter is given by;

$$d = 1.68\sqrt{L \cdot (B + D)} + 25$$

Where d is the diameter of the pipe in millimeter, L is the length of the vessel, B is the breadth of the vessel and D is the depth of ship to bulkhead deck, the last three variables are in meters. The minimum diameter of the main pipe line is;

$$d_1 = 1.68\sqrt{140 \cdot (27.8 + 10)} + 25 = 147.2mm$$

The diameter of pipes in the ballast system of WindFlip was calculated in the last chapter and was found to exceed this minimum value due to high flow-rates during flooding and purging of tanks.

4/6/6-A concerns wall thickness of pipes and fittings and is, of course, largely dependent on material. The largest thickness found in table A2 in A300 or calculations in A305-312 should be used as minimum wall thickness. A300 concerns wall thickness of pipes subjected to internal pressure, which is highly relevant, especially to the pressure air pipes. Table A2 concerning steel pipes states the required thickness of a pipe with an external diameter of 406-457 mm should at least be 8.8 mm if going through other tanks such as ballast tanks. A footnote of the table states that the thickness can be reduced by 20 % but not exceeding 1 mm if effective corrosion protection is added. This section also indicates that special considerations are very likely for special designs.

A305 states the minimum wall thickness of a straight pipe:

$$t = t_0 + c$$

Where t is the minimum required thickness, t_0 is the strength thickness and c is the corrosion allowance, all in millimeters. The corrosion allowance for steel pipes with compressed air is 1 mm according to table A5. However, if the pipe is efficiently protected against corrosion, the corrosion allowance may be reduced up to 50%.

A306 states:

$$t_0 = \frac{p \cdot D}{20 \cdot \sigma_t \cdot e + p}$$

The calculation of strength thickness is only relevant for pipes with a wall thickness to outside diameter ratio of 0.17 or less. p is the design pressure in bars, σ_t is the permissible stress in N/mm^2 of a pipe and e is the non-dimensional strength ratio. The strength ratio is according to A312 is 1 for approved manufacturers of seamless and welded pipes. For welded pipes from other manufacturers e is 0.9. The latter is used for a more conservative calculation of t.

The permissible stress is based on the type of steel used and the manufacturing of the pipe. The permissible stress is set to be 50 N/mm^2 based on table 1 in part four/chapter 6/section 2 in the book concerning classing of steel vessels made by (ABS, 2010)[14] and after conferring with Professor Maurice White.

$$t_0 = \frac{16 \cdot 400}{20 \cdot 50 \cdot 0.9 + 16} = 6.99mm$$

By adding the corrosion allowance, t is discovered to be about 8 mm. t can further be corrected for imperfect production, therefore;

$$t_1 = \frac{t}{1 - \frac{a}{100}}$$

Where a is the percentage of negative manufacturing tolerance. An error of three percent was set, the final thickness of a straight pipe is 8.23 mm.

In order to use the formula of A306 it has to be confirmed as relevant, the wall thickness in relation to outside diameter as to be below 0.17 to be relevant.

$$Ratio = \frac{t}{D+t} = \frac{8.23}{400 + 8.23} = 0.02 < 0.17$$

The minimum wall thickness found by calculations in A305-A312 is higher than the minimum value of table A2 in A300 and is therefore final restriction set by DNV.

Further on the wall thickness in bends are calculated:

[14] ABS – American Bureau of Shipping, classing society established in 1862. Headquarters: Houston, Texas, USA.

$$t' = t_1 + b$$

Where t' is the minimum required thickness for bends and b is the bending allowance, both in millimeters. B equals according to A310:

$$b = \frac{1}{2.5} \cdot \frac{D}{R} \cdot t_0$$

If the bending ratio (D/R) is not given, like in this case, one third is to be used.

$$b = \frac{1}{2.5} \cdot \frac{1}{3} \cdot 6.99 = 0.93mm$$

The thickness in bends equals 9.17 mm.

Pipe dimensioning – Feeder pipe

The dimensions of feeder pipes have been calculated in the same manner as the main pipe. Note that 16 bars of pressure have been used even though some of the feeder pipes will be exposed to a significantly lower pressure. The only difference in the calculations is that the diameter has been reduced to 300 mm. The minimum pipe thickness of feeder lines is 6.43 mm and 7.13 mm in bends.

This complies with the restriction of minimum internal branch pipe diameter in regulation 4/6/4-H403 should not be less than 50 mm and;

$$d_1 = 2.15\sqrt{l \cdot (B + D)} + 25$$

Where d_1 is the diameter of the pipe in millimeter, l is the length of the tank, B is the breadth of the vessel and D is the depth of ship to bulkhead deck, the last three variables are in meters. All input is known from earlier. The minimum internal pipe diameter is:

$$d_1 = 2.15\sqrt{10 \cdot (27.8 + 10)} + 25 = 66.8mm$$

Pipe dimensioning – Sea water pipe

Lastly the dimensions needed for the sea water pipes were calculated. The diameter in this case was set to 400 mm and the same pressure (16 bars) as in the lines above was used. This gave a pipe thickness of 8.23 mm and 9.17 mm in straight lines and bends, respectively.

Pipe dimensioning – Pipe intersections

Branching of the main pressure pipe will be considered next. The actual intersection is meant by branching. The minimum dimensions of branches is based on 4/6/6-A315. The thickness at the intersection is calculated by the same formulas for t_0 and t as above. The calculation of the strength ratio is on the other hand different:

$$e = e_1 \cdot \sin\left(\gamma \cdot \frac{1.15}{1.25 + \frac{d_{max} - d_{min}}{2 \cdot d_{min}}} \right)$$

Where gamma is the angle of the branch in radians and d_{max} and d_{min} in millimeter can be seen in the figure below:

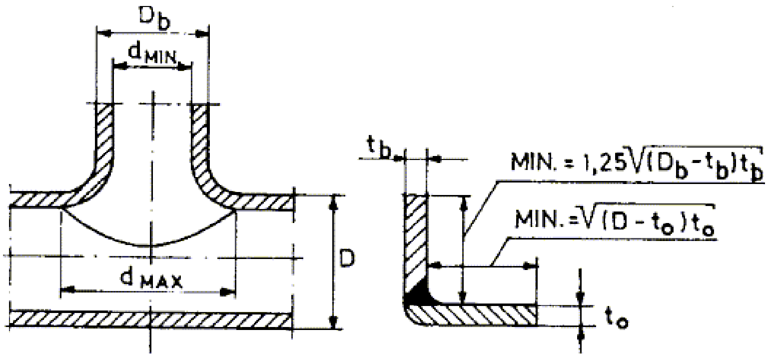


Illustration 21 - Branch annotation (DNV, 2010)

e_1 is found by calculating $\frac{D_b}{\sqrt{D \cdot t_b}}$ and finding the corresponding value in the next figure. t_b is the wall thickness of the branch, in this case the feeder line.

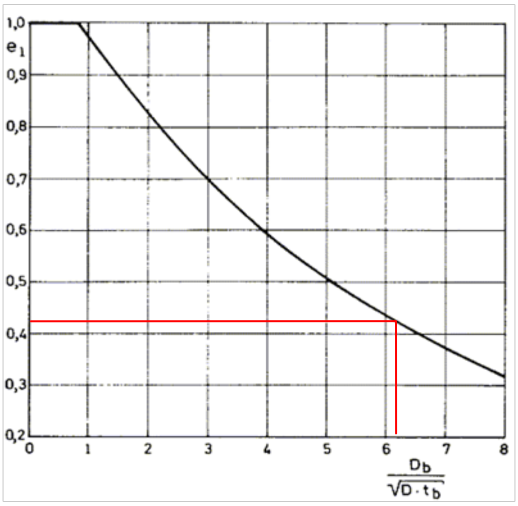


Diagram 13 - Distinguishing of e_1 (DNV, 2010)

A new value of the strength ratio was calculated based on a branch angled 90 degrees. The wall thickness in the intersection was found to be at least 17.1 mm.

The extra thickness is to be extended onto both main pipe and branch. The enforced length at the main pipe is:

$$L_{mp} = 1.25 \cdot \sqrt{(D_b - t_b) \cdot t_b} = 80.3mm$$

The enforced length on the branch is:

$$L_{bp} = \sqrt{(D - t_0) \cdot t_0} = 54.6mm$$

An overview of the branch dimensions can be seen below.

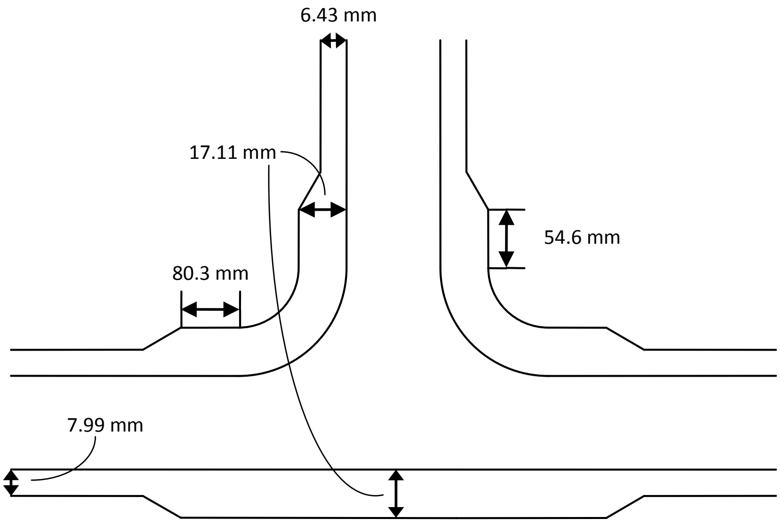


Illustration 22 - Branch geometry

Air pipes
4/6/4-K states that air pipes shall be fitted to all tanks with pipe installations.

Air pipes are an integral part of the ballast system design. Both ventilation and compressed air line(s) will be fitted onboard WindFlip. There will there be no real problem of not having ventilation of the tanks.

K102 states the following:

"Air pipes shall not be fitted with valves that may impair the venting function."

This may be an issue as the possibility of failure of a vent could occur. Normally the valves in the ventilation system will be open. A failure in this state will result in valve locked in open position, still ventilating the tank. In some cases, e.g. when the ballast tank is completely full of water and at high pressure, ventilation will not be performed and the valve will be closed. If failure of the valve occurs in this position a redundant system should be considered fitted to ensure ventilation.

Placement of piping
In order to have sufficient access to piping and valves it should be considered if the piping should to a large extent be externally. This means exposing the pipes to the environment. 3/3/6-I301 concerns placement of air pipes. The rule states that the pipes shall be of substantial construction and that:

"The height from the deck to the point where water may have access below shall be at least 760 millimeters on the freeboard deck"

This should be considered for WindFlip in horizontal position.

5.3.3.2 Valves
4/6/4-H605 states that valves have to be located in "readily accessible positions". This is a concern for WindFlip as none of the submerged hull will be accessible. The solution could be to place valves externally and use types that can be operated by ROVs in emergency situations.

4/6/6-C107 concerns monitoring of the current condition of a valve. The section informs that an indicator displaying open or closed condition should be available. In WindFlip this will probably be handled by monitoring signals from each valve. There are also more indirect ways of monitoring the state of some of the valves, like checking filling level of tank or pressure.

The manufacturer will provide valve bodies that are capable of handling pressures up to 1.5 times the nominal pressure, according to C201. Certifications are required from DNV for valves with diameters above 100 mm and pressure exceeding 16 bars. This is highly relevant for WindFlip.

5.3.3.3 Ballast Pumps

In the introduction to the chapter of rules and regulations it was acknowledged that barges are allowed to have only one ballast pump. 4/6/4-G202 allows ballast pumps be used as bilge pumps. However, if only one bilge pump is installed it shall not be used as a fire pump.

4/6/6-B101 states that ballast pumps fitted shall be delivered with a certificate from DNV. Certified pumps have been through design verification and testing by DNV. B301 specifies hydrostatic testing of pumps in general at 1.5 times the maximum working pressure, but not above 70 bars. Specifically for centrifugal pumps is that the test should be at the maximum pressure on the head-capacity curve. The curve shows how head limits capacity (flow rate) and vice versa.

B401 concerns capacity tests, the capacity of a pump have to be tested at design condition (rated speed, pressure, viscosity, etc.). The manufacturer of a centrifugal pump with a flow rate less than 1 000 m^3/h is obliged to determine the head-capacity curve for each type of pump. For rates above, a suitable range on each side of the design point has to be tested.

H103 states that one bilge/ballast pump me be used as an ejector if a sufficient amount of water is delivered to the ejector by a separate pump.

4/6/4-H201 craves that a bilge or ballast pump have to be able to speed water to 2 m/s through the main pipe.

H203 states the following:

"The pump capacity Q in m^3/hour may also be determined from the formula: $Q = \frac{5.75 \cdot d^2}{10^3}$ *"*

Where d is the pipe diameter in millimeter and Q is the flow rate in m^3/h. This formula indicates that a flow rate at about 5000 m^3/h (like found in Chapter 5.3.2) gives a pipe diameter above 900 millimeter. This is however not a binding restriction as seen in the quote. A check of various centrifugal pump manufacturers showed that the formula seemed sensible for lower capacity pumps. The larger CVL 500-2 delivered by DNV approved Shinko Limited Industries in Japan, delivers 5000 m^3/h to a discharge bore of 500 mm at a total head of 35 meters (3.5 bars), the pump in use weighs about five tons (Shinko Ltd. Ind., 2010).

If a centrifugal pump is used, it has to be either self-priming or connected to a central priming system according to H204.

H205: if large centrifugal pumps are used for pumping water at velocities exceeding 5 m/s in the main pipe line, pump characteristics, calculations of head loss and arrangement plans of the system needs to be presented DNV for approval.

Regulation 4/6/4-G205 states that bilge pumping may be portable but will need to have their own powers supply onboard the barge.

Having power supply onboard is not wanted by the designers of WindFlip. This is because of the rotating ability of the barge. Most power generators are built for being level and are therefore not optimal for WindFlip. There is however a possibility of DNV allowing WindFlip to disregard the rule if special considerations are done and the design is proven to be sufficient.

If not a possible solution is to have a smaller power supply could be fitted to support a smaller bilge pump, whereas the large pump is supplied by the umbilical. Such a solution is dependent on hinging the generator like the solution based on R/P FLIP's generators which was proposed in the first WindFlip report. This way the turbine is always kept level.

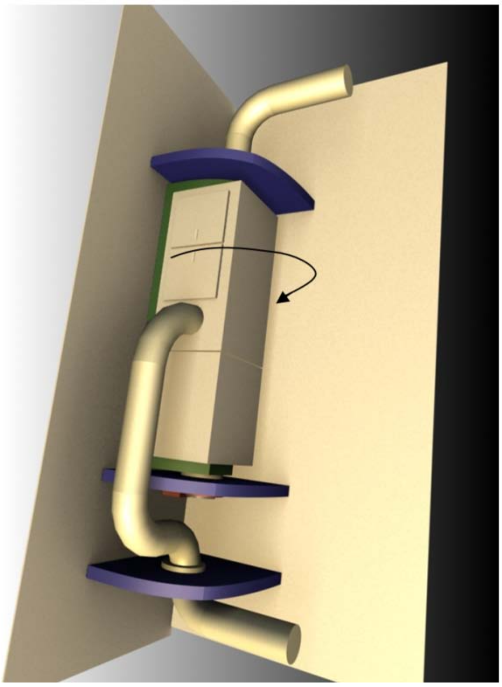


Illustration 23 - A gas turbine of the first WindFlip concept seen from above (WindFlip AS, 2008)

5.3.3.4 Ballast tanks

It is very important that all tanks of WindFlip have access for inspection. This is referred to in 3/3/6-I101:

"The number of hatchways and other openings in the tank deck shall not be larger than necessary for reasonable access to and ventilation of each compartment."

WindFlip should have manholes in every ballast tank in order to provide access. Openings may either be from inside the barge or from the top deck. Some tanks will have two openings as the division of tanks makes it necessary reach some tanks by going through another.

5.3.3.5 Filtering and Treatment

Possibilities of filtering and treating ballast water is subject to ballast water management classing (BWM) and is considered as supplementary to the main class. If a vessel is classed with Ballast Water Management it has to meet or exceed the Ballast Water Performance Standard in Regulation D-2 of "The International Convention for the Control and Management of Ship's Ballast Water and Sediments".

The classing may become more important in the future as regulations could change to a more strict shape and is therefore considered to be relevant for WindFlip. The class notations of ballast water exchange will be withdrawn as exchanged is to be phased out in the future.

6/18/1-C101 states:

"Details related to additional classes regarding design, arrangement and strength are in general to be included in the plans specified for the main class."

The current main four classes can be derived from 4/18/1-A201:

BWM-E ( )	Ballast water exchange. Letters in the bracket denote the method for the exchange.
BWM-EP ( )	Ballast water enhanced exchange-performance. Letters in the bracket denote the method for the exchange.
BWM-T	Ballast water treatment.
BWM-TP	Ballast water treatment (prototype).

Ballast exchange is seen as most fitting for the WindFlip concept though being phased out at a later stage. It is unclear how rules will be set for unmanned barges and for barges/vessels with an operational profile of WindFlip, an environmentally friendly ballast water management plan may be sufficient. This will have to be discussed with DNV at a later design stage. Only regulations concerning exchange will be denoted next.

Exchange can be performed by three methods:

D	Dilution method	- Replacement ballast water is filled through the top of the ballast tank ballast with simultaneous discharge from the bottom at the same flow rate and maintaining a constant level in the tank or hold. The tank volume shall be pumped through the tank at least three times.
S	Sequential method	- A ballast tank is first emptied of at least 95% or more of its volume and then refilled with replacement ballast water.
F	Flow-through method	- Replacement ballast water is pumped into a ballast tank allowing water to flow through overflow or other arrangements. The tank shall be pumped through the tank at least three times.

6/18/3-B102 informs that for the sequential method each tank shall only be emptied and refilled once in one sequence. If the ship is in operation this requirement may be especially considered.

Every ballast tank has to contain isolating vales for filling and/or emptying purposes according to B201.

B301: Ballast intake and discharge openings have to be placed in a manner which will not contaminate replacement ballast water.

B501: The exchange process shall have means for remote control of ballast pump(s) and valves, flow/speed control shall also be provided.

B502 and B503 require local manual controls for handling the exchange.

The control and monitoring system have to include the following by B504:

- Valve position indicating system
- Tank level indicating system
- Tank level alarm (not applicable for tanks using flow through)
- Draught indicating system
- Communication means between the central ballast control station and spaces containing the local control for the ballast pumps and the manually operated independent control for the valves.

6/18/3-C102 states that the flow-through method with water flowing over deck is not permitted for ice classed ships with BWM-E(f). According to E103 such is never allowed if classed BWM-EP(f).

E102 restricts ballast pumps to be able to fill the biggest ballast tank or group of tanks within three hours during BMW-EP(s).

E104 states that arrangements of BWM-EP(d) shall include a manual emergency stop of pumps in case of valve or control malfunction.

5.3.3.6 Control Equipment

4/6/4-J concerns remotely controlled ballast systems. The section does however not mention much information highly relevant for remote control of WindFlip, with one exception. J201 states;

“Remotely controlled bilge and ballast pumps shall be provided with operating indications at the remote maneuvering panel.”

5.3.4 Summary of functional requirements and constraints

The most important requirements to the ballast system is listed below.

- If only one pipe is used during purging the ballast tanks with compressed air, the diameter should at least be 400 mm, this will give a head loss of 0,7 bars. Such a diameter requires a wall thickness of at least 8,23 mm for straight lines and 9,17 mm in bends. If the diameter is reduced two pipes have to be used simultaneously to fulfill time constraints. Smaller pipe does however increase pressure loss.
- Based on one main pipe, the feeder lines should have a diameter of at least 300 mm, this gives a pressure loss of 0,2 bars. The wall thickness should at least be 6,43 mm for straight pipes and 7,13 mm in bends.
- Based on only one pipe used for flooding the ballast tanks, the diameter should at least be 400 mm, which also gives a pressure loss of 0,2 bars. The minimum wall thickness of the flood pipes is the same as for the main pressure line.
- The minimum dimensions of branching of the main pressure line into a feeder line can be seen in Illustration 19.
- All tanks have to be fitted with pipes for ventilation.
- There has to be means for monitoring valve position and possibly remote control.
- Barges are allowed to have only one ballast pump. A centrifugal pump needs to have means for priming. Power supply has to be discussed with DNV.
- Every ballast tank needs to be accessible for inspection.
- There has to be a plan for ballast water treatment. The minimum is to have possibilities for ballast water exchange.

5.4 Step Two – Risk Assessment

Identification of hazards will be done by using FMEA worksheets. The different components will be assessed with a “what-can-go-wrong”-mentality, this will help to discover and identify possible hazards to the system.

In this part the different components will be studied to get an overview of the most common failures and causes. The effect of a specific failure will also be elaborated. Input in the FMEA sheet is based on reliability data provided by OREDA (OREDA Participants, 2009), more information about OREDA in chapter 5.8. Note that only the most common critical failures according to OREDA will be addressed in this study.

The following components will be studied:

- Gate Valve
- Pressure Relief Valve
- Pressure Reduction Valve
- Butterfly valve
- Stop Check Valve
- Switch Sensor
- Pressure Sensor
- Control Unit
- Centrifugal Pump
- Electric Motor
- Eductor

The FMEA worksheets can be seen in Appendix G – FMEA worksheet of components.

In the step three of the risk assessment the failures of each component will be studied in relation to the system it is a part of. Actual hazards will be clearer when considering failures of systems.

5.5 Step Three – Design

The following ballast system has to be able to facilitate the following functions and performances;

- Flooding of ballast tanks during rotational mode
- Ventilation of ballast tanks in all operational modes
- Purging of ballast tank during rotational mode
- Monitoring of ballast tank level and pressure during all operational modes
- Filling and emptying of ballast tanks during transit and onloading of payload
- Perhaps Stripping of ballast tanks used during continental transit
- Ballast water handling during continental transit

5.6 Step Three – Risk Assessment

In the following an FMEA have been completed in order to identify if the functions and systems of chapter 5.5 are critical or not. The FMEA worksheet can be seen in Appendix H – FMEA worksheet of systems.

If the system for flooding is not able to perform its task this would be picked up by the sensor system. The operation could be halted and the valve for flooding would be inspected. If a tank is unable to flood this would mean that WindFlip will not be able to follow preset procedures. The rotation can however continue depending on the size and location of the tank. The pressure system would secure that the pressure of the ballast tank resembles the surroundings while submerging. To continue the operation with an unfloodable tank should however not be done for safety reasons. A redundant valve would help if the flood valve is locked in closed position, if closed in open position redundancy has no effect.

Purging of the ballast seems to be a critical system as it is in control of rotating the barge back to horizontal. The system should to a large extent be able to do this even if a critical failure in the system should occur. There should be an alternative way of purging each tank as this system will regulate the pressure in the tanks during ballasting and deballasting. Regulating the pressure is essential as tanks can be damaged by wrong pressures in the tanks. A solution is to have a redundant pressure reduction valve. If a failure should occur this would be registered by the sensor system and measures aiding the operation could be conducted.

Ventilation is also very important as it is used in all operational phases. Ventilation is used to regulate pressure and is essential when ballasting. Sensors will pick up issues in the system, but there should still be redundancy providing ventilation options.

Monitoring of the ballast tank is of outmost importance. Without information about the tanks no actions can be carried out as this would be as working with a blindfold. The monitoring is essential especially during rotation of the vessel, but also during ballasting for transit and onloading. The sensor system is not only important for performing correct actions, it is also a great tool for monitoring valves and the compressed air system as it can provide information what the effect of an action is. In this sense it could be used for system diagnosis. Redundancy of sensors will not only work as backup, it will also increase preciseness of measurements.

The eductor system is not a critical system as it will not be causing delays. The system may even not be required by DNV.

The system for ballast water handling has not been included as ballast water exchange is likely to be used. A full ballast water treatment plant should be made room for as it might be mandatory in the future, but this has to be further discussed with DNV. The exchange solution can be performed by using the ballast for transit and onloading.

5.7 Step Four – Design

The layout of the ballast system is presented next. The design is based on all considerations mentioned previously.

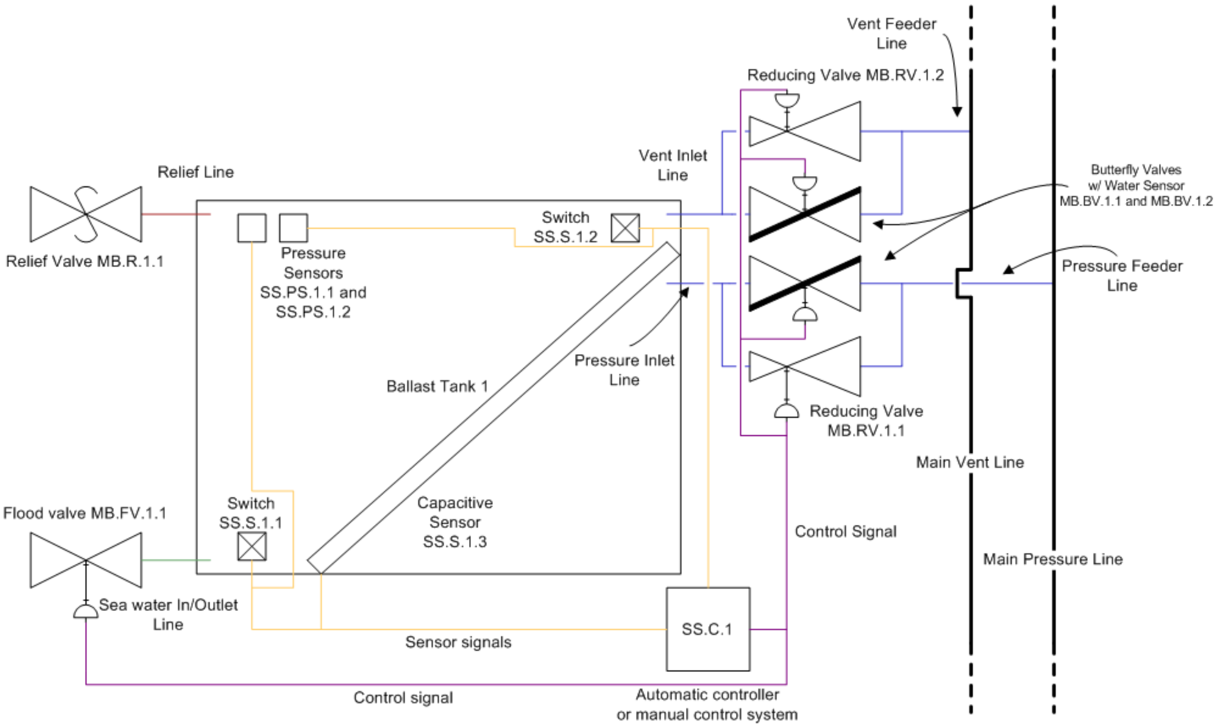


Illustration 24 - Ballast tank layout

The layout above displays the basic connections of each tank. Each tank will have one valve relieving the tank of pressure if a pressure build-up should occur. There will be two identical main lines responsible for ventilation and compressed air. Both the ventilation and pressure line is led into each tank through a pressure reducing valve and a butterfly valve. The two main lines are meant for redundancy in case something disables the connection to a tank or if the one of the inlets are dysfunctional. A single line can provide compressed air and ventilation, however not simultaneously. The pressure reducing valve is one way and can be closed. This valve reduces pressure in the main line of 16 bars to a level suiting the ballast tank for a given situation. The butterfly valve is meant for ventilation and can be adjusted to cope with any situation. The sensors measuring filling level and pressure of the tank sends signals to a controller. The controller uses the information to perform an action like adjusting a valve position. The signal from the sensor may also be sent to a control board monitoring the process and an action may be issued manually. The flood valve will open during ballasting and remain open in order to balance pressure in the tank and outside while the barge is reaching larger depths. During flooding the butterfly valve will be open and secure ventilation of the tank. When the tank is full, i.e. some water goes through the valve and is picked up by a water sensor, and the valve closes. The ventilation pipe(s) will remain at atmospheric pressure, this is no problem as they are built to withstand outside and inside pressure, the two main pipelines are built for withstanding pressure differentials above 16 bars.

During ballasting pressure will be maintained at a sufficient level compared to the surrounding tanks and the outside by utilizing the pressure line. During deballasting ventilation will control that pressure within a tank is not largely higher than the surroundings.

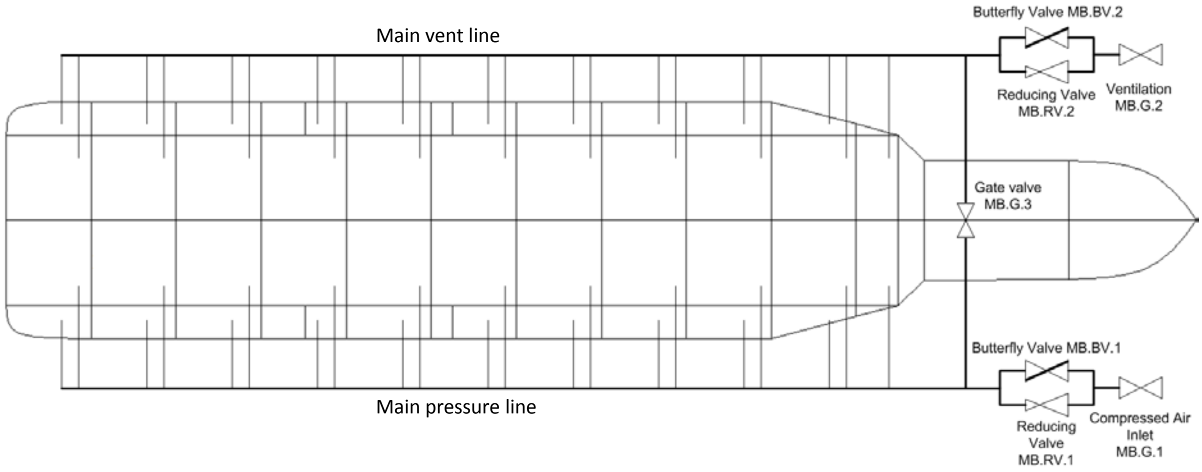


Illustration 25 - Overview of the main ballast system

The illustration above shows the extension of the main lines shown in Illustration 21. The two lines have feeder lines reaching out to *every* tank. The illustration above is simplified and does not show all feeder lines. The extreme right valves are for connection to a compressor or just ventilation. Both inlets may be switched or used with either the lower or upper lines by going through the interconnection between the two main lines (MB.G.3). The butterfly valve connected to each line is used if the line is used as ventilation. If compressed air comes through the inlet this goes through a pressure reducing valve in case incoming compressed air is at a higher pressure than the line is designed for.

The two previous illustrations displays units included in the main ballast system, except the sensors and control unit which is a part of a system called the sensor system which stretches over the whole vessel.

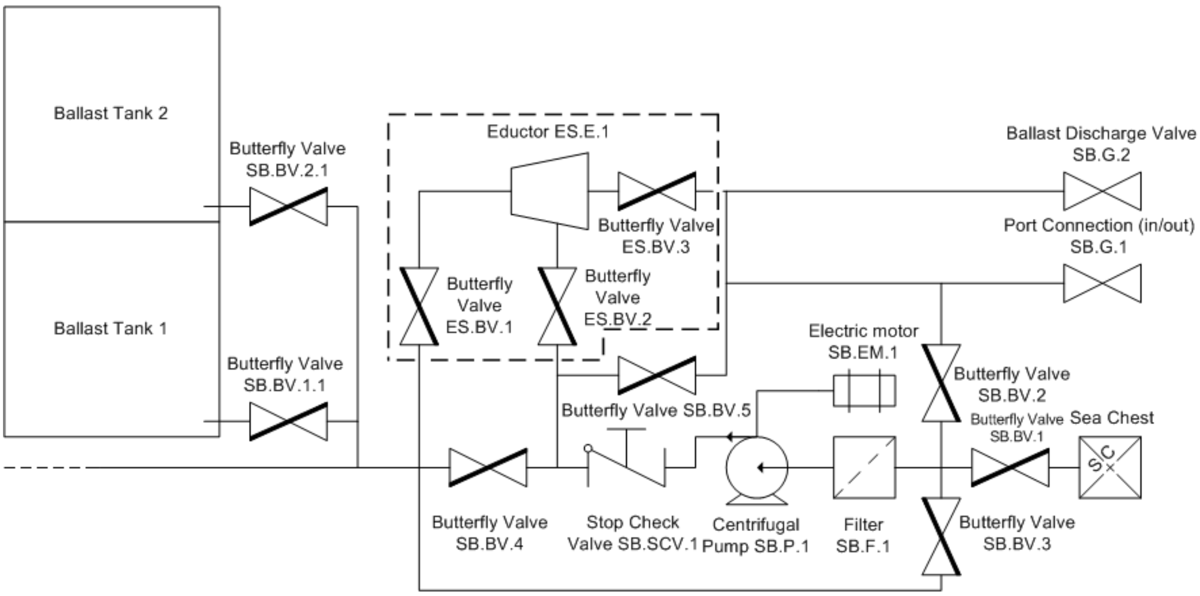


Illustration 26 - The secondary ballast system

The system above is called the secondary ballast system and is only connected to the ballast tanks filled during the loadcondition for on loading the wind turbine (with 5 degrees forward trim) and for transport without payload. The system has a separate line. Water is let in through the sea chest on the suction side of the centrifugal pump, the water is filtered before entering the pump and sent to a ballast tank. The electric motor, connected to the pump, has the soft start function to prevent water hammer. The bypass line in the lower part of the illustration is used when deballasting. Deballasting can of course also be done by using compressed air.

The inlet/outlet to the ballast tank is placed forward of the tank. The reason for this is that the forward trim will make the forward part the lowest point of the tank.

The area bounded by the dotted line is an additional system for stripping the ballast tanks. As described earlier (Chapter 3.4) an eductor will empty the last percents of ballast which usually is most “contaminated”. The system could also be fitted to a separate pump with less capacity saving power compared to using the larger pump. This would also enabling parallel use of the two pumps. The eductor system is not mandatory but may be fitted onboard WindFlip, it has been included in this study as portrayed above in Illustration 23.

The valve beneath the ballast discharge valve is either a connection to a possible treatment plant or a connection to portside equipment. This may be needed due to new the ballast treatment regulations mentioned earlier. A ballast treatment system will however probably not be needed as WindFlip primarily will be operating in local waters and not between continents, but this has to be discussed with the classing society. If transported continentally the thesis proposes either to perform ballast exchange amid sea or to be supplied with clean water from port. If this is not done and “unclean” ballast is onboard, this can be discharges through the same connection and be sent to onshore ballast treatment. If ballast exchange is performed this will be done by using the sequential method described in chapter 5.3.3.5. The inlet and discharge are not placed close to each other.

Butterfly valves have been preferred instead of gate valves in most cases, one of the main reasons is that they have the ability of regulating flow. Another reason is due to the fact that OREDA has presented higher critical failure rates of the gate valve. The butterfly valve also seemed to be preferred in M/T BW ULAN’s ballast system.

Minimum requirements of the pipes can be found in chapter 5.3.4.

Measures for corrosion protection are very important for the system. There should at least be coating and anodes in each ballast tank. Tar epoxy will be included in valves and pipes as commented in chapter 3.4.2. Suitable measures for other parts of the system have not been addressed further in this study.

All ballast tanks will be accessible for inspection and maintenance.

To summarize the ballast system may be divided like this;

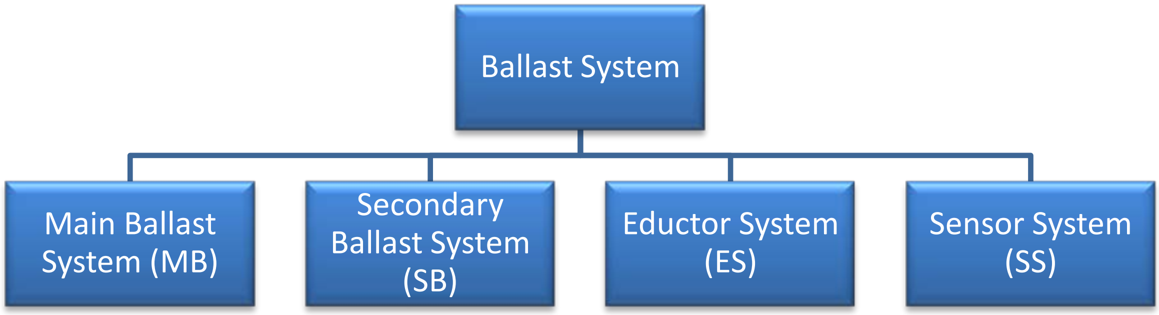


Illustration 27 - Subsystems of the ballast system

The items in the illustrations of the last few pages are firstly named according to the subsystem they are included in, then component type and lastly numbered. As an example MB.BV.2.1 is the first butterfly valve connected to ballast tank 2 of the main ballast system. Only one number indicates that the valve is not directly connected to a ballast tank. A full overview of item naming can be found in Appendix C - Component belonging and naming.

5.8 Step Four – Risk Assessment

In this chapter two models for assessing the reliability of the purposed system will be made. The reliability data has been found in the book of OREDA, (OREDA Participants, 2009). The book is made by SINTEF[15], they have collected reliability data from several of the large actors in the offshore industry, like Chevron, BP and Statoil. The gathered data is thoroughly analyzed and used to generate average failure rates for specific types of equipment. The data can be used to analyze system reliability, maintenance intervals, etc. Information is also provided for identification of causes of different failure modes which were used in the previous FMEA analysis.

The equipment is primarily used in the oil and gas industry, it is therefore exposed to a different operational environment than WindFlip will. For this reason some of the figures used may be somewhat inaccurate for the ballast system of WindFlip, the difference is however regarded as negligible.

An overview of the failure data for the units/components of WindFlip's ballast system can be found in Appendix D – Unit failure rates. The tables includes the taxonomy number, equipment name, failure modes, severity class, failure rates, calendar time and operational time. The failure rates used are related to operation time and not calendar time, see definitions below. Application of failure rates according to operational times seems to be accurate.

OREDA definitions:

Failure

- Complete failure of item
- Failure of part of the item that causes unavailability of the item for corrective action
- Failure discovered during inspection, testing, or preventive maintenance that requires repair.
- Failure on safety devices or control/monitoring devices that necessitates

[15] SINTEF – An independent research organization founded in 1950 with headquarters in Trondheim, Norway.

	shutdown, or reduction of the capability below specified limits
Failure mode	Describes the loss of required function(s) that result from failures, or an undesired change in state or condition. There are two main classes: • Demanded change of state not achieved • Undesired change in conditions (state)
Severity Class	• Critical failure: A failure which causes immediate and complete loss of a system's capability of providing its output. • Degraded failure: A non-critical failure, but which prevents the system from providing its output within specifications. Such a failure would usually, but not necessarily, be gradual or partial, and may develop into a critical failure in time. • Incipient failure: A failure which does not immediately cause loss of a system's capability of providing output, but which, if not attended to, could result in a critical or degraded failure in the near future. • Unknown: Failure severity not recorded or could not be deducted.
Calendar Time	Interval of time between the start and end of data surveillance for a particular item.
Operational time	The period of time during which a particular item performs its required function(s), between start and end of data surveillance.

5.8.1 Fault Tree

5.8.1.1 *Description of Fault Tree Analysis*

The fault tree analysis method came to light in 1962, the method was developed by Bell Laboratories under a contract by the US Air Force. The method was later expanded by Boeing, among others, and is today one of the most used risk and reliability tool in the world. (Rausand, et al., 2004)

Fault tree analysis (FTA) starts with defining a top event (TE) which may be a failure or an accident. The tree is structured with causal events that could alone or in combination lead to the top event. The events are connected with the top event by logic gates, the most common is the AND-gate and the OR-gate. The events are statistically independent. The events, also called nodes, represent a probability or frequency of failure of a function, sub system or component. This makes the method qualitative as a logical expression of the top event is derived and quantitative by assigning probabilities to the nodes and calculating the probability of the top event.

The tree is created by working backwards, going *from* the top failure and to the lowest level called basic events. This type of analysis is binary, meaning it only treats occurrence or incurrence. This means that reduced operability is not an option, the unit either works or not.

The probability of the top event is calculated by adding possible cut sets initiating the top event, this is formulated as follows;

$$\text{Prob}(TE) = \sum_{\text{minimum cut sets } K_j} \prod_{i \in K_j} q_i(t)$$

Where K_j is a minimum cut set, and $q_i(t)$ is the probability of event i in minimum cut set[16] K_j occurs at time t.

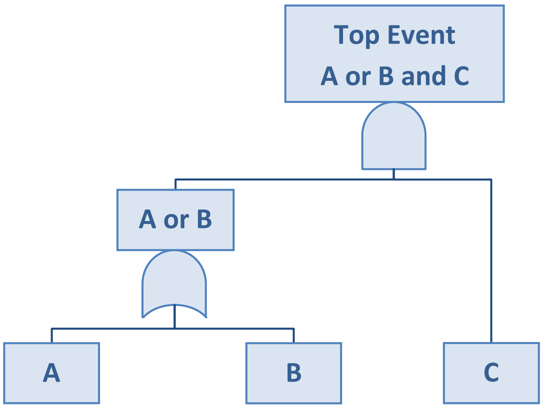


Diagram 14 - Example of a Fault tree

In the presented example the minimum cut sets would be [A, C] and [B, C], this would give the following frequency of the top event;

$$\Pr ob(TE) = A \cdot C + B \cdot C$$

Where A, B and C are probabilities of failures.

Before naming the top event it is important to set boundary conditions, this may be physical boundaries like what systems are to be included in the analysis. The boundary conditions also have to consider external stresses that are to be included in the analysis, this may be stresses like operating in harsh weather, earthquake or even being in a war zone, etc. The depth of the analysis also needs to be determined in order to use a general basic level, like valves, pumps and not components within these. The top event should be clearly defined by describing what type of accident, where it occurs and when.

The boundary condition used in this analysis is limited to the ballast system.

External stress other than normal operating conditions is not included. Weather which is good enough for WindFlip to execute an installation is meant by the term “normal condition”.

The depth of the study has been limited to valves, pumps, sensors, etc.

As my analysis will not further evaluate the full risk, I have chosen to find the overall reliability of the system in order to present useful information. This means that the top event the probability of failure in the ballast system leading to delay the operation of WindFlip in all operational phases, this equals the reliability of the ballast system.

A more risk oriented approach would divide the fault tree I have created into smaller pieces and then see what accidental events the failures would lead to.

The analysis has considered critical failures exclusively as this would result in a defect component needing repair. Failure rates of all the units can be found in Appendix D – Unit failure rates.

[16] Minimum cut Set – Minimum of occurred events for the top event to occur.

The failure rates are converted to unreliability (probability of failure) by;

$$F(t) = 1 - R(t) = 1 - e^{-\lambda_c \cdot t}$$

Where R(T) is the reliability, λ_C is the is the failure rate and t is the mission time.

5.8.1.2 Operational phases

The fault tree will find the probability of a failure in the ballast system during operation. Before proceeding with presenting the fault tree, operational time in each operational phase will be quantified and functions needed in these phases will be presented.

WindFlip's operation consists of onloading the wind turbine, transporting it to site, rotation to 85^{o}, releasing the turbine, rotation back and transport back to production site. In the work of Ane Christophersen operation time for one cycle has been estimated. The figures are based on installation of wind turbines by the state Maine in the United States. (Christophersen, 2010)

Onloading of turbine	16 h
Transport to site	25 h
Ballasting to 85^{o}	6 h
Installation, other	4 h
De-ballasting	6 h
Transport back	25 h
Total time	82 h

It is anticipated that WindFlip will mostly working from April to September with 20% downtime due to bad weather. This gives 146 days available for operation, in which time about 42 wind turbines may be installed.

The time estimates from above can be divided further when considering the different tasks of the ballast system. Note that some of the phases listed below could be occurring simultaneously.

	Per cycle
Ballasting for onload	1,5 h
Onloading of turbine	16,0 h
Transport to site	25,0 h
Ballasting to 90^{o}	6,0 h
De-ballasting	6,0 h
Ballasting for transit	1,5 h
Transport back	25,0 h
Stripping of tanks	1,0 h
Total time	82,0 h

The table below shows what parts of the ballast system will be functioning for each of operational phases presented above;

Phases	Active ballast sub-systems			
	Main ballastsys.	Secondary ballastsys.	Eductor system	Sensor system
Ballasting for onload		X		X
Onloading of turbine		X		X
Transport to site		X		X
Ballasting to 85°	X			X
De-ballasting	X			X
Ballasting for transit		X		X
Transport back		X		X
Stripping of tanks		X	X	X

Table 6 - Active ballast sub-systems during different operational phases

Based on the above, the operational time in which each system/function is operating or in stand-by can be derived;

System	Function	Time [h/cycle]	Time [h/year]
Secondary ballast system	Ballasting	34,5	1449
	Deballasting	34,5	1449
Main ballast system	Ballasting	6,0	252
	Deballasting	6,0	252
Eductor system	Stripping	1,0	42
Total time		82,0	3444

Table 7 - Operational time per system/function

The main and secondary ballast system has two functions, ballasting and deballasting. The function of the eductor system is stripping and the sensor system monitors. Fault trees have been made for each of these functions with a top event of failing to perform the function.

As mentioned earlier 102 ballast tanks are in use during rotation while 27 tanks are used during the other operational phases.

5.8.1.3 Failure in main ballast system during ballasting and deballasting

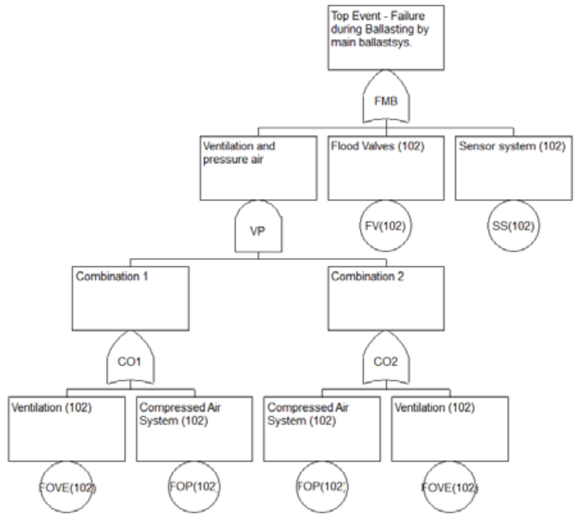


Diagram 15 - Failure in main ballast system during ballasting

The tree presented above shows the structure of a failure in the main ballast system during ballasting. The structure, nodes and therefore also the probability of the top event will be the same for deballasting as the functions needed to be performed remain the same.

The OR-gate implies that if failure occurs any of the nodes below, the top event will occur. The basic nodes here hide underlying structure which will be worked through in the next few paragraphs.

Make note that the function of compressed air and ventilation has to combinations through an AND-gate. The two functions can be carried out by the use of both pipelines as seen in chapter 5.7, so if a valve leading into a ballast tank would fail one could changing around the line’s function, e.g. transforming the vent line to the pressure line and vice versa. This means that there is an alternative for serving all ballast tanks. There is also four more combinations that still would ensure operability, but they include using the interconnection between the main lines and switching of function provided at the inlets. Using these options could double operation time during rotation and is therefore not included in the analysis. Structuring the fault tree in this manor could be seen as conservative.

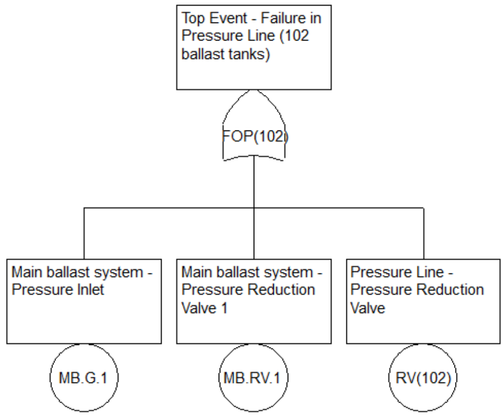


Diagram 16 - Failure in the line supplying compressed air to the ballast tanks

The two basic nodes to the left are the valves at the inlet. The right node is actually an OR-gate for all the 102 pressure reduction valves leading into each ballast tank. The ventilation line is similar except for the reduction valves being replaced with butterfly valves.

The FV(102) hides 102 gate vales in series.

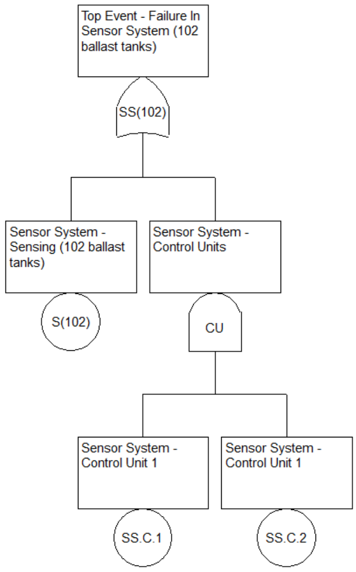


Diagram 17 - The sensor System

The sensor system is divided into two functions, "sensing" and "control". All the sensors are connected to two controllers, the redundancy of the control function is symbolized by an AND-gate, meaning that both control units need to fail for the ability "control" to fail. "Sensing", marked as S(102) includes the sensors of all the 102 ballast tanks. The node actually equals 102 instances of S(1). The structure of a single tank can be seen below;

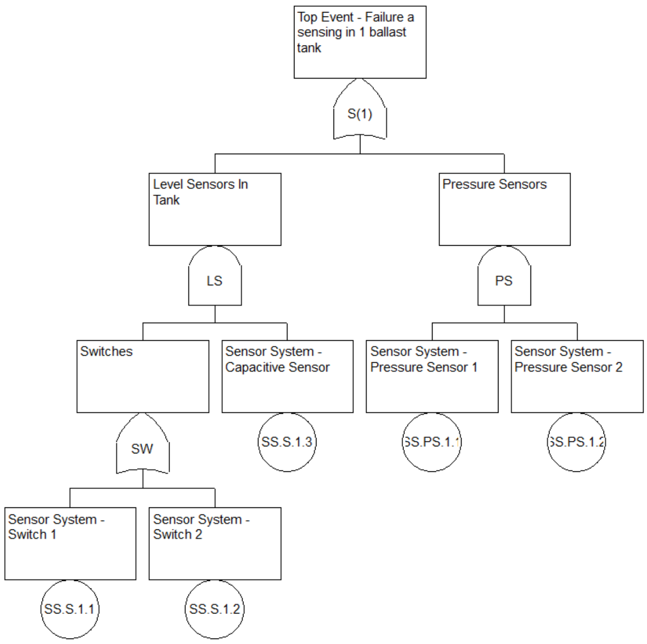


Diagram 18 - The function called "sensing" which includes all sensors

Sensing is divided into measurement of ballast level and pressure in the tank. Both have redundancy in order to secure monitoring of the system but also for improving precision of the measurements. Measurement of a tanks level is achieved by either the continuous capacitive sensor or by both switches.

5.8.1.4 Failure in secondary ballast system during ballasting and deballasting

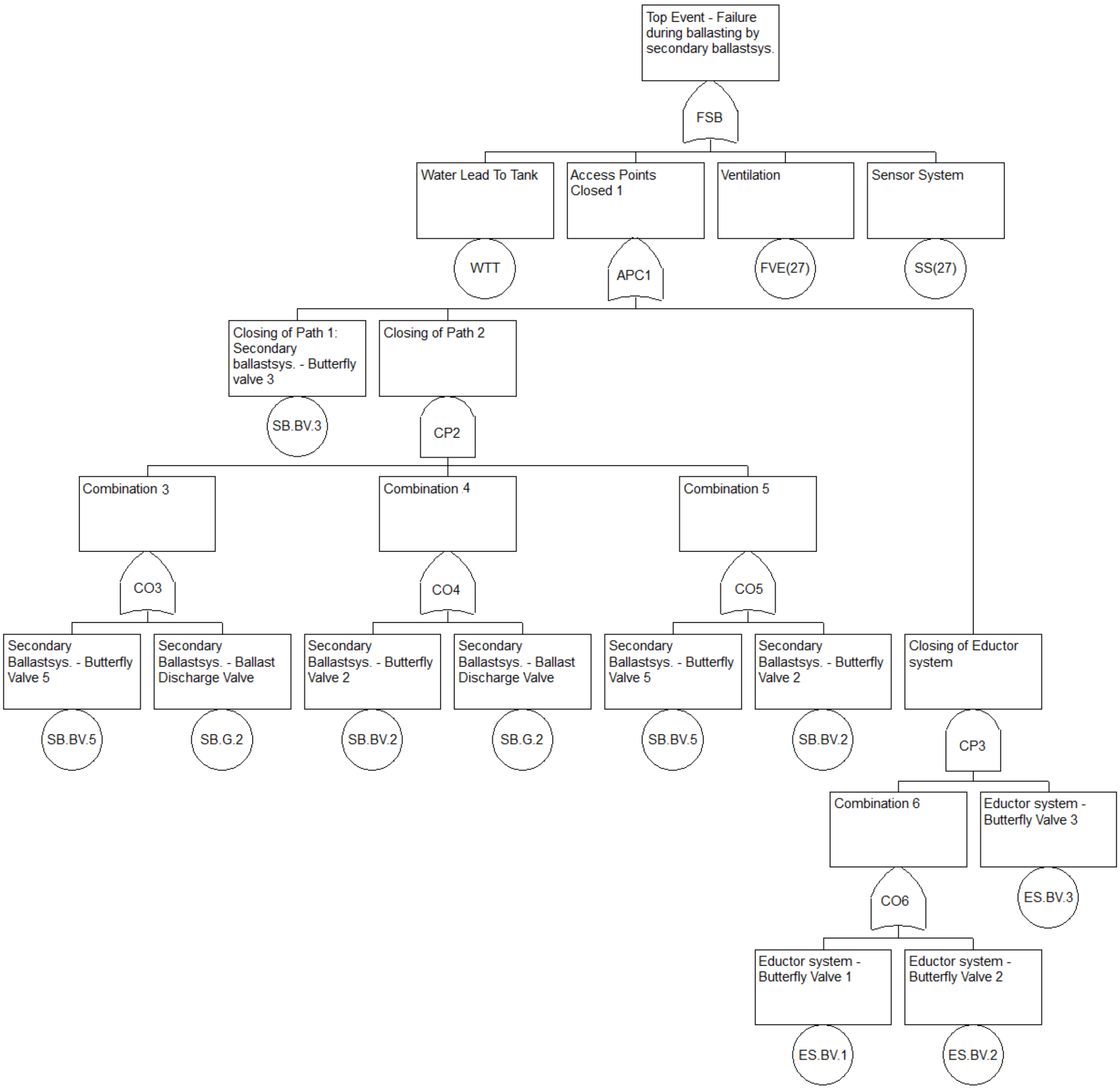


Diagram 19 - Failure in secondary ballast system during ballasting

Four functions is the fundament of the secondary ballast system during ballasting. The water needs to be lead from the sea chest to each ballast tank, there have to be ventilation and the tanks need to be monitored. An additional function is "closing of access points", this means that certain passages need to be closed in order not have loops or leading the water out of the system. The node called SB.BV.3 is the closure of the by-pass line, while CP2 include valve combinations that will retain water from leaving the system. The eductor system is also closed off in order to avoid a loop.

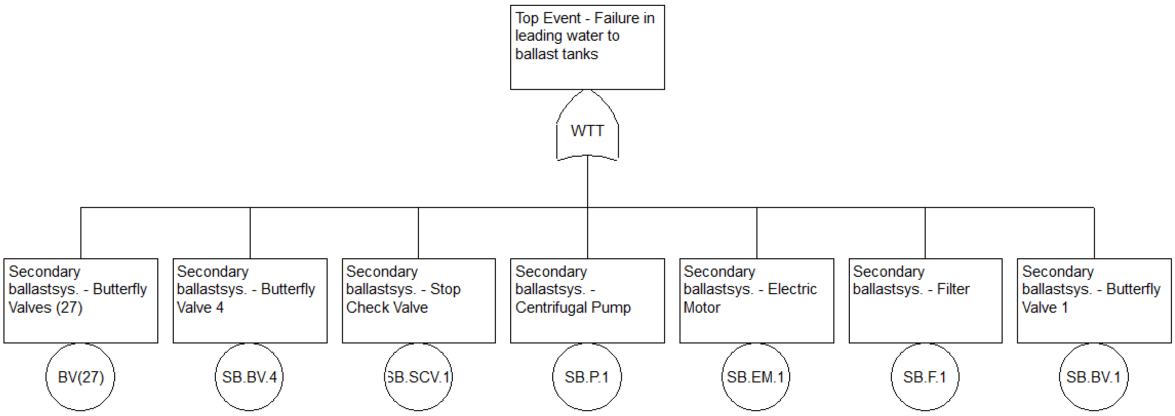
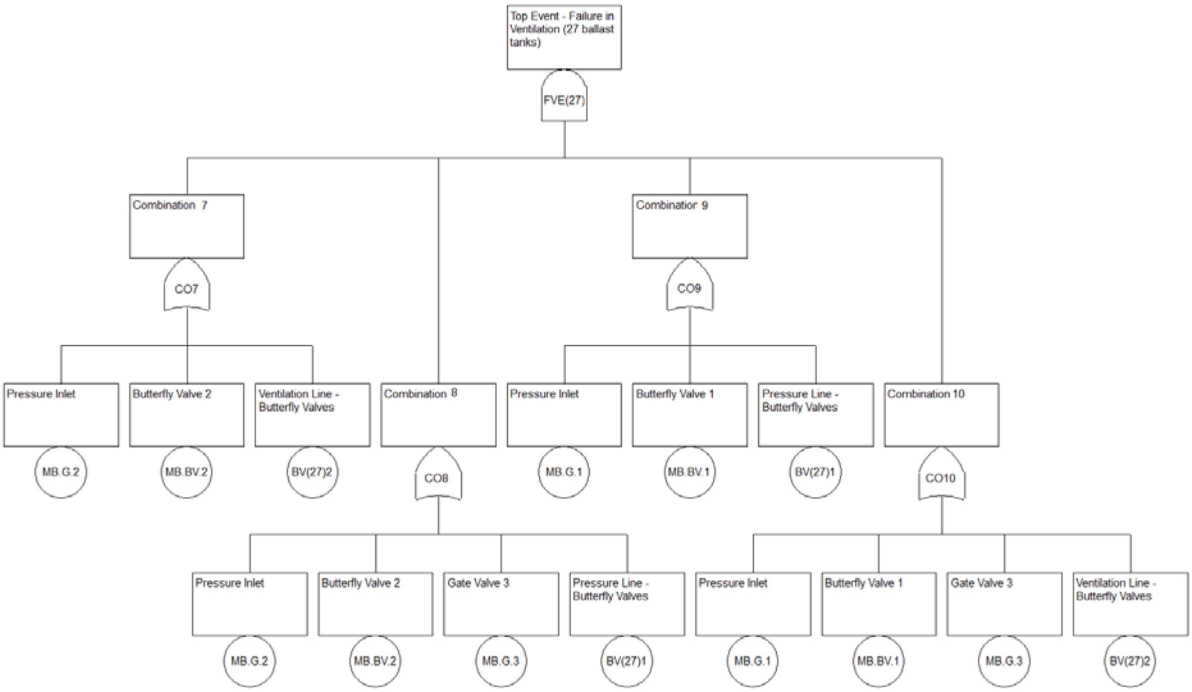


Diagram 20 - Water lead into tanks

Diagram 19 shows the waters path from the sea chest, through the pump (with a working electric motor) and to each of the 27 tanks needing ballast.



During ballasting there is no need for compressed air, therefore both main lines may be used as ventilation, therefore four valve combinations need to fail for ventilation being disabled.

The sensor system is structured in the same way as in Diagram 16 and Diagram 17, the only difference is that the sensor system only need to attain information for the 27 tanks being ballasted.

Deballasting through the secondary ballast system occurs differently;

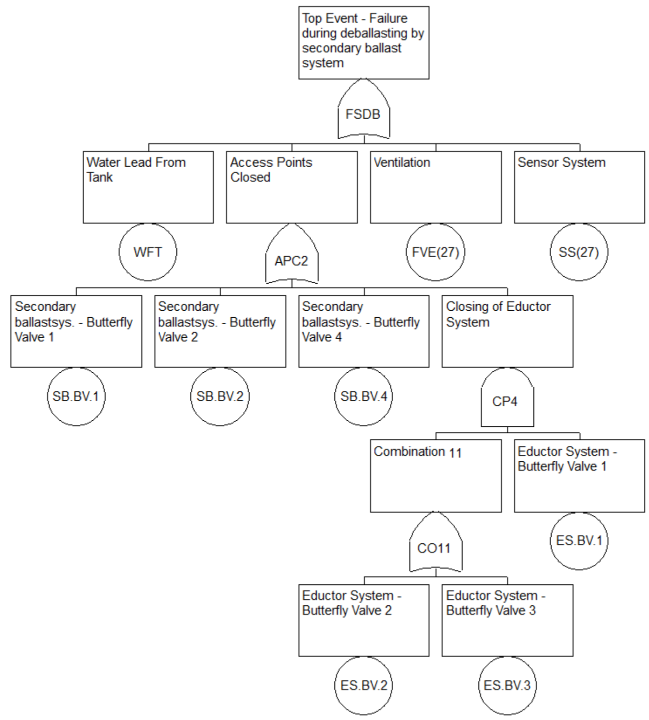


Diagram 21 - Failure in secondary ballast system during deballasting

Now the water is lead differently by going through the by-pass line, through the pump and out of the ballast discharge valve. By changing water route the closed points are changed and the eductor system is still cut off. Ventilation and monitoring remains the same.

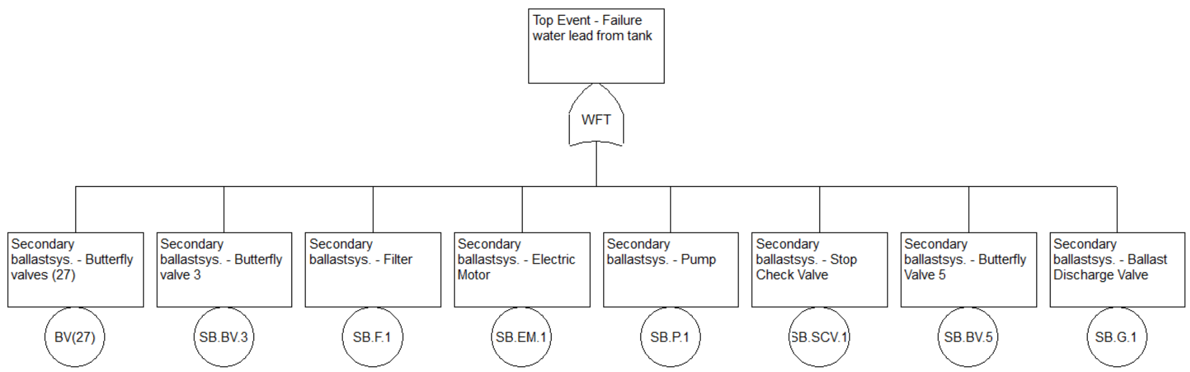


Diagram 22 - Water lead from tanks

5.8.1.5 Failure during stripping of ballast tanks

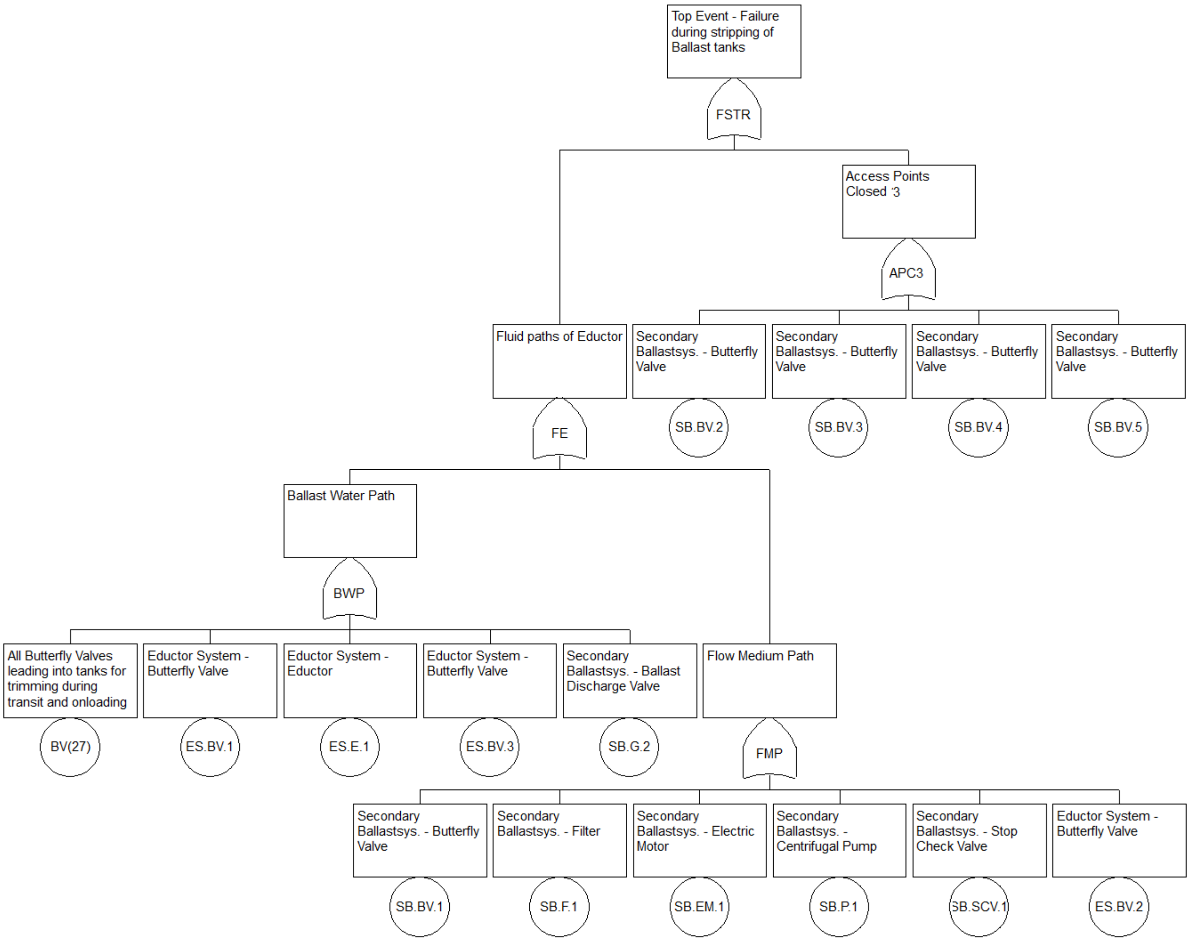


Diagram 23 - Failure during stripping of ballast tanks

During stripping neither ventilation nor monitoring is needed as ballast water quantities are so low. There are two functions; stripping and closing access points to enable proper paths for ballast water and “flow medium” (sea water from the sea chest). The eductor is split in two, the first path is from the sea chest to the eductor, only with the “flow medium”. The second path is the path from the tanks to the eductor (only ballast water) and through the eductor and out the discharge valve (ballast water and “flow medium”. Note that node FE could have been split in three; the two paths before the eductor and the path after, this would still amount to the same probability of failure in E.

5.8.1.6 Failure rate of ballast system

Unreliability of all the trees presented in the previous chapters can be found in Appendix F – Fault tree probabilities. The unreliability of the top level functions is displayed below.

Top Event	t_1	t_2	$F_C(t_1)$	$F_C(t_2)$
FMB	6,0	252	0,29 %	16,9 %
FMDB	6,0	252	0,29 %	16,9 %
FSB	34,5	1449	0,38 %	18,0 %
FSDB	34,5	1449	0,41 %	19,2 %
FSTR	1,0	42	0,02 %	0,8 %
Total	82,0	3444	1,37 %	71,8 %

Table 8 - Unreliability of top level functions

The result is that there is a 1,37 % chance that a critical failure could happen during one cycle, the probability of a critical failure is 71,8 %. As defined earlier, a critical failure means that the unit seizes to perform its function and needs to be fixed in order to continue operation. Such a failure is most critical during rotation as accessibility in this phase is limited, the probability of a failure occurring during rotation is only 34 %. This means that WindFlip may have such a failure once every third year after installing about 120 wind turbines, which seems fair. It should be mentioned that this probability is even lower as a few alternative ways of maintaining ventilation and purging was left out of the analysis, see chapter 5.8.1.3.

The probability of failure during other operational phases is most probable, almost 40%. This probability may also be even lower as the secondary ballast system was assumed to be in stand-by during the whole transit, which equal about 50 hours per cycle. It is reasonable to believe that the operation time of the secondary ballast system in reality would be lower. If a failure should occur during other operational phases than during rotation, it would probably not be very critical. The secondary ballast system is not crucial for WindFlip, except during onloading of payload. However, making repairs should be fairly simple as there is good accessibility in horizontal position.

Another point which should be considered in relation to the reliability found here is that the actual reliability may be even lower if correct and effective maintenance is performed on the system. The failure rates of OREDA are average values of units, the units serve in slightly different environments and with different operators, meaning that failure rates may be both higher and lower than the value used in this analysis. Good maintenance could therefore reduce the unreliability.

Criticality in terms of the failure leading to a severe event has not been addressed here. A severe event could for instance be a pressure build-up and a failure of a relief valve making it unable to relieve a tank of pressure. However, most of the errors in the ballast system will not lead to severe events, only a delay in the operation due to redundancy and backup systems. Additionally, the extensive monitoring system will largely reduce the probability of a failure leading to a severe event. The reason is that the monitoring system will signal when an unexpected instance occur and give the opportunity to contain to the situation.

5.8.2 Bayesian Network

5.8.2.1 Description of the Bayesian Network

Note that some parts of the following have been excerpted from my project thesis.

Thomas Bayes (1702-1761) was the British mathematician who purposed what is known today as Bayes' theorem which forms the basis of the Bayesian Network (BN). But it was not until the 1980s the real boom of belief in Bayesian Networks started. Systems needed to be analyzed were getting more complex in terms of number of components and dependencies, a methodology for handling such systems was needed. At this point the Markov Chain Monte Carlo methods emerged and eased calculations, at the same time there were great improvements in computer's hardware and software. The Bayesian methods became easier to apply and gave good results. (Wolpert, 2004)

The BN has been implemented with success as a diagnosis tool in medical science. By inputting evidence, in this case observed symptoms, probabilities of having different diseases are the output.

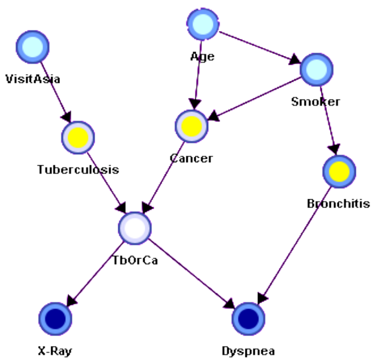


Illustration 28 - BN used as a medical diagnosis tool (Bayesia, 2009)

Bayesian theory has also gained ground in the science of artificial intelligence due to the dynamic use of posterior results, which could mean the ability to learn and improve.

The BN is a directed acyclic graph with nodes connected to each other by edges. The nodes are commonly assigned with discrete random variables (though continuous variables could also be used according to (Marquez, et al., 2007)) with conditional dependence between parent and child nodes. Marginal prior probabilities are assigned to nodes without parents, called root nodes. The quantitative analysis can go forward as predictive analysis by using prior probabilities of root nodes and the onwards conditional dependencies and go backwards as a diagnostic analysis by using posterior probabilities based on given evidence. (Bobbio, et al., 2001)

The feature of local conditional dependency is specified by defining a Conditional Probability Table (CPT) for each node. The CPTs will be adjusted to suit the AND-gates and the OR-gates.

An explanation of how Baye's Rule is constructed follows below;

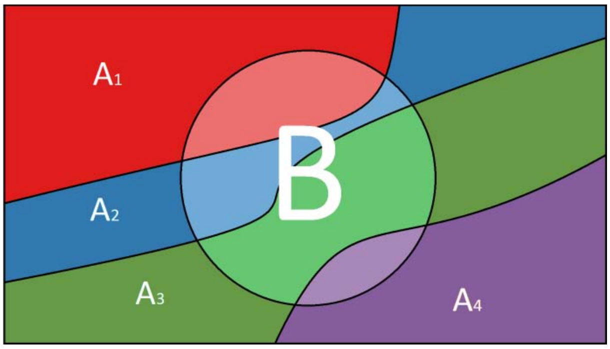


Illustration 29 - Space S

The square above is a space S, divided into a number of subsets; events A_i which are mutually exclusive, any A does cannot occur at the same time as another A. B is a subset in S which also is divided by A_i, A_i can be seen as factors that can produce an outcome B. So, $B \subset S$, where $S = \cup_{i=1}^{n} A_i$ and $B = \cup_{i=1}^{n} (B \cap A_i)$, $i = 1,...,n$. It follows that the probability of B is a construct of the parts of B in A_1-A_4, the common parts;

$$P(B) = P(\cup_{i=1}^{n} \{B \cap A_i\}) = \sum_{i=1}^{N} P(B \cap A_i)$$

The multiplication rule states that;

$$P(B \cap A_i) = P(A_i) \cdot P(B \mid A_i)$$

The above formula can also be expressed as $P(B \cap A_i) = P(B) \cdot P(A_i \mid B)$. By combining the above, the probability of event A happening given event B already has happened is; (Panik, 2005)

$$P(A_i \mid B) = \frac{P(B \cap A_i)}{P(B)} = \frac{P(B \cap A_i)}{\sum_{i=1}^{N} P(B \cap A_i)} = \frac{P(A_i) \cdot P(B \mid A_i)}{\sum_{i=1}^{N} P(A_i) \cdot P(B \mid A_i)}$$

Now that the fundament of the BN has been established, the conversion process from FTA to BN can be studied. (Bobbio, et al., 2001) presented an algorithm which can be used for converting the FTA to a BN (making the BN binary), the algorithm is quoted below;

- for each *leaf node* (i.e. primary event or system component) of the FTA, create a *root node* in the BN; however, if more leaves of the FTA represent the same primary event (i.e. the same component), create just one root node in the BN;
- assign to root nodes in the BN the prior probability of the corresponding leaf node in the FTA (computed at a given mission time *t*);
- for each *gate* of the FTA, create a corresponding *node* in the BN;
- label the node corresponding to the gate whose output is the TE of the FTA as the *Fault* node in the BN;
- connect nodes in the BN as corresponding gates are connected in the FT;
- for each gate (OR, AND or *k*:*n*) in the FT assign the equivalent CPT to the corresponding node in the BN.

The algorithm has been exemplified for AND-gates and OR-gate below;

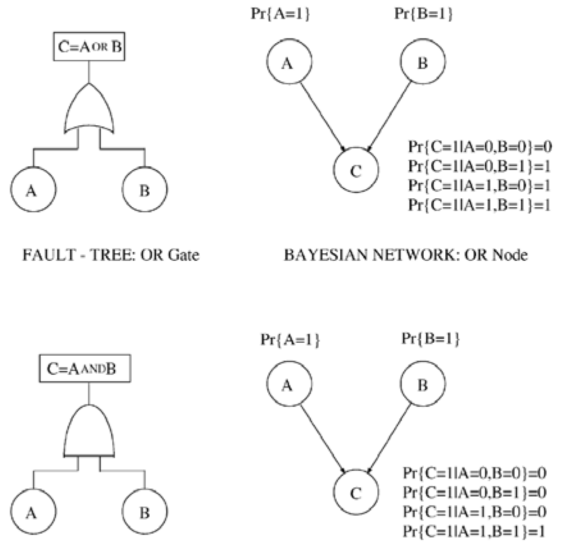


Illustration 30 - Conversion of AND-gates and OR-gates (Bobbio, et al., 2001)

As it can be seen in Illustration 30, the conversion is quite simple. The OR-gate is modeled by setting the probability of C being faulty to 1 if either or both A and B are faulty. The AND-gate is only faulty if both A and B are faulty.

I have chosen to only make a model of one of the fault trees of the previous chapter. By showing how it is structured and how probability turns out the same as the fault tree, I have thereby shown that the model could be extended to include all components of the ballast system correctly and could replace the fault tree.

The Bayesian network software GeNIe was used to create and calculate the probability of "sensing", the fault tree can be found in Diagram 18.

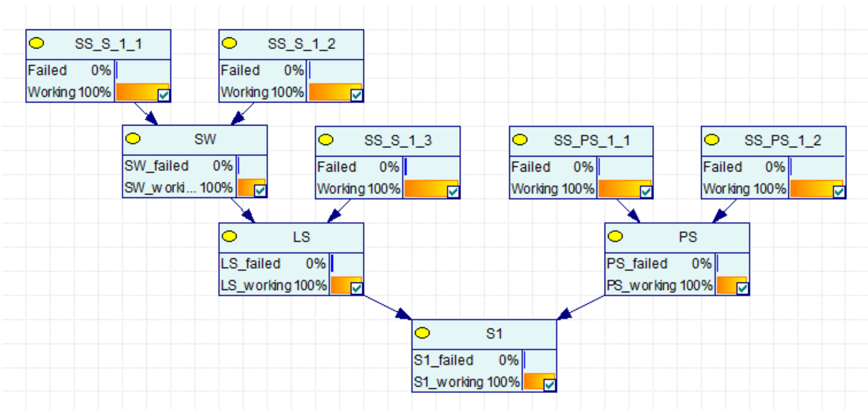


Illustration 31 - Screenshot of sensing in one tank in GeNIe

Node input and values can be found in Appendix I – Bayesian Network.

The analysis yielded that the probability of "sensing" failing is $1{,}918 \cdot 10^{-8}$, which equals the result found in the fault tree analysis.

5.8.3 Evaluation of FTA and BN

The Bayesian network proved that it could replace the fault tree in this analysis. In my analysis I only studied conversion of AND-gates and OR-gates. (Bobbio, et al., 2001) also presents solutions for conversion of k:n-gates, gates with common cause failures and discusses a few more gate types.

In my view the Bayesian network generally offers more flexibility compared to the fault tree, though it should be mentioned that there are extensions of the fault tree which allows more complex gates. Still the fault tree may be considered more rigid with less modeling options. There are especially three features I see giving the BN an advantage;

- Implementing complex dependencies is far easier than in FTA.
- Continuous random variables can be used not only discrete random variables (Marquez, et al., 2007). This way a failure degrading a system's functionality could also be included for a more realistic analysis.
- The BN analysis may be predictive by using prior probabilities, but may also be diagnostic by calculating posterior probabilities based on inputted evidence.

5.9 Step Five – Design

The last design step of RBD is to evaluate the system performance. This design process has a status as preliminary and the system has therefore not been fully assessed; among other aspects maintenance and costs have not been fully analyzed. Costs and maintenance have however been considered as I have tried to minimize the system but at the same time achieving a good reliability.

The ballast system will be able to handle the operation profile of WindFlip with the layout I have proposed. Provided that there are no failures, rotation could happen in about 6 hours. The design has included safety margins along the way.

There is especially one area where the design could be improved and that is the monitoring system. An alternative solution could be to also use the pressure sensors to measure ballast level, then one sensor in each tank could be dropped while reliability would not decrease much and cost is decreased.

If reliability during rotation needs to be improved further I see two main solutions. The first one is to have a redundant flood valve in each tank, a second solution is to extend the ballast line of the secondary ballast system going to the 27 ballast tanks.

5.10 Step Five – Risk Assessment

In this chapter the design should have been evaluated in relation to the risk acceptance criteria and possible risk control measures should be proposed. As mentioned earlier, risk will not be quantified here. In a full RBD process for the ballast system of WindFlip risk has been proposed to be evaluated in terms of costs, as probability of loss of life is expected to be low.

Instead of evaluating quantitatively, the ballast system will be addressed in terms of the qualitative requirements set in chapter 5.2.

- The first goal was to minimize the unreliability to a reasonable level. The results of the FTA yielded a probability of failure in the ballast system during rotation to be 34 % per year. This result seems fair as it indicates that such a failure could occur once every third year. The probability of a failure during any operational phase is 1,37 % in one cycle. It could also be mentioned that the probabilities may be even lower as there are some conservative assumptions in the analysis and good maintenance routines could lower unreliability further.
- The next goal was to have effective system monitoring. The monitoring system proposed is the subsystem with the highest reliability in my analysis. The system will work as guidance during operation, but could also be diagnostic as it will register the effects of each action and therefore distinguish if there is a threat to operability. The system can also be used to identify the faulty unit if this is not picked up by integrated monitoring in valves, etc.
- The barge should also be controllable if a failure occurs during the rotational phase. The ballast system has two main pipelines which both can be used as ventilation and supply compressed air. There is also an interconnection between the pipelines which increases flexibility of rotating back to horizontal further. The only issue I see that could be a problem is that if a flood valve has failed in closed position it would be impossible to empty it if it is not connected to the secondary ballast system. This problem is however avoided by sizing the ballast tanks so that one full ballast tank would not be critical when rotating back to horizontal.

6 Further Work

Designing a complete system is an extensive task as many different aspects should be considered. The thesis is just meant as a preliminary study. Further work will essentially include looking at alternative design solutions and quantifying risk further;

Quantifying risk further will first and foremost means that a risk criterion should be studied and defined. Then the fault tree analysis should be elaborated further into accident scenarios and severity should be established. With both probability and severity quantified, the actual risk is found and can be compared to the risk criterion.

Next the components of the ballast system should be specified further. This also applies to the pipe specifications, a trade-off study considering pipe diameter in relation to costs would be useful. Cost estimates related to purchase and operation of the system should also be included. Further study of measures against corrosion is also important. Maintenance should be considered by studying the effect of using different component types and different configurations. The alternative solutions for the ballast system should be compared with each other in terms of cost, maintenance and risk.

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Appendix A – Thesis outline

NTNU
Det skapende universitet

Master Thesis in Marine Systems Design

Spring 2010

Atle Alvheim

"Analysis of the ballast system of WindFlip"

Background

WindFlip is a concept for handling transportation and installation of floating wind turbines. The design carries one wind turbine resting horizontally on deck during transit. During the installation phase the vessel rotates by ballast until both vessel and wind turbine reaches vertical position. Next step is to release the turbines from WindFlip and anchor them to the seabed.

The ballast system enables WindFlip to rotate and is therefore a very important part of the design. However, until now the system has only been described on a superior level. In the project thesis of Atle Alvheim a stability analysis was carried out in order to specify the ballast systems operation (meaning specifying size and position of ballast tanks and filling sequence). A Bayesian network model was also made for learning the dynamics of the methodology.

In February 2010 an extensive model test of WindFlip will be performed in the towing tank of Marintek. The test will cover transit mode, the flip operation, and the release operation. The flip operation, or rotational phase, might give new input on how the ballast system should work and what might cause errors.

Overall Aim and Focus

The main aim of the master thesis is to assess the ballast system in terms of safety and efficiency by the use of the Risk-Based Design methodology. An analysis securing the development of a system meeting all requirements for safe and efficient design and operation is the objective of the thesis.

Scope and Main Activities

1. *Gather requirements, information and experience concerning ballast systems in the industry.*

2. *Describe WindFlip's operation and the ballast system's requirements for fulfilling the operation.*

3. *Make a detailed overview of components available for the ballast system and construct a possible system design for the ballast system onboard WindFlip.*

4. *Develop a basis for a risk and reliability analysis on component and system level to assess improvement potential from a safety risk point of view. Failure probabilities from existing data have to be found.*

5. *Use the structure of the system and failure probabilities to create two models, a FTA model and a Bayesian Network model. Describe the two methods.*

6. *Compare the results from each model and elaborate on the comparative performance of the models (pros and cons, possible improvements of the models etc.).*

7. *Assess design improvements in the ballast system design and do a cost-benefit analysis on the alternatives.*

8. *Present a fully functional ballast system that meets the requirements for efficiency and safety.*

Modus Operandi

At NTNU, Professor Bjørn Egil Asbjørnslett will be the responsible advisor and Professor Svein Kristiansen co-supervisor.

The work shall follow the guidelines given by NTNU for the MSc Thesis work. The final delivery may either follow the format of a report or a scientific paper.

The candidate will collaborate with WindFlip AS during the project. The paper restricted according to NTNU's standard agreement concerning intellectual property rights, the extended agreement of ownership and the extended economic agreement. The agreements secures that the thesis will be treated confidentially by NTNU.

Bjørn Egil Asbjørnslett
Professor/Responsible Advisor

Appendix B – Tank numbering

Z=3	X=1	X=2	X=3	X=4	X=5	X=6	X=7	X=8	X=9	X=10	X=11
Y=4					5.4.3	6.4.3	7.4.3	8.4.3	9.4.3	10.4.3	
Y=3							7.3.3	8.3.3	9.3.3	10.3.3	11.3.3
Y=2							7.2.3	8.2.3	9.2.3	10.2.3	11.2.3
Y=1					5.1.3	6.1.3	7.1.3	8.1.3	9.1.3	10.1.3	

Z=2	X=1	X=2	X=3	X=4	X=5	X=6	X=7	X=8	X=9	X=10	X=11
Y=4	1.4.2	2.4.2	3.4.2	4.4.2	5.4.2	6.4.2	7.4.2	8.4.2	9.4.2		
Y=3	1.3.2	2.3.2	3.3.2	4.3.2	5.3.2	6.3.2	7.3.2	8.3.2	9.3.2	10.3.2	11.3.2
Y=2	1.2.2	2.2.2	3.2.2	4.2.2	5.2.2	6.2.2	7.2.2	8.2.2	9.2.2	10.2.2	11.2.2
Y=1	1.1.2	2.1.2	3.1.2	4.1.2	5.1.2	6.1.2	7.1.2	8.1.2	9.1.2		

Z=1	X=1	X=2	X=3	X=4	X=5	X=6	X=7	X=8	X=9	X=10	X=11
Y=4	1.4.1	2.4.1	3.4.1	4.4.1	5.4.1	6.4.1	7.4.1	8.4.1			
Y=3	1.3.1	2.3.1	3.3.1	4.3.1	5.3.1	6.3.1	7.3.1	8.3.1	9.3.1	10.3.1	11.3.1
Y=2	1.2.1	2.2.1	3.2.1	4.2.1	5.2.1	6.2.1	7.2.1	8.2.1	9.2.1	10.2.1	11.2.1
Y=1	1.1.1	2.1.1	3.1.1	4.1.1	5.1.1	6.1.1	7.1.1	8.1.1			

	X=1	X=2
Finn tanks	1	2

Number of tanks	102

Appendix C - Component belonging and naming

Main ballast system		Secondary ballast system		Eductor system		Sensor system	
Tank 1 units		***Tank 1 units***		***Tank 1 units***		***Tank 1 units***	
Butterfly Valve - Pressure Line	MB.BV.1.1	Butterfly Valve	SB.BV.1.1			Switch (Lower)	SS.S.1.1
Reducing Valve - Pressure Line	MB.RV.1.1					Switch (Upper)	SS.S.1.2
Butterfly Valve - Vent. Line	MB.BV.1.2					Capacitive sensor	SS.S.1.3
Reducing Valve - Vent. Line	MB.RV.1.2					Pressure Sensor 1	SS.PS.1.1
Flood Valve (Gate)	MB.G.1.1					Pressure Sensor 2	SS.PS.1.2
Relief Valve	MB.R.1.1						
Top level units		***Top level units***		***Top level units***		***Top level units***	
Butterfly Valve - Pressure Line	MB.BV.1	Butterfly Valve 1	SB.BV.1	Butterfly Valve 1	ES.BV.1	Logic Control Unit 1	SS.C.1
Reducing Valve - Pressure Line	MB.RV.1	Butterfly Valve 2	SB.BV.2	Butterfly Valve 2	ES.BV.2	Logic Control Unit 2	SS.C.2
Ventilation inlet (Gate)	MB.G.1	Butterfly Valve 3	SB.BV.3	Butterfly Valve 3	ES.BV.3		
Butterfly Valve - Vent. Line	MB.BV.2	Butterfly Valve 4	SB.BV.4	Eductor	ES.E.1		
Reducing Valve - Vent. Line	MB.RV.2	Butterfly Valve 5	SB.BV.5				
Compressed Air Inlet (Gate)	MB.G.2	Ballast Discharge Valve (Gate)	SB.G.1				
Gate Valve	MB.G.3	Port Connection (Gate)	SB.G.2				
		Filter	SB.F.1				
		Electric Motor	SB.EM.1				
		Centrifugal Pump	SB.P.1				
		Stop Check Valve	SB.SCV.1				

Appendix D – Unit failure rates

Taxonomy number	Unit	Operational time [10^6h]
2.2.2	Electric equipment	2,0165
Page 281	Electric motor	
	For pump	

Failure Mode	Failure mode abbr.	Mean Failure rate [per 10^6h]
Critical		**15,70**
Breakdown	BRD	3,24
Fail to start on demand	FTS	5,10
Noise	NOI	0,56
Overheating	OHE	0,45
Spurious stop	UST	3,48
Structural deficiency	STD	2,64
Vibration	VIB	1,03
Degraded		**11,65**
External leakage - Utility medium	ELU	0,45
Fail to start on demand	FTS	1,48
Fail to stop on demand	STP	1,48
Parameter deviation	PDE	4,35
Structural deficiency	STD	3,02
Vibration	VIB	1,22
Other	OTH	3,10
Incipient		**6,88**
Abnormal instrument reading	AIR	4,80
Minor in-service problems	SER	1,78
Other	OTH	0,90
All modes		**35,42**

Taxonomy number	Unit	Operational time [10^6h]
4.5.5	Valves	4,1853
Page 719	Valvese described by taxonomy code	
	Gate	

Failure Mode	Failure mode abbr.	Mean Failure rate [per 10^6h]
Critical		**4,63**
Delayed operation	DOP	0,28
External leakage - Process medium	ELP	0,36
Fail to open on demand	FTO	2,05
Fail to close on demand	FTC	0,36
Spurious operation	SPO	0,29
Structural deficiency	STD	0,70
Vave leakage in closed position	LCP	0,23
Other	OTH	0,31
Degraded		**5,07**
Abnormal instrument reading	AIR	0,41
Delayed operation	DOP	0,79
External leakage - Process medium	ELP	1,37
External leakage - Utility medium	ELU	1,40
Minor in-service problems	SER	0,31
Other	OTH	0,31
Structural deficiency	STD	0,22
Vave leakage in closed position	LCP	0,52
Incipient		**4,02**
Abnormal instrument reading	AIR	2,08
Delayed operation	DOP	0,51
Minor in-service problems	SER	0,52
Other	OTH	0,79
All modes		**15,75**

Taxonomy number	Unit	Operational time [10^6h]
4.2.2	Control and Safety Equipment	0,561
Page 463	Process Sensors	
	Level	

Failure Mode	Failure mode abbr.	Mean Failure rate [per 10^6h]
Critical		**16,32**
Abnormal output - Low	AOL	1,78
Fail to function on demand	FTF	1,78
Spurious operation	SPO	3,56
Degraded		**1,78**
Other	OTH	1,78
Incipient		**1,78**
Minor in-service problems	SER	1,78
All modes		10,69

Taxonomy number	Unit	Operational time [10^6h]
4.5.2	Valves	0,7352
Page 681	Valves described by taxonomy code	
	Butterfly	

Failure Mode	Failure mode abbr.	Mean Failure rate [per 10^6h]
Critical		**1,92**
Fail to regulate	FTR	1,92
Degraded		**11,09**
Delayed operation	DOP	1,33
External leakage - Utility medium	ELU	3,26
Minor in-service problems	SER	3,73
Vave leakage in closed position	LCP	3,73
Incipient		**1,22**
Internal leakage	INL	1,22
All modes		**16,23**

Taxonomy number	Unit		Operational time [10^6h]
4.2.3	Control and Safety Equipment		1,122
Page 553	Process Sensors		
	Pressure		
Failure Mode		**Failure mode abbr.**	**Mean Failure rate [per 10^6h]**
All modes			0,42

Taxonomy number	Unit		Operational time [10^6h]
3.2.9	Mechanical Equipment		0,0471
Page 388	Vessels		
	Stripper		
Failure Mode		**Failure mode abbr.**	**Mean Failure rate [per 10^6h]**
All modes			10,20

Taxonomy number	Unit		Operational time [10^6h]
4.5.3	Valves		3,2212
Page 689	Valves described by taxonomy code		
	Check		
Failure Mode		**Failure mode abbr.**	**Mean Failure rate [per 10^6h]**
Degraded			**1,73**
External leakage - Utility medium		ELU	1,73
All modes			1,73

Taxonomy number	Unit		Operational time [10^6h]
4.3.3	Control Logic Units		0,0701
Page 487	Process control		
Failure Mode		**Failure mode abbr.**	**Mean Failure rate [per 10^6h]**
All modes			5,54

Taxonomy number	Unit		Operational time [10^6h]
4.4.13	Valves		3,0262
Page 607	Valves described by application		
	Relief		
Failure Mode		**Failure mode abbr.**	**Mean Failure rate [per 10^6h]**
Critical			**1,03**
Fail to open on demand		FTO	0,98
Fail to close on demand		FTC	0,57
Degraded			**5,90**
Delayed operation		DOP	4,64
External leakage - Utility medium		ELU	0,98
Other		OTH	0,29
Incipient			**3,23**
Low Output		LOO	0,81
Minor in-service problems		SER	1,00
Structural deficiency		STD	0,83
Other		OTH	1,24
All modes			**10,37**

Taxonomy number	Unit		Operational time [10^6h]
4.4.9	Valves		0,4734
Page 567	Valves described by application		
	Pressure Reduction		
Failure Mode		**Failure mode abbr.**	**Mean Failure rate [per 10^6h]**
Degraded			**4,22**
High output		HIO	2,11
Other		OTH	2,11
Incipient			**2,11**
Minor in-service problems		SPO	2,11
All modes			6,34

Taxonomy number	Unit		Operational time [10^6h]
1.3.1	Machinery		2,129
Page 146	Pumps		
	Centrifugal		
Failure Mode		**Failure mode abbr.**	**Mean Failure rate [per 10^6h]**
Critical			**86,51**
Abnormal instrument reading		AIR	0,58
Breakdown		BRD	4,65
Erratic output		ERO	0,66
External leakage - Process medium		ELP	8,89
External leakage - Utility medium		ELU	8,86
Fail to start on demand		FTS	7,86
High output		HIO	6,11
Internal leakage		INL	0,91
Low Output		LOO	2,25
Noise		NOI	1,28
Overheating		OHE	0,92
Parameter deviation		PDE	2,45
Spurious stop		UST	16,75
Structural deficiency		STD	4,87
Vibration		VIB	73,17
Other		OTH	0,58
Degraded			**114,16**
Abnormal instrument reading		AIR	1,33
Erratic output		ERO	12,04
External leakage - Process medium		ELP	3,79
External leakage - Utility medium		ELU	41,92
Internal leakage		INL	8,43
Low Output		LOO	78,83
Minor in-service problems		SER	0,71
Noise		NOI	0,45
Parameter deviation		PDE	0,47
Structural deficiency		STD	3,65
Vibration		VIB	15,05
Other		OTH	8,52
Incipient			**759,71**
Abnormal instrument reading		AIR	304,28
External leakage - Process medium		ELP	6,68
External leakage - Utility medium		ELU	7,20
Internal leakage		INL	2,22
Low Output		LOO	0,42
Minor in-service problems		SER	285,79
Noise		NOI	1,72
Parameter deviation		PDE	4,85
Structural deficiency		STD	1,43
Vibration		VIB	0,45
Other		OTH	19,03
All modes			**1021,22**

Appendix E – Relevant units and failure rates per operational phase

Secondary ballast system - ballasting		Secondary ballast system - deballasting		Main ballast system - ballasting		Main ballast system - ballasting		Eductor system - stripping	
Operation time [h]	34,5	Operation time [h]	35	Operation time [h]	6	Operation time [h]	6	Operation time [h]	1
Active Units	λ - critical [failures/10^6h]	Active Units	λ - critical [failures/10^6h]	Active Units	λ - critical [failures/10^6h]	Active Units	λ - critical [failures/10^6h]	Active Units	λ - critical [failures/10^6h]
SB.BV.1.1	1,92	SB.BV.1.1	1,92	MB.BV.1.1	1,92	MB.BV.1.1	1,92	SB.BV.1.1	1,92
SB.BV.1	1,92	SB.BV.1	1,92	MB.RV.1.1**	6,34	MB.RV.1.1**	6,34	SB.BV.1	1,92
SB.BV.2	1,92	SB.BV.2	1,92	MB.BV.1.2	1,92	MB.BV.1.2	1,92	SB.BV.2	1,92
SB.BV.3	1,92	SB.BV.3	1,92	MB.RV.1.2**	6,34	MB.RV.1.2**	6,34	SB.BV.3	1,92
SB.BV.4	1,92	SB.BV.4	1,92	MB.G.1.1	4,63	MB.G.1.1	4,63	SB.BV.4	1,92
SB.BV.5	1,92	SB.BV.5	1,92	MB.R.1.1	1,03	MB.R.1.1	1,03	SB.BV.5	1,92
SB.G.1	4,63	SB.G.1	4,63	MB.BV.1	1,92	MB.BV.1	1,92	SB.G.1	4,63
SB.F.1*	1,00	SB.F.1*	1,00	MB.RV.1**	6,34	MB.RV.1**	6,34	SB.F.1*	1,00
SB.EM.1	15,70	SB.EM.1	15,70	MB.G.1	4,63	MB.G.1	4,63	SB.EM.1	15,70
SB.P.1	86,51	SB.P.1	86,51	MB.BV.2	1,92	MB.BV.2	1,92	SB.P.1	86,51
SB.SCV.1**	1,73	SB.SCV.1**	1,73	MB.RV.2**	6,34	MB.RV.2**	6,34	SB.SCV.1**	1,73
ES.BV.1	1,92	ES.BV.1	1,92	MB.G.2	4,63	MB.G.2	4,63	ES.BV.1	1,92
ES.BV.2	1,92	ES.BV.2	1,92	MB.G.3	4,63	MB.G.3	4,63	ES.BV.2	1,92
ES.BV.3	1,92	ES.BV.3	1,92	SS.S.1.1	16,32	SS.S.1.1	16,32	ES.BV.3	1,92
SS.S.1.1	16,32	SS.S.1.1	16,32	SS.S.1.2	16,32	SS.S.1.2	16,32	ES.E.1	10,20
SS.S.1.2	16,32	SS.S.1.2	16,32	SS.S.1.3	16,32	SS.S.1.3	16,32	SS.S.1.1	16,32
SS.S.1.3	16,32	SS.S.1.3	16,32	SS.PS.1.1**	0,42	SS.PS.1.1**	0,42	SS.S.1.2	16,32
SS.PS.1.1**	0,42	SS.PS.1.1**	0,42	SS.PS.1.2**	0,42	SS.PS.1.2**	0,42	SS.S.1.3	16,32
SS.PS.1.2**	0,42	SS.PS.1.2**	0,42	SS.C.1**	5,54	SS.C.1**	5,54	SS.PS.1.1**	0,42
SS.C.1**	5,54	SS.C.1**	5,54	SS.C.2**	5,54	SS.C.2**	5,54	SS.PS.1.2**	0,42
SS.C.2**	5,54	SS.C.2**	5,54					SS.C.1**	5,54
								SS.C.2**	5,54

* - Reliability data lacking, λ assumed to be 1e-6 and 4e-6

** - No λ for critical failures in OREDA, all mode failure used instead

Appendix F – Fault tree probabilities

Fault tree for top event: FMB

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
FOP(102)	MB.G.1	4,63E-06	2,78E-05	1,17E-03
Mission time	MB.RV.1	6,34E-06	3,80E-05	1,60E-03
t_1 6	MB.RV.x.1	6,34E-06	3,80E-05	1,60E-03
t_2 252				
Prob(TE)			3,95E-03	1,66E-01

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
FOVE(102)	MB.G.2	4,63E-06	2,78E-05	1,17E-03
Mission time	MB.BV.1	1,92E-06	1,15E-05	4,84E-04
t_1 6	MB.BV.x.1	1,92E-06	1,15E-05	4,84E-04
t_2 252				
Prob(TE)			1,21E-03	5,10E-02

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
CO1/CO2	FOVE(102)		1,21E-03	5,10E-02
Mission time	FOP(102)		3,95E-03	1,66E-01
t_1 6				
t_2 252				
Prob(TE)			5,16E-03	2,17E-01

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
S(1)	SS.S.1.1	1,63E-05	9,79E-05	4,10E-03
Mission time	SS.S.1.2	1,63E-05	9,79E-05	4,10E-03
t_1 6	SS.S.1.3	1,63E-05	9,79E-05	4,10E-03
t_2 252	SS.PS.1.1	4,20E-07	2,52E-06	1,06E-04
	SS.PS.1.2	4,20E-07	2,52E-06	1,06E-04
Prob(TE)			1,92E-08	3,37E-05

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
SS(102)	S(1)		1,92E-08	3,37E-05
Mission time	SS.C.1	4,20E-07	2,52E-06	1,06E-04
t_1 6	SS.C.2	4,20E-07	2,52E-06	1,06E-04
t_2 252				
Prob(TE)			1,96E-06	3,44E-03

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
FMB(102)	SS(102)		1,96E-06	3,44E-03
Mission time	FV(1)	4,63E-06	2,78E-05	1,17E-03
t_1 6	C1		5,16E-03	2,17E-01
t_2 252	C2		5,16E-03	2,17E-01
Prob(TE)			0,0029	0,17

Fault tree for top event: FSB

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
WTT	SB.BV.1/4/x.1	1,92E-06	6,62E-05	2,78E-03
Mission time	SB.F.1	1,00E-06	3,45E-05	1,45E-03
t_1 34,5	SB.EM.1	1,57E-05	5,42E-04	2,25E-02
t_2 1449	SB.P.1	8,65E-05	2,98E-03	1,18E-01
	SB.SVC.1	1,73E-06	5,97E-05	2,50E-03
Prob(TE)			3,68E-03	1,47E-01

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
APC1	SB.BV.x	1,92E-06	6,62E-05	2,78E-03
Mission time	SB.G.2	4,63E-06	1,60E-04	6,69E-03
t_1 34,5	CO3		2,26E-04	9,46E-03
t_2 1449	CO4		2,26E-04	9,46E-03
	CO5		1,32E-04	5,56E-03
	CP3		8,77E-09	1,54E-05
Prob(TE)			6,62E-05	2,79E-03

Top Event	Cut sets	λ - critical [failures/h]	$F_C(t_1)$	$F_C(t_2)$
FVE(27)	MB.BV.1/2	1,92E-06	6,62E-05	2,78E-03

Mission time	MB.G.1/2/3	4,63E-06	1,60E-04	6,69E-03
t_1 34,5	CO7		2,01E-03	8,45E-02
t_2 1449	CO8		2,17E-03	9,12E-02
	CO9		2,01E-03	8,45E-02
	CO10		2,17E-03	9,12E-02
Prob(TE)			1,92E-11	5,93E-05

Top Event	**Cut sets**	**λ - critical [failures/h]**	**$F_C(t_1)$**	**$F_C(t_2)$**
S(1)	SS.S.1.1	1,63E-05	5,63E-04	2,34E-02
Mission time	SS.S.1.2	1,63E-05	5,63E-04	2,34E-02
t_1 34,5	SS.S.1.3	1,63E-05	5,63E-04	2,34E-02
t_2 1449	SS.PS.1.1	4,20E-07	1,449E-05	6,08E-04
	SS.PS.1.2	4,20E-07	1,449E-05	6,08E-04
Prob(TE)			6,34E-07	1,09E-03

Top Event	**Cut sets**	**λ - critical [failures/h]**	**$F_C(t_1)$**	**$F_C(t_2)$**
SS(27)	S(1)		6,34E-07	1,09E-03
Mission time	SS.C.1	4,20E-07	1,45E-05	2,08E-02
t_1 34,5	SS.C.2	4,20E-07	1,45E-05	2,08E-02
t_2 1449				
Prob(TE)			1,71E-05	2,99E-02

Top Event	**Cut sets**	**λ - critical [failures/h]**	**$F_C(t_1)$**	**$F_C(t_2)$**
FSB	WTT		3,68E-03	1,47E-01
Mission time	APC1		6,62E-05	2,79E-03
t_1 34,5	FVE(27)		1,92E-11	5,93E-05
t_2 1449	SS(27)		1,71E-05	2,99E-02
Prob(TE)			3,77E-03	1,80E-01

Fault tree for top event: FSDB

Top Event	**Cut sets**	**λ - critical [failures/h]**	**$F_C(t_1)$**	**$F_C(t_2)$**
WFT	SB.BV.3/5/x.1	1,92E-06	6,62E-05	2,78E-03
Mission time	SB.F.1	1,00E-06	3,45E-05	1,45E-03
t_1 34,5	SB.EM.1	1,57E-05	5,42E-04	2,25E-02
t_2 1449	SB.P.1	8,65E-05	2,98E-03	1,18E-01
	SB.SVC.1	1,73E-06	5,97E-05	2,50E-03
	SB.G.2	4,63E-06	1,60E-04	6,69E-03
Prob(TE)			3,84E-03	1,54E-01

Top Event	**Cut sets**	**λ - critical [failures/h]**	**$F_C(t_1)$**	**$F_C(t_2)$**
APC1	SB.BV.x	1,92E-06	6,62E-05	2,78E-03
Mission time	CO11		1,32E-04	5,56E-03
t_1 34,5	CP4		8,77E-09	1,54E-05
t_2 1449				
Prob(TE)			1,99E-04	8,35E-03

Top Event	**Cut sets**	**λ - critical [failures/h]**	**$F_C(t_1)$**	**$F_C(t_2)$**
FSDB	WFT		3,84E-03	1,54E-01
Mission time	APC2		1,99E-04	8,35E-03
t_1 34,5	FVE(27)		1,92E-11	5,93E-05
t_2 1449	SS(27)		1,71E-05	2,99E-02
Prob(TE)			4,06E-03	1,92E-01

Fault tree for top event: FSTR

Top Event	**Cut sets**	**λ - critical [failures/h]**	**$F_C(t_1)$**	**$F_C(t_2)$**
FSTR	SB/ES.BV.x.1/x	1,92E-06	1,92E-06	8,06E-05
Mission time	ES.E	1,02E-05	1,02E-05	4,28E-04
t_1 1	SB.F.1	1,00E-06	1,00E-06	4,20E-05
t_2 42	SB.EM.1	1,57E-05	1,57E-05	6,59E-04
	SB.P.1	8,65E-05	8,65E-05	3,63E-03
	SB.SVC.1	1,73E-06	1,73E-06	7,27E-05
	SB.G.2	4,63E-06	4,63E-06	1,94E-04
Prob(TE)			1,87E-04	7,85E-03

Appendix G – FMEA worksheet of components

Description of unit			Description of failure			Effect of Failure		Risk reducing measures	Comments
Ref. no	Unit/Function	Operational mode	Failure mode	Failure cause or mechanism	Failed subunit	On the subsystem	On the system function		
1	Electric Motor	Ballasting for transit and onloading of payload, stripping of ballast tanks	Failure to start on demand	Electric failure	Wiring, unknown	Centrifugal pump disabled	Fluid flow stopped	Maintenance and condition monitoring	
		"	Spurious stop	Mechanical failure, control failure, vibration	Stator, unknown	"	"	"	
		"	Breakdown	Breakage	Subunit, unknown	"	"	"	
2	Centrifugal Pump	Ballasting for transit and onloading of payload, stripping of ballast tanks	External leakage - Process medium	Mechanical failure	Seals, piping	Leaking fluid can expose surrounding equipment to corrosion and damage electrical equipment	Degraded flow rate of fluid	Condition monitoring and routine inspections.	
		"	External leakage - Utility medium	Mechanical failure	Seals, piping	"	"	Condition monitoring and routine inspections.	
		"	Fail to start on demand	Instrument failure, earth/isolation fault, unknown	Instruments, unknown	Not able to perform ballast procedure	Fluid flow not initiated	Condition monitoring and routine inspections. Redundancy, extra pump for stripping of ballast tanks. Improve isolation	
		"	High output	Material failure, instrument failure	Unkown	Could strain valves due to high flow rate, quicker filling/emptying of ballast tank	Less control of process	Condition monitoring and routine inspections.	
3	Gate Valve	Relevant for all operational modes	Fail to open on demand	Blockage, instrument failure, mechanical failure	Subunit, unknown	-	No flow through	Corrosion protection, visual inspection	
		"	Fail to close on demand	Blockage, mechanical failure	Pilot valve, valve body w/internals	-	Unable to shut off flow	"	
		"	Structural deficiency	Instrument failure, material failure, misc. External influences	Pilot valve, valve body w/internals, cabling and junction boxes	-	Degraded/unstable function	"	
4	Pressure Relief Valve	Ballasting between zero and 85 degree of trim	Fail to open on demand	Corrosion, unknown	Unknown	Build up of pressure in tank	Unable to relieve of pressure	Visual inspection. Redundant valve. Monitoring of condition to stop process if a pressure build-up occurs.	The unit is designed to relieve pressure with control, if the unit is disabled relief will occur when the unit is breached. Strength should be lower than, ballast tank.
		"	Fail to close on demand	Unknown (fatigue?)	Spring	Loss of pressure in tank	During ballasting increased pressure is needed inside ballast tank due to increasing outside pressure	"	
5	Pressure Reduction Valve	Ballasting between zero and 85 degree of trim	High output	Instrument failure	Valve body w/internals	Output at wrong pressure compared to needed in ballast tank	Degraded control of ballast tank filling	Corrosion protection, visual inspection	
		"	Other	Erosion	Closure member	-	-	"	
6	Butterfly valve	Relevant for all operational modes	Fail to regulate	Blockage/plugged	Valve body w/internals	-	Unable to control flow rate	"	
7	Stop Check Valve	Ballasting for transit and onloading of payload, stripping of ballast tanks	External leakage - Utility medium	Material failure	Unknown	Leaking fluid can expose surrounding equipment to corrosion and damage electrical equipment	Reduced flow	"	
8	Switch Sensor	Relevant for all operational modes	Abnormal output - Low	Out of adjustment	Sensing element	Monitored ballast tank level not correct	Degraded control of ballasting	Redundant unit to increase accuracy	
		"	Fail to function on demand	Blockage	Sensing element	No information of ballast level	No control of ballasting	Redundant unit to do measurments instead	
		"	Spurious operation	Blockage, no signal	Sensing element, other	Monitored ballast tank level not correct	Degraded control of ballasting	Redundant unit to increase accuracy	
9	Pressure Sensor*	Ballasting between zero and 85 degree of trim	Disfunctional	Corrosion, out of adjustment	Sensing element	Pressure in tank not measured	Pressure in tank not monitored, unable to regulate pressure according to sitation	Redundant unit to increase accuracy	
10	Control Unit*	Relevant for all operational modes	Disfunctional	Corrosion, electric failure	Wiring	Valves not controlled	Unable to control ballasting	Isolate, redundant	
11	Eductor*	Stripping of ballat tanks	Disfunctional	Blockage	-	-	Tanks not completely emptied		
		"	"	No fast fluid	Pump	-	"		

* - no provided data by OREDA, input in worksheet based on judgement

Appendix H – FMEA worksheet of systems

Description of unit			Description of failure			Effect of Failure		Risk reducing measures	Comments
Ref. no	System/Function	Operational mode	Failure mode	Failure cause or mechanism	Failed subunit	On the subsystem	On the system function		
12	Flooding	Ballasting to 85 degrees, may also be used during deballasting	Fail to flood on demand	Mechanical failure of flood valve, valve blocked	Flood valve, actuator, controller	Water not lead into ballast tank	Unable to follow ballasting schedule, may result in abort of ballasting	Corrosion protection, visual inspection	
		"	Fail to stop flooding on demand	Mechanical failure of flood valve, valve blocked	"	Unable to block water outside of the tank	Unable to follow deballasting schedule, may result in delay of deballasting	"	
		"	Wrongfully flooding or not flooding	Instrument failure	Dysfunctional controller, actuator failure on valve	Unexpected ballasting or deballasting	Lost control of ballasting of specific tank	"	
13	Purging of ballast tanks	Ballasting between zero and 85 degree of trim	Fail to let in compressed air	Pressure thresholdof valve to high, valve locked in closed position	Pressure reducing valve, actuator, controller	Unable to adjust pressure in tank	Unable to follow ballasting schedule	Redundant valve, corrosion protection, visual inspection	
		"	Compressed air let in at wrong pressure	Wrong pressure threshold of valve, wrong information provided by sensors	"	Wrongly adjusting pressure in tank	Lost control of ballasting of specific tank	"	Valve could still be closed down
		"	Fail to stop letting air in	Instrument failure, mechanical failure	"	Unable to adjust pressure in tank	Unable to follow ballasting schedule	Could have a redundant line which could be closed down	
14	Ventilation	All operational phases, less necessary for stripping	Fail to ventilate	Instrument failure, mechanical failure	Butterfly valve, actuator, controller	Pressure could build up in tank if not sensors pick up the issue and process is stopped	Unable to control state of ballast tank, operation should be aborted	Redundant valve, corrosion protection, visual inspection	
		"	Fail to stop ventilating	"	"	Loss of desired pressure, fail to shut off water in ballast tank	"	Could have a redundant line which could be closed down	
		"	Wrongful ventilation	Dysfunctional actuator, controler, wrongful information provided by sensors	"	Unable to control pressure in tank	Could perform wrong actions due to being mislead, this should however be picked up by the monitoring system	Redundant valve, corrosion protection, visual inspection	Valve could still be closed down
14	Monitoring	All operational phases, less necessary for stripping	No signals recieved	Sensor damaged, cabling damaged, corrsoion, wear and tear	Sensor, cabling	State of ballast tank unknown	Cannot perform operation as proceding would be to proceed blindfolded	Redundant sensor with separate circut	
		"	Wrong information recieved	Sensor damaged	Sensor	"	Could perform wrong actions due to being mislead	Redundant sensor	Redundancy will also improve precision during normal operation
15	Eductor system	Stripping of ballast tanks	No water stripped	Blockage	Eductor	Still water in ballast tank	No possible to completely empty ballast tank	Corrosion protection, visual inspection	
		"	"	Blocked valve, fluid path not according to plan	Valves connected to paths	"	"	"	

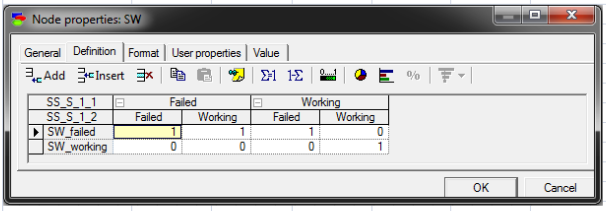
Appendix I – Bayesian Network

Sensing

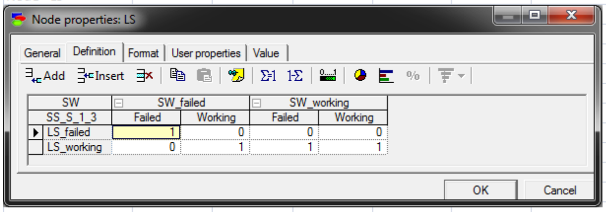
Time t 6 h

Unit		λ - critical [failures/h]	F(t)
Switch (Lower)	SS.S.1.1	1,63E-05	9,79152E-05
Switch (Upper)	SS.S.1.2	1,63E-05	9,79152E-05
Capacitive sensor	SS.S.1.3	1,63E-05	9,79152E-05
Pressure Sensor 1	SS.PS.1.1	4,20E-07	2,52000E-06
Pressure Sensor 2	SS.PS.1.2	4,20E-07	2,52000E-06

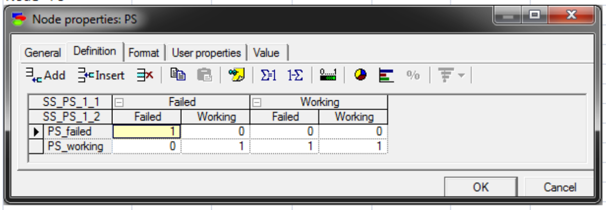
Node - SW



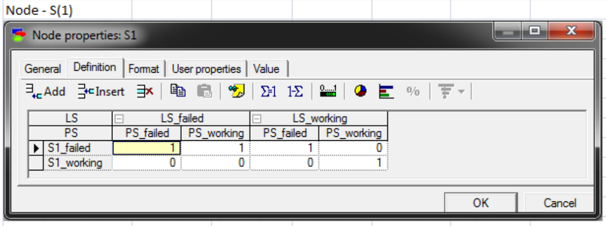
Node - LS

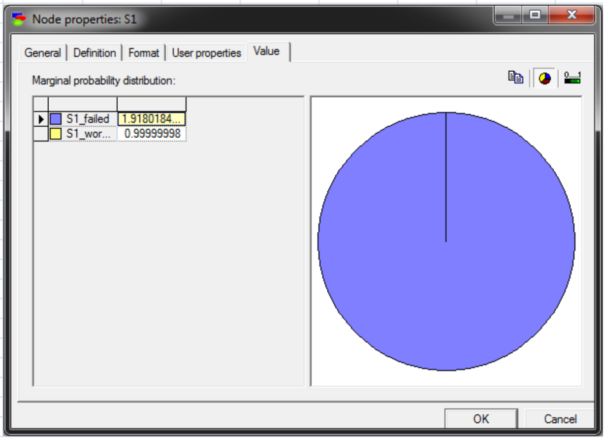


Node - PS



Node - S(1)





Node values	BN	FTA
SW failed	0,000195821	0,000195830
SW working	0,999804179	0,999804170
LS failed	0,000000019	0,000000019
LS working	0,999480170	0,999999981
PS failed	0,000000000	0,000000000
PS working	1,000000000	1,000000000
Sensing failed	0,000000019	0,000000019
Sensing working	0,999999981	0,999999981

Note that the input values were rounded off and is the reason for a small difference in the probabilities.