Autonomous sailing

Propulsion and maintenance

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Management review

The information in this report is about the upcoming topic autonomous sailing. In detail the subject propulsion and maintenance has been researched. The main question, “how can the technical department of an autonomous vessel be operated safely and efficiently” will be answered with the following sub question.

- What is the influence of autonomous sailing on machinery and equipment in the technical department?
- How is maintenance done in an autonomous vessel?

What is predictive maintenance?
How can predictive maintenance be applied on autonomous vessels?
What is preventive maintenance?
How can preventive maintenance be applied on autonomous vessels?
What is corrective maintenance?

How can corrective maintenance be applied on autonomous vessels?
- What are the requirements of energy supply for autonomous vessels?
- How can the engine room be made fail-safe?
- What are the requirements for a fail-safe backup system?

In the sub question, “what are the requirements of energy supply for autonomous vessels” is about the energy supply on board and how to make it different. So the engine room will become fail safer. The following systems will be examined: shaft generator, hybrid propulsion and low loss concept.

In the sub question, “how can the engine room be made fail-safe” will be examined how to make the engine room more fail-safe and redundant. There will also be looked at the pipeline systems, making the engine room inert and the standardization of the engine room.

In the sub question, “maintenance in an autonomous vessel” is explained how the maintenance on board of autonomous vessels will be carried out. There will be looked at predictive, preventive and corrective maintenance.

In the sub question, “what is the influence of autonomous sailing on machinery and equipment in the technical department” there will be looked at the change that autonomous sailing will bring and how this will influence the machinery.

Answering of the sub questions will bring the answer to the main question.
Preface

The upcoming topic of these days is unmanned shipping. Therefore the Rotterdam Mainport University of applied sciences (RMU) is doing research on this new topic. This will be done by several groups. Every group starts a research about different subjects concerning unmanned shipping. One of these groups is group five. Group five decided to take this topic because this is the most interesting in our line of study and the subject made everyone very curious. This research will be done by five persons under supervision. This research is for study purpose and is for everyone interested in the subject.

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Enjoy!
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Introduction

Autonomous sailing impossible?
The occasion of this report is the hot topic: autonomous shipping. This research is commissioned by the Rotterdam Main port University of applied sciences (RMU). The theme of the research is autonomous sailing, the topic of this research is propulsion and maintenance. This research is needed because this is a new item and no research has been done on this topic yet.

Problem description:
Nowadays about 80% of the accidents at sea are caused by the human factor. Many of those accidents on seagoing vessels can be prevented. Accidents like injuries, casualties, collisions, damage and grounding cause unnecessary problems. This is a problem not only for the vessel’s crew, but also for the shipping companies because their reputations will become impaired and financial losses will be experienced. Those accidents do not only have an influence on the shipping crew and shipping companies but also on the world economy. (Hugo Kidston, Tom Chamberlain, 2015)

To achieve the goal of autonomous sailing, some changes need to be made both on shore and on the vessels themselves. First aspects that will be encountered are black-out prevention in the technical department by the means of fail-safety and redundancy. Even when a black out occurs there needs to be an automatic backup system that can recover the vessel from its black out condition. Secondly the predictive-, preventive- and corrective maintenance for the technical department needs to be adjusted for autonomous sailing. However, all these aspects need to be executed within the current valid emission control regulations.

The technology has now reached a point where autonomous sailing can be achieved. Before this vision can be realized on board seagoing vessels, extensive research must be done on autonomous sailing.

Automation on board the seagoing vessels will be found on the entire vessel to sail autonomously. However not only the vessel will be autonomous, this also requires shore systems to be autonomous.

Above mentioned aspects can be possibly rectified by the use of sensors, cameras and robots for maintenance. For a reliable and fail safe technical department redundancy will be necessary. To meet the current valid emission control regulations fuel efficient engines will be examined.

Problem definition:
Operations in the technical departments on autonomous vessels can cause problems regarding safety and efficiency.

Main question:
How can the technical department of an autonomous vessel be operated safely and efficiently?
Sub-questions:
- What is the influence of autonomous sailing on machinery and equipment in the technical department?
- How is maintenance done in an autonomous vessel?
  - What is predictive maintenance?
  - How can predictive maintenance be applied on autonomous vessels?
  - What is preventive maintenance?
  - How can preventive maintenance be applied on autonomous vessels?
  - What is corrective maintenance?
  - How can corrective maintenance be applied on autonomous vessels?
- What are the requirements of energy supply for autonomous vessels?
- How can the technical department be made fail-safe?
- What are the requirements for a fail-safe backup system?

Project borders:
- Financial aspects.
- Detection bridge navigation.
- Interconnectivity.
- Laws, liability and legalization.
- Organization, structure and manning.
- Piracy and cybercrime.

Objective:
Safe and efficient autonomous sailing.

Research methods:
Desk research is collecting and analyzing of existing data. This data has already been researched by others and can appear as literature, previous researches, databases, papers, archives, pictures and etcetera. The desk research phase is a preparation for the field research phase.
Field research is the collecting analyzing and interpretation of new data. Field research therefore is all about personal findings about the subject as a researcher. Field research can be done by arranging interviews, handout surveys, observations and etcetera.

The chapters will follow the sequence of the sub-questions.
1 Requirements for energy supply on autonomous vessels

In this chapter the sub question: What are the requirements of energy supply for autonomous vessels will be answered. Electrical installations are present on all traditional vessels, this installation delivers power to pumps, navigation equipment, accommodation, air-condition and even to propulsion engines in a diesel electric configuration. Traditional merchant vessels have a man engine for the propulsion and for the electrical power they have several generators to provide the vessel whit electricity. This traditional configuration does not meet the specifications for an autonomous vessel. This because when something occurs with the main engine there is no back up and the vessel is out of control. When sailing with mechanical engineers onboard the problem can be solved by the engineers. But when sailing autonomous this is not possible so there needs to be an integrated back up system also called redundancy. To meet the requirements for an autonomous vessel there needs to be an electrical installation that is capable of providing electrical power in every circumstance.

The main requirements for the energy supply on an autonomous vessel are:
- High redundancy factor
- No harmonic distortion

1.1 Redundancy factor

Redundancy means that critical systems or components are duplicated with the intention to decrease the effects of a default in the system. In case of an event the backup systems take over.

1.2 Harmonic distortion

Harmonic distortion means that the sinus of the electrical phase is not a perfect sinus. This will affect the efficiency of the electrical systems and the lifetime of electrical components. A harmonic distortion can occur due to several events. In the event of a large demanded of electrical power, the power supply is reacting "slow" to the demanded electrical power. This means the perfect sinus will be affected. But when the engine reacts, this type of harmonic distortion will disappear. There is also a distortion caused by electrical components. This type of distortion needs to be filtered out. This can be done by the use of power electronics or electrical transformers.

Three electrical installations have the requirements to be used safely in an autonomous vessel. Firsts the shaft generator, Secondly hybrid propulsion (MAN, 2008), and lastly Low Loss Concept (LLC) (wartsila, 2015)

1.3 Shaft generator

On traditional merchant vessels the vessel is equipped with a shaft generator. This generator is providing the power on sea trails. As can be seen in figure 1 the shaft generator is supplying the vessel of electrical power. This configuration has proven to be an energy saving solution in the past. That is also why this set up is relatively in expensive. The down side of this configuration is when the power to the vessels propeller is fluctuating, this can occur when in heavy weather the propeller is above the water and then submerge again. This fluctuation of the propeller power is affecting the power
output of the generator. Fluctuations in the power can be captured by an auxiliary engine. Only the harmonic distortion cannot be filtered out. Harmonic distortion has a negative influence on the life time of electrical components, especially on sensors. When sailing autonomous sensors are a key part of the operations. Also in case of an event with the main engine there is no possibility to deliver power to the propeller by the shaft generator.

Figure 1 (WETech, 2013)

1.4 Hybrid propulsion
Hybrid propulsion with PTO/PTI as shown in figure 2 is a better configuration of the traditional shaft generator. In this setup the shaft generator can deliver power to the electrical system but it also can take power from the electrical system to power the propeller. In this hybrid propulsion system redundancy is significantly higher than in the traditional setup. Also by the use of Power management system (PMS) the fuel consumption reduced. The disadvantage of this configuration is that when the shaft generator is providing power to the electrical system there will be a harmonic distortion. If the shaft generator is only be used in the case of an event the harmonic distortion is not an issue. But when it is only there for the redundancy factor it will be an expansive investment.
1.5 Low Loss Concept (LLC)

The Low loss Concept (LLC) as shown in Figure 3 patent by Wärtsilä is a new concept based on the hybrid propulsion concept. When using the LLC the need of a transformer for every frequency driven equipment is not necessary. The LLC concept is based on the 30 degrees phase shifting transformer. The benefits of this configuration are:

- **High redundancy**
  - The switchboard has 4 individual parts in case of a worst case single failure the available power will be reduced to 75% so that all propellers are still running (wartsila, 2015)
  - Any fault gives minimum operational consequences (wartsila, 2015)
  - Reduced power due to less consequences of major faults (wartsila, 2015)

- **Instant power restoration**
  - All transformers remain connected during black out, enabling instant restart of power supply (wartsila, 2015)
  - Network disturbances are dampened by the LLC transformers connected in series (wartsila, 2015)

- **Total harmonic distortion (THD)**
  - LLC transformers reduce THD to a maximum of 5% and approximately 3% (wartsila, 2015)

- **Safer operation**
  - Centralized location of the vital equipment enables easy and secure commissioning, operation, control and maintenance (wartsila, 2015)
The danger of short circuit is significantly reduced, this increases the personnel safety. (wartsila, 2015)

- Significant savings in space and weight
  - No transformers/converters in propulsion area, more cargo room available (wartsila, 2015)
  - Low voltage system allows a more flexible compact switchboard room (wartsila, 2015)
  - Fewer and smaller components saves weight when LV components can be chosen instead of MV components (wartsila, 2015)

- Fuel savings
  - Power feed directly from generators to converters saves fuel. Eliminates electrical losses in the transformer (wartsila, 2015)
  - Total electric losses reduced to 5.5-7%. Which is 2-3% lower than competing concepts (wartsila, 2015)

- Redundant power generation
  - The power of one generator to be transferred across the LCC transformer enables optimal and “free” choice of generators to be running (wartsila, 2015)

- Increased network stability
  - Transformer impedances reduce the impact of a large failure in the network, such as major voltage disturbances (short circuit on or close to the main bus bar) or frequency oscillations (wartsila, 2015)

- Green energy
  - Making use of the sun and wind as power supply

1.5.1 Redundancy
Redundancy for an autonomous vessel is highly important. This because no matter what happened there needs to me a connection. To get this high redundancy will be looked at
the Environmental Regularity Number (ERN). 'The ERN number Defining a vessel’s ability to maintain its position Developed in the 1970s by Det Norske Veritas (DNV), the Environmental Regularity Number (ERN, also ern) is a theoretical way of defining a vessel’s ability to maintain its position in different weather and sea conditions. As only lateral forces are involved - wind, waves and current come in on the beam - the calculations involved are relatively simple. The ERN consists of four groups of integers, each of which is stated by DNV to reflect “the probable regularity for keeping position in a defined area”. The format of an ERN is a series of four numbers ranging from 0 to 99. ERNs are stated in shipping registers in the form ern (a, b, c, d), in which a represents the optimal use of all thrusters, b represents the minimum effect of a single-thruster failure, c represents the maximum effect of a single-thruster failure, and d represents the effect of the worst case single failure(s). In a guidance note, DNV says: “The fourth number d shall represent the case where stop of the redundancy group resulting in the largest reduction of position and heading keeping has occurred. (106)” In practical terms, a represents the probability that a vessel will be able to maintain a required position at a certain location in the North Sea when all its systems are fully operational, b indicates the probability that it will be able to maintain its desired position if the least effective thruster fails, c indicates the probability that it will be able to maintain position if the most-effective thruster fails, and d indicates the probability that it will be able to maintain position in the worst-case single failure. The highest possible ERN rating - a score of 99 for a, b, c and d - is 99.99.99.99’ (I, K, & M)

This number is already widely spread in the offshore. This ERN number can now also be used in the autonomous vessel. This because if a vessel can maintain its position is it also possible to maintain the course of the vessel. The redundancy number of the Wärtsilä low loss concept is 99,99,99,99 this is the highest possible. This means that even when a worst case single failure occurs the vessel will have 75% of the installed power and all of the essential systems still having power. (wartsila, 2015)

1.5.2 Instant power restoration
If a vessel is sailing autonomously and there is an event of power loss onboard, restoring the power has then priority to maintain contact with the vessel. With traditional systems the electrical transformers have to be reset. In the Wärtsilä LLC the electrical transformers do not has to be reset. So only a command from the shore to start an engine is enough to provide the vessel with power. This will speed up the power restore, and there by also the safety of the vessel.

1.5.3 Total harmonic distortion (THD)
When a ship is sailing diesel electric the power supply can be reacting “slow” to the power demand. This results in a distortion of the voltage and/or current. This is called harmonic distortion. This THD is affecting the life time of electrical components especially from the sensors. When THD occurs in the Wärtsilä Low Loss system the harmonic distortion is filtered out by the transformers, these transformers will damp the THD to max 5% and approximately to 3%. (wartsila, 2015)
1.5.4 Safer operations
A safer operation is not directly an obvious advantage. But when autonomous vessels need repairs when in the harbor, specialized crew will work onboard with unfamiliar engine room/technical space. By the use of the Wärtsilä LLC the voltage can be lower with a higher power output. This is achieved by the use of two separate bus bar systems as can be seen in Figure 3. The advantage of this lower voltage is the maintenance of the system. When having a low voltage system, the components are less expensive and the maintenance is easier and when arriving in a port. Not every port has qualified engineers to work on a high voltage system.

1.5.5 Significant saving in space and weight
Compared to current installations where every frequency converter needs an individual transformer for operation and filtering out the THD, the Wärtsilä low loss concept is equipped with only two 30 degrees phase shifting transformers. This is already a huge saving of weight and space. Nowadays when a vessel has an ERN of 99,99,99,99 their generators are capable producing 100% of the demanded power but by using the Wärtsilä low loss concept each generator delivers 33% of the demanded power. In the traditional setup two generators deliver 200% power. And in the Wärtsilä low loss concept four generators deliver 133% of the demanded power. When applying the Wärtsilä LLC the power of the generators can be brought down with 54%. This is a significant saving in weight and space. This saving in weight and space will benefit the cargo space and the load that can be carried by the vessel. (wartsila, 2015)

1.5.6 Fuel savings
As mentioned before when the vessel is equipped with the Wärtsilä low loss concept the power of the engines can be brought down. Nowadays the engines are way too big so they are not running on the optimal load. This results in higher specific fuel consumption and a less effective combustion. There is also another aspect that reduces the fuel consumption. The LLC reduces the electrical losses in the electrical system. This is reached by the use of only 2 transformers and not a transformer for every frequency drive. The fuel saving can be as much as 9%. (wartsila, 2015)

1.5.7 Redundant power generation
In a vessel propelled by the Wärtsilä LLC there is a free choice of witch engines are delivering electrical power to the main bus-bar. For the electrical system it does not matter which engine is running. This is a great advantage. Even in the event of an engine failure the connection to shore will not be interrupted. The loss of this engine will not affect the distribution of the electrical power but only affects the available power. This loss of power is not affecting the heading of the vessel, because the vessel has the highest possible ERN number.

1.5.8 Increased network stability
As mentioned before, by making use of the 30 degrees phase shifting electrical transformers the HTD is reduced to maximum of 5% this will increase the stability of your network and there for also the lifetime of electrical components. Even if there will be
a short cut in the electrical system or generator the electrical transformer will block this so only one side of the transformer is affected.

1.5.9 Green energy
When a vessel is full electric the power obtained from solar panels or wind energy can be put directly on the power distribution onboard. When green energy is supplied the PWS of the vessel will reduce the power of the engines. This will result in a fuel saving and saving of the emission. In the rare event of a black out onboard the solar panels and/or wind energy can provide the critical systems of the vessel of electrical power.

1.6 Conclusion
The best choice of the power supply on an autonomous vessel will be fully electrical especially the Wärtsilä LLC. This because this configuration has the highest ERN number possible and has many advantages compared to other fully electrical vessels with the highest ERN number.
2 The fail-safe engine room

2.1 Introduction
In this chapter the sub question: How can the engine room be made fail-safe will be answered. This chapter describes, the meaning of fail-safe and redundancy and how this can be realised and will be done. Fail-safe and redundancy are related to each other and are coming together in this chapter.

2.2 General description
Making a system fail safe is important because, with autonomous sailing there is nobody on board to repair the system in case of an event. Making the system fail-safe the vessel can reach the harbour and the necessary repairs will be done by experts. On this way the autonomous vessel is made safe.

2.3 What is fail safe
A fail safe system design is only safe against the failure modes which are provided during the design. A second assumption by fail safe systems is that there occurs only a single fault simultaneously. Due to the chance that there can be more than one fault at the same time, this is considerably small. To make the system fail safe there is redundancy. In chapter 2.4 redundancy will be explained.

2.4 What is redundancy
Redundancy is something to make the system fail safe, defects will be excluded. Redundancy means that the system is (partly) duplicated. When a component fails another component will take the function of the failing component over. On this way the system is still working properly. If the redundancy takes over in case of an event the damaged part needs to be repaired as soon as possible. How this is done is found in the next chapter 2.5.

2.5 How failsafe and redundancy can be achieved
In this chapter there will be explained how failsafe and redundancy can be applied. Not all systems need duplication. Only the primary systems where failure is catastrophic for the vessel need redundancy. Without duplicating every system only the weak spots are partly duplicated. Completely duplicating of systems is not desired. This can be achieved by duplicating pumps or pipelines.
3 Standardisation of the engine room

3.1 Introduction
In order to make the engine room redundant and the vessel fail-safe, it is important to standardize the engine room. This means that there will be a standard layout of the engine room. For example; a standard engine of the same brand with a certain power and a standard consumption. Nowadays this is not the case. Each engine room is different and therefore always a different error or defect will occur. Every engine room uses other techniques, for example; there are many varieties of propulsion and auxiliaries. In this chapter will be explained: the standard layout of the engine room, the advantages and disadvantages.

3.2 Standardisation
The meaning of standardisation is to observe the current techniques for a certain system and hereby the process that leads to the best possible product and/or the least possible effort. The foregoing can be seen as the first step on the way to standardize: the joint establishment of a first standard. This setting of the standard is determined by professionals. After determining it will be tested several times until all the defects have been removed. Using an iterative process the best layout for the engine room comes forward. (standarisation, 2016)

3.3 Operation
After determining the best layout for the engine room there need to be looked into the requirements for the machinery. These requirements could be the type of engine, engine power, performance and etcetera. This will vary by type of vessel. For example a smaller vessel needs less power for the same speed than a larger vessel. A multiple layout is necessary. With the use of these layouts the most suitable can be chosen for the different types of vessels.

In the standardization of the engine room there are many advantages which make the work easier, safer and cheaper. Compare a standard engine room layout with the current situation. The advantages are: the training of engineers will cost less because every technique is the same in a standardized engine room, this way the study can be shorter, also building a new vessel is less expensive because the design cost, material cost and staff cost will be reduced by the standard layouts.

Most important is that the engine is redundant and that the systems will be failsafe. Those are the two most important aspects to sail autonomously. This way the chance of defects in the engine room will be reduced.

3.4 Conclusion
The topic is not further investigated because this is not applicable at the time. However in this subject is worth to take this seriously in the future. Because standardisation increases the safety on board and reduces the risk of human and mechanical errors.
4 Pipe systems

4.1 Introduction
Many errors and breakdowns in the engine room are due to wear and tear of the pipes. If this problem is reduced or eliminated than the failsafe goes up and the redundancy will increase.

The pipes currently used on board of ships are made of steel and covert with paint to protect the pipes against corrosion. The reason why steel pipes are used in the technical department is that they are very strong, can resist a lot of pressure, and that they are heat resistant. However there are a lot of disadvantages encountered by the use of steel pipes such as, pipes lines wear out rapidly, no acid-resistance, gets damaged by corrosion, pipes are heavy and very difficult to work with.

These disadvantaged will be good as eliminated by the new technologies that are not yet applied on seagoing vessels. With time a few devolvement where made and so arose some new pipe line systems. Those pipe lines need a further examine whether this is applicable in shipping.

The advantages and disadvantages will be examined. The application for each pipe line system will be mentioned and which system it is the best. The three pipe line systems that will be investigated are:

- Powder coated pipelines
- Fiberglas reinforced plastic pipeline
- Fusiotherm

4.2 Powder coated pipelines

4.2.1 Introduction
A coating (also known as coating or surface treatment) is a mixture of substances which can be ironed on different products. When the coating is applied to the pipe line the system gets better characteristics than before. The coating is applied on ordinary steel pipes of the vessel this will give an extra advanced. The difference is that instead of paint on the pipelines there will be a layer of coating.

The coating can be applied in different ways. There is chosen for powder coating. This is an electrostatic paint process. The grand difference between conventional liquid paint and powder coating is that the powder coating does not need a solvent in order to keep the binder and the filler in a liquid suspension. As a result the adhesion to the pipes lines is much better. (snaas metaalwerken, 2016)

4.2.2 Advantages and disadvantages of powder coating
There are several advantages of powder coating compared to conventional liquid coatings:

- Powder coatings emit zero or near zero volatile organic compounds out.
**Powder coatings** can produce much thicker coatings than conventional liquid coatings without running or sagging.

- Powder coating residues can be reused. It is by this way possible to use almost 100% of the powder.
- Powder coating production lines produce less hazardous waste than conventional liquid coatings.
- Material and operating costs of a powder line are generally lower than for conventional liquid coating lines.
- Objects provided with a powder coating generally have fewer differences between the horizontal and vertical coated surfaces. Compared with liquid lacquer.
- A wide range of special effects is easy to achieve, that would be impossible to achieve with other coating processes. This allows to recognized different systems quicker.

While powder coating has many advantages compared with other coating processes, there are some drawbacks to the technology. Although it is relatively easy to apply thick coatings with a smooth, texture-free surface, it is not so easy if you want a smooth and thin coating. When more film thickness is reduced then the coating gets a more bumpy structure. Like the peel of an orange. This is due to the particle size and the glass transition temperature of the powder.

For optimal treatment and applicability most powder coatings used with a particle size between 30 to 50 micrometres (microns) and a glass transition temperature of 200 °C. For such powder coatings is a layer of more than 50 microns required for a nice smooth layer. Depending of the final product is determined which film thickness is acceptable. Many manufacturers prefer a certain degree of roughness, as this helps to hide the defects of the metal. The coating is then less prone to fingerprints.

There are very specialized processes whereby powder coatings of less than 30 microns, or be used with a glass transition temperature below 40 °C produce smooth thin films. A variation of the dry powder, the powder slurry process, combines the advantages of powder coatings and liquid coatings by very fine powders of 1-5 microns dividing particle size in water. By this way coatings can be produced with a low layer thickness. (snaas metaalwerken, 2016)

### 4.2.3 Species of powder coatings

There are two main categories of powder coatings: thermosets and thermoplastics. Thermosets include a cross-linking agent or cross-linker. When the powder mixture is baked a reaction will occur between the various powder components to form a polymer. Thermoplastics not undergo additional reactions during the baking process. They melt and flow out and form the final coating.

The most commonly used polymers are polyester, polyurethane, polyester-epoxy (known as hybrid), straight-epoxy (fusion bonded epoxy), and acrylic. (snaas metaalwerken, 2016)
4.2.4 The powder coating process
The powder coating process consists of three steps. The first step is the preparation or pre-treatment of the coated workpiece the application of the powder coating and curing. (snaas metaalwerken, 2016)

4.2.5 Preparation
The removal of oil, sand, grease, metal oxides, welding slag is essential of preparation for the powder coating process. It can be done by a variety of chemical and mechanical methods. (snaas metaalwerken, 2016)

When a chemical pre-treatment phosphates or chromates are used it will be immersed or sprayed. This is often done in several steps. These steps consist of the removal of dirt, degreasing, etching, multiple rinses, and the final phosphating or chromating of the workpiece. This preparation improves the adhesion of the powder on the metal.

Another method of preparation of the surface is sand blasting or grit blasting. This is used for products made of wood, plastic, glass, and to give a texture to be etched and degreased.

4.2.6 Application of the powder coating
The most common method of application of powder coating on metal objects is by spraying the powder with an electrostatic spray gun. The spray gun gives the powder a negative electrical charge with is so-called corona-charging. Then the powder is drawn to the work piece by the electrostatic charge.

The powder can also be charged by means of friction pressure. This is called a “tribo-charging. The powder is charged positively while it rubs along the wall of a Teflon tube in the spray gun. These charged powder particles adhere to than the grounded surface.

4.2.7 Curing
When a thermosetting powder is exposed to an elevated temperature it begins to melt and it will flow out on the workpiece. Then there is a chemical reaction whereby a higher molecular weight is created. This process is called cross-linking. It requires a certain temperature for a certain period of time in order to achieve full cure. For most powders this is at 200 ° C for 10 minutes. (Powder coating)

4.2.8 Recommendations
The piping will remain basically the same as the original only is the protection layer is different instead of paint it is powder coating. The powder coating can be applied for every piping system. As a result the pipes are protected much better on the exterior and are therefore a good replacement for the painted pipelines. The recommendation after the research is to apply power coating on the piping system in an autonomous vessel.
4.2.9 Conclusion
Powder coating gives many advantages to the traditional way of coating. By the use of powder coated pipelines benefits will exist of better corrosion protection and extended life span. However, powder coating is expensive and must be applied in specialized factories.

4.3 Fiberglas reinforced plastic pipes

4.3.1 Introduction
FRP stands for fiberglass reinforced plastics. With the use of fibreglass the characteristics of the pipes are improved. FRP is not the only plastic reinforced pipes it also consist of glass reinforce epoxy (GRE) and glass reinforced plastic (GRP). The difference lies in the type of plastic that is used. A different type of plastic used will give different type of characteristics to the pipes. Because of this they will be better suited for a number of piping systems on board. In this chapter, is discussed how this is made, what are the pros and cons and what the recommendations are. (lever kunstoftechnieken, 2016)

4.3.2 How it is made.
This material is built up from glass fibres which are impregnated with a resin. The base of plastic pipes consists of reaction resin, glass fibres and pure solid quartz sand. The resin will harden after adding a hardener. It is an irreversible process and the end product is very strong and does not rust or rot. These FRP piping systems are employed for many years including in the petrochemical industry, refineries, shipbuilding, offshore, oil and gas and power plants. Fiberglass is in fact very resistant to corrosive conditions and so a very good pipe system to use. (lever kunstoftechnieken, 2016)

4.3.3 Pros and cons FRP
FRP state as previously described for fiberglass reinforced plastics, a composite which is relatively strong and resistant to many chemicals which ensure that the tube wall is resistant against aggressive environmental factors such as sulfuric acid. Because of the low weight there is a fast installation possible. The weight reduction will increase the tonnes of cargo that can be carried by the autonomous vessel. Another advantage is a long life span (50 years) at a constant high flow and the cost for maintenance and installation are low.

Even though it is very suitable for chemicals this type of pipe is not common on board seagoing vessels due to the disadvantages of this product. Maintenance is low, however, the product requires if damaged special materials and a specialist to repair the pipes. The melting point of the pipes is relative low, only 225 degrees Celsius.

4.3.4 Recommendations
FRP is resistant to acids and is also very suitable for this purpose. By this it is very suitable to use it in the sewage installation. The disadvantage is that it is not resistant to high temperatures and high pressures. As a result the applicability of this system is not very high. However it can also be used for the protection of batteries or other systems that use acids. When a leak occurs, this acid remains in the tank and cannot affect the other systems which make it safer.

4.3.5 Conclusion
FRP is a good material from making pipes. It has characteristics that meet most systems requirements on board vessels. The key for autonomous sailing is that it has a long life span and is reliable. This means the pipes require little maintenance, and the maintenance that must be executed can be done in port.
However it is not recommend applying this type of pipes on board. This is because the safety requirements are not met, due to the melting point of the material. However the material is resistant to many chemicals and can be used to improve safety on board for the chemical systems.

4.4 Fusiotherm

4.4.1 Introduction

Fusiotherm is a technique of how pipes are made. The pipes are made of polypropylene (PP-R) a plastic and fiberglass. Those two materials are taken into one and make the final product. This technique has been around for more than 25 years but is still not widely used in shipping. In this chapter can be read what fusiotherm is and why it can be applied on board seagoing vessels. At last some recommendations will be made.

4.4.2 How is fusiotherm made

The pipe is composed of several layers. The middle layer (the base) is made of polypropylene and glass fibre. The layers around the base consist on various plastics to improve the characteristics of the pipes. This technique of making polypropylene pipes is also called faser.

The outer layers of the pipes exist of various plastics which will create different types of pipes. Because of this some lines are more resistant to heat, and others are weather wear-resistant pipes. Every color-coded pipe has its own characteristic in example orange, black, red, blue and green. For example, the red piping is very suitable for sprinkler system because of the heat resistance. The blue piping is very suitable for chilled water.

Fusiotherm is not only used for pipelines. For making fittings, couplings and valves the same technique is used. So by this way the entire system exist out of the same material. (aquatherm belux, 2016) (eriks, 2016)

4.4.3 Installation

Installation is very simple. The pipes are much lighter than the original steel pipes so they are much easier to lift and assemble. To install those fittings, couplings, and valves to each other there is a special technique that can be used named by poly fusion.

By this technique there arise a homogeneous fitting. The tube and the coupling are both heated shortly with a suitable tool, after which the parts are pressed together in a simple way. After a few seconds, the result is a perfect connection without vulnerable joints. The double wall thickness at the level of the couplings provides an additional reinforcement. This usually is a weak point in traditional systems. Also in the existing pipes there is a possibility to make taps using branching. This is also a big benefit. The use of this technique also allows for a great saving on parts and time. This is a great advantage over the traditional pipes. Also when the pipeline is damage it is easy to fit. This can be done by two different technics named by poly-fusion of welding with electrofusion sleeve.

4.4.4 Applications of fusiotherm

The special characteristics of this technique make the application of this system very wide. So the system can be used in many sectors like:

- Pipes for sanitary
- For cold and hot water
• Connections from a heat source
• Rise pipes
• Circulation pipes for swimming pools
• Pipes for compressing air
• Pipes for ice water
• Pipes for heating in buildings
• Pipes for agriculture and horticulture
• Pipes for heat pumps
• Industrial pipes
• Aggressive liquids (bases, acids...)

The system is available in different diameters and lengths. Hereby is the application wider. In appendix 2 the properties for the green pipes this is an example. By this way there is an indication for what is available in the industry.

4.4.5 Specifications
The lifetime of a plastic pipe will dependent on the pressure-temperature combination. Appendix 3 shows the different parameters. For example, a fusiotherm of the type SDR11 has an expected lifespan of 50 years, at a constant pressure of 9.2 bars and a constant temperature of 40°C. (aquatherm belux, 2016) (eriks, 2016)

However, it is no problem to use fusiotherm pipes at higher temperatures in example for heating systems. In that case, expected service life is also affected by the number of days per year that the temperature is higher than 70°C. In appendix 4 is a table that shows the parameters for use in heating. (eriks, 2016)

Fusiotherm pipes and fittings meet the requirements of fire class B2 (normal flammability). Compared with natural materials like wood, cork or wool give fusiotherm pipes during combustion no toxic gases and creates no dioxins.

These specifications of the pipes can be widely used in shipping. Below is described in which system fusiotherm is applicable and what the minimum specifications are.

Entire cold and hot water systems; with temperatures within 0°C to 70°C and pressures up to about 4 bar.

Whole lubricating oil system; temperature up to about 70°C and a pressure of up to about 4 bar.

Transfer fuel system; temperature up to 70°C and a pressure of up to 5 bar.
(aquatherm, belux)

4.4.6 Pros and cons
The advantages and disadvantages will be seen from the present system which are used in the shipping industry namely the steel pipes (painted or not). The fusion gives the pipes a much better stability and strength. Also the pipe lines have less expansion by the heat than the traditional pipes. This will reduce stress in the piping and extends the lifespan. Because of the strength and the low expansion of the pipes fewer brackets are required to secure the pipes. The pipes have a lower density than steel pipes which makes them a lot easier to carry, this result in weight reducing. This means that the vessel can care more tonnes of cargo.
The expected lifespan of fusiotherm pipes is more than 50 years. Peaks to 100°C are no problem for the pipes, however, this will reduce the lifespan. The best operating temperature is between 70 and 90 degrees Celsius.

The fusiotherm pipeline is also very environmentally friendly.

- They are free of polyvinylchloride (PVC)
- They contain less than 3% addition material compared with the base material fusiofen PP-R (80)
- It’s free of heavy metals.

This all gives a little or almost no damage to the environment during production. Also the pipes are non-toxic to the environment.

A disadvantage is that the pipes are sensitive for ultra-violet light. This will damage the pipes and therefore the expected lifespan is affected. However the piping can get protected by an additional protective layer of polyethylene so that the effect of UV light will be minimalized.

Fire protection fusiotherm pipes and fittings meet the requirements of fire class B2 (normal flammability). Compared with natural materials like wood, cork or wool give fusiotherm lines during combustion no toxic gases and creates no dioxins.

The advantage of fusiotherm is that is corrosion resistant. This means that no paint is required to protect the pipes. Also the fusiontherm pipes are shock resistant. Even when the pipes get damaged it is easy to repair or replace the pipes.
Various combinations in the plastics will be provided for special properties and additional enhancing property see table below:

<table>
<thead>
<tr>
<th>Property</th>
<th>PP-R</th>
<th>PP-R C</th>
<th>PP-R FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tasteless and odorless</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physiologically neutral</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistant to corrosion</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Outstanding characteristics of assembly</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Assembly by polyfusion</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Good insulation and acoustic properties</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Low pressure losses</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>High resistance to friction</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>High resistance chocks</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Resistance to chemicals</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Stabilized against the influence of metal</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Recyclable</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Stability at high temperature</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability at elevated temperatures (peak area)</td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Low flammability</td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

Explanation table (eriks, 2016)

4.4.7 Recommendations
Fusiotherm is a very suitable pipe system for nearly every system on board. Not for hydraulics and cooling systems, because of the high pressures and temperatures. As a result the recommendation is to apply fusiotherm where possible for example, cooling systems, fuel systems and lubricating oil systems.

4.4.8 Conclusion
The benefits and wide applicability of fusiotherm are perfect for sailing autonomously. After the research using fusiotherm is strongly recommend in the near future. However it is better to use a combination of the systems that where examined. This is because fusiotherm is not applicable in each system, but this system has the most advantages. This makes it wise to use this system as much as possible.
5 Inerted engine room

5.1 Introduction
To make sure that the autonomous vessel is failsafe and has increased redundancy, the idea came up to reduce the oxygen in the engine room to almost zero. This means the engine room is inert. When there is something wrong in the engine room for example there is a bearing locked. The jammed bearing may heat up and cause a fire. The ignition of fire needs three things namely oxygen, fuel and the proper ignition temperature. This is also named the fire triangle. By taking away the oxygen the triangle is not complete and it is impossible to start a fire.

The idea is to reduce the oxygen in the engine room. It is not necessary to make the engine room complete oxygen free because fire needs a specific amount of oxygen about 15%. Lowering the oxygen level around 5% is enough. When this is accomplished the fire that could be started by the jammed bearing cannot ignite.

5.2 Exhaust gases
The engine room will be made inert by using the exhaust gasses of the main engine(s) or auxiliary engine(s). The exhaust gasses coming from the engine lack of oxygen. In this way it is possible to reduce the oxygen ratio of 21% to less than 1%. Also the exhaust gases are basically free so that no additional costs are incurred.
The engine exhaust gas contains not only harmless products such as water vapour, carbon dioxide and nitrogen, it also contains harmful substances that are hazardous to people and the environment such as carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide (NOx). These types of harmful substances are a very small part of the overall emission of a modern engine. Only 1.1% of the total emission with an Otto engine and 0.2% with a diesel engine. The largest part of the exhaust gas is water and carbon dioxide. (marine in sight, 2016) (ngk, 2016)

Harmful substances constitute only a very small part of the overall emissions of a modern engine - only 0.2%. The largest part of the exhaust gas is made up of nitrogen (73.8%), water (9%) and carbon dioxide (8%).
Since carbon monoxide is heavier than air it stays above the ground. For that reason, it is also dangerous for humans to use the exhaust gases to inert the engine room. For that reason good ventilation is necessary before someone is entering the engine room for safety matters.

The exhaust gasses also contain soot. The soot is caused by incomplete combustion. Soot is unhealthy for humans, pollutes the engine room and can cause defects in the electronics.
A soot filtration system to filter all the particles out of the air is necessary. A soot filter can get 95% out of the air. (marine in sight, 2016) (ngk, 2016)
5.3 Concept theory
The concept idea is as previously described to make the engine room oxygen arm with the exhaust gases of the main engine or auxiliary engine. However there are some disadvantages like, the engine room is not directly accessible for humans, risk of oxygen-poor angles, good ventilation is required, cooling the air and most important the starting air and turbo for the engines need an air mixture with oxygen. All those points can be executed and will be discussed point by point.

5.3.1 Accessible engine room
This is easily accomplished. When a vessel is sailing towards the harbour to unload cargo, then the engine room needs to be oxidized by the rules of confined spaces.

5.3.2 Oxygen arm corners
As previously explained carbon dioxide is heavier than air, this means carbon dioxide sinks to the bottom. This makes it more difficult to ventilate the entire engine room. To measure the corners for oxygen so called oxygen sensors will be placed. If all the sensors give a green light the people can enter the room and if not they need to wait. It is also important that the sensors are measuring all the time so the safety is to be maximizes.

5.3.3 Soot in the engine room
This is a big disadvantage due to unhealthy environment for humans and it may cause defects in the electronics of the vessel. In order to build a particulate filter in the system, this means it gets 95% of the soot out of the air. It is also necessary that only exhaust gases are introduced into the engine when the engine is up to speed and gives the correct power. In this way the combustion is the cleanest and contains less soot.

5.3.4 Cooling
In practice the engine room is normally vented by the outside air. This is to prevent that components or equipment in the engine room will overheat. Cooling by the outside air is not possible. That is why another way of cooling is necessary. This can be achieved by placing coolers in the engine room. Despite this sort of cooling uses a lot off electrical power the benefits of an inert engine room are way greater.

5.3.5 Starting air and turbo
As previously described the turbo and starting systems need an air mixture with at least 21% oxygen. Otherwise the systems do not operate in good order. In the research there can be read how this will be accomplished. (ngk, techniek)

5.4 Concept practice
The turbo and the starting air system need an oxygen-rich air mixture otherwise they lose their function for the engine. For this the following is demanded. By bringing the suction of the turbo and starting air to deck, there is no problem with the inert engine room. The concept and catalogue is shown in Appendix 5.

In the Annex (draft) is shown that the suction from the turbo is attached to deck. This is done because the engine room is inert to prevent a fire as a safety aspect. However the turbo requires an oxygen-rich air mixture for operation. For this reason the turbo should get somewhere else air and that place is on deck. There are several aspects that need to be overtaken to achieve this plan. Things like wind, rain, waves, organisms and dust are not wanted in the turbo.
The turbocharger (2) sucks air through a pipe (3). The pipe must have a certain thickness to a certain length and power of the turbo. This is because the pipe may not provide resistance for the turbo. The more air (litres/minutes) the thicker the pipe. Also the longer the pipe (more resistance) the wider the pipe should be. There need to be special calculations (those are excluded from the research). The pipe ultimately comes out of the turbo housing (6). The housing is sure to block out the harmful nature aspects thinking of the wind, rain and waves. The housing contains holes (4) those are the turbo air holes. These holes are designed for the air supply to the turbo. Those holes need to be big enough to provide enough air to the turbo without causing resistance. The holes are also provided with filters (7) in order to keep dust/ sand and all another unwanted materials outside. Suppose that water can still come inside (via the air holes). So there are placed water sensors to detect the water (8) for the safety. There are special waterholes made those are non-return valves. Due to the non-return valves the water can flow away from the turbo housing. By this way it keeps the housing dry. The turbo pipe itself has a so-called mushroom (5). This is to prevent to that stuff can get into the turbo pipe for extra safety. This design is exactly the same for the starting air system and is therefore disregarded in the story.

Because of this design all the negative aspects of the turbo and starting air are eliminated. By this it is impossible to carry out the system. However there need to be calculations for the turbo air holes and (4) and the intake pipe (3) this requires further investigation.

The ventilation is carried out by a number of fans and windscreens.

The principle is as follows: the fans are mounted into the ceiling and sucking the air into the engine room. This results in an over-pressure in the room. The air must somehow be blown away to prevent overpressure. Overpressure is disastrous for the ventilation because the pressure can be so high that the fan cannot run anymore.

To prevent this there are two options namely;

1. Air holes at the bottom of the walls. The air can blow away because of those holes.
2. Or fans in the walls. The fans are blowing the air outwards. This gives an advantage that the process is faster.

Option two has been chosen because, how faster the process how longer the safety in the engine room can be kept secure.

It is intentional that the air is circulating from high to low. This is because carbon monoxide is heavier than air and is easier to get out of the engine room on this way. By is way the carbon monoxide is faster out of the engine room.

There are also so-called wind dividers placed in the engine room. These windscreens ensure that the fresh air will be transported to the blind spots within the engine room so that no carbon monoxide will remain. The windscreens provide vortices in the air and are so adjusted that the air will blow to the blind spots. This will have to be calculated and is regarded as a boundary. Appendix 6 gives an indication on how the wind will behave approximately.

The principle of making a space inert is already being used in the tanker vessels. In order to ensure that the mixture in the tanks remain below the explosion limit. This concept is
used by that same principle and the technique only now to prevent fire and not an explosion.

How it works, the system takes the exhaust gases from the main engine. From here the inert gases are used. There is a valve (operating automatically) between the main engine and filter system. The purpose of this valve is to control the absorption of the inert gas to the system or to take the system out of use (to stop the system).

The filter system also referred as scrubbing tower is a tower type in which the exhaust gases are filtered by water spray and filters. As a result the SO2 concentration decreases by 90% and the gas is released from soot. See appendix 7 for the scrubber tower. Oxygen meters measure how much percent oxygen remains in the space. This will give an indication for when there is enough inert gas in the room for the system to stop. Also it gives an indication when to stop or start the ventilation. (marineinsight,marine) (marine in sight, 2016)
6 Maintenance in an autonomous vessel

Lots of work these days is performed by machinery, electronics and other equipment. The uses of these assets have brought many benefits to the working environment on board of vessels. But in order for them to continue seeing those benefits maintenance on these aspects is inevitable. A maintenance program must be implemented. Within this program maintenance can be categorized in three forms: predictive, preventive and corrective. These three types are being done worldwide the same way on sea and on the shore.

6.1 Predictive maintenance

In this chapter will be explained why predictive maintenance is important on autonomous vessels.

Predictive maintenance or condition based maintenance is a maintenance form where measurements decide over the working condition of components. The normal working condition of components gives a constant measurement. When this measurement changes this indicates that the component is not in optimal working condition anymore and need to be checked or replaced. (processingprofs, 2016)

There are a couple of forms of predictive maintenance but for the autonomous vessels only one form can be used; continues condition monitoring, because the human factor will be deleted.

The continuously condition monitoring is the oldest form of maintenance. In the past the engine room was manned 24 hours a day by qualified engineers whom maintained and checked the systems continuously. This check, decide and action form is not used anymore. The form of predictive maintenance that will be used on unmanned vessels will be modern and with accurate measurement instruments and sensors. (Maanen, 2000)

The sensors and other measurements need to be connected to a system that processes and record this data in a program. There is a great variety in programs available, only action points for the autonomous vessel are that the program must include both condition-driven and time-driven tasks. Condition driven tasks are live information from the sensors. Time-driven tasks are like filling in checklists a couple of times a day and the maintenance needed with running hours (preventive maintenance). These tasks are different for every system and need to be specifically determined for every system. For minimal standards the program must be accessible for engineers on shore and reports must be transmitted a couple of times a day. Even if the system does not detect a fault engineers on shore can still intervene, and plan maintenance activities. (Mobley)

Why use predictive maintenance on unmanned vessels, before breakdown of a system occurs there are already indicators that show that there will be a failure in the system. This will be noticed by the sensors installed. When change of working condition of the system is noticed then maintenance can be planned for the next port. Monitoring the systems this way is important for the vessel to prevent failing underway. With use of predictive maintenance, the planning of maintenance is three steps ahead of the failure and there is less chance of an autonomous vessel drifting “broken” at sea.
With the information received from the sensors there is an indication of what is going to cause a failure and so spare parts can be ordered in time. In port a team of engineers can repair or replace the almost broken parts.

6.1.1 Advantages and disadvantages
This type of maintenance has like every type of maintenance advantages and disadvantages. With the list below this maintenance type can be compared with preventive and corrective maintenance.

Advantages

- The use of predictive maintenance will cause less maintenance cost. This is because parts are used to their maximum operating time, and replaced if planned correctly before the parts actually break down and can cause secondary damages.
- Maintenance can be planned during voyage and spare parts can be ordered in time. This way only the necessary spare parts are ordered reducing spare parts cost. Also time efficiency with doing maintenance is reduced if planned correctly.
- System reliability is increased, because correct maintained systems will work in optimal condition and this reduces chance of breakdown.
- Less events so unwanted downtime is reduced to a minimum. Because components are replaced or repaired before they actually breakdown.
- Parts can be ordered when needed so on board spare parts are reduced to a minimum.
- Less secondary damages because things are repaired or replaced before components are failing.
- Equipment have maximum lifetime, because with good maintenance machinery will work longer in optimal condition.
- Less damages by engineers during voyage because there are none.

Disadvantages

- Constant monitoring is required on autonomous vessels to achieve the desired level of predictive maintenance.
- Advanced monitoring and decision system required. Because all the information coming from the sensors need to be checked by a program that decides what to do and also record and save information that will be send to shore a couple of times a day.
- In case of sensor failure corrective maintenance is required, also redundancy need to be installed like a live zero electrical signal to make sure the sensor is working correctly.
- All the extra sensors and monitoring equipment will make purchasing costs higher.
- Increased number of parts and sensors that need maintenance over time.
- Data transfer to shore is still limited. Because of the connection coverage and speed so on the data send to shore must not be too much.
- Measured values must be interpreted correctly. Otherwise wrong maintenance is planned and wrong spare parts ordered.
- Still catastrophic failures cannot be avoided, therefore redundancy must be applied.

6.1.2 Application
Nowadays on board of manned vessels the predictive maintenance is done by the engineers and by the help of the sensors. When an engineer fills in the checklists and
checks the values for changes this is already called predictive. If a value changes to much the engineers know maintenance is necessary.

There are already systems that send information to shore. On shore the information is checked and if needed feedback will be transmitted back to the vessel. These systems are now for predicting and for helping the engineers with running the engine room without too many failures.

Fig (kongsberg, 2016)

The desired situation is that the entire engine room is autonomous without engineers. The sensors will have a vital role in this and can be used for the following purposes:

Measuring the component and checking for changes like vibration/frequency measurement, but also temperature, noise, flow, and visual. When components wear they vary in values of the factors pointed out above. With all these components a complete idea of the correct working is achieved. This information can be used for planning maintenance for the systems.

When these kinds of circumstances are not noticed the system can fail. The desired situation for a loaded vessel is that the systems are starting up in normal running condition, when going on a long voyage. An engineer on shore notices after a couple of days that the values are running different from normal working condition. The engineer gets info from a system like a checklist so values can be compared. This way maintenance can be prepared for the next port of call.
When the vessel arrives in port a team of engineers is standby to fix the problems in time and make sure the vessel is ready to sail again with minimum delays. This situation can be achieved by making good use of predictive maintenance.

A control record should be made to provide detailed information about the system, including the history of use, history of maintenance and repairs, calibrating information and normal working values.

Engineers of the future do not sail anymore but are working in teams on shore to provide maintenance for the autonomous vessels. This way the engineer does not lose his job, only the working area and time changes. The maintenance is planned by an engineer who also orders spare parts. This way the team of engineers in port can immediately start with repairs and maintenance when the vessel is moored.

6.1.3 Conclusion
Installing sensors that are related to predictive maintenance help with preventing unwanted issues on sea and make an organized maintenance in port. This is pre action instead of reaction on failing issues. It makes preventive maintenance essential for unmanned vessels. The seafaring engineers will not lose their jobs but work in other environments. Without predictive maintenance the planning of maintenance and the preventing of events are much more difficult.

6.2 Preventive maintenance
Preventive maintenance is, as the name implies, the pre-planned maintenance of machinery, electronics and other equipment designed to eliminate unexpected breakdowns and increase of the life span. This pre-planned maintenance schedule is critical for the performance and reliability of the machinery, electronics and other equipment. (ROBOT EQUIPMENT MAINTENANCE)

In order to have a successful preventive maintenance program it is important to execute a strict schedule which has to be carefully monitored. The preventive maintenance system is focused on cleaning, lubrication, and fixing problems found during the pre-planned inspections. (Corrective versus Preventive Maintenance)

Preventive maintenance should generally be used on a scheduled fixed interval if failures that cannot be detected in advance can be reduced, or if indicated by the production requirements.

A good maintenance program should contain knowledge and past experience of all the equipment it is written for. Previous tests will often show what the expected lifespan of a part or consumable will be. This information is normally researched by the manufacture. Of course it is possible that such information is unavailable. In this case the program requires the support of production, with immediate notification of any potential problems and willingness to coordinate equipment availability for inspections and necessary tasks.

A part of the preventive maintenance is the prediction of failures this is explained in the previous chapter about predictive maintenance.

6.2.1 Advantages and disadvantages
Overall preventive maintenance has many advantages. It is beneficial, however, to overview the advantages and disadvantages so that the positive may be increased and
the negative reduced. In most cases the advantages and disadvantages vary with the type of preventive maintenance tasks and techniques used. Use of on-condition or condition-monitoring techniques is usually better than fixed intervals.

Advantages of preventive maintenance are:

- Management control, unlike corrective maintenance, which must react to failures, preventive maintenance can be planned. This means pre-active instead of reactive management. Workloads may be scheduled so that equipment is available for preventive activities at reasonable times.
- Overtime, overtime can be reduced or eliminated. Unexpected breakdowns are reduced. Work can be performed when convenient. However, proper distribution of the time-driven preventive maintenance tasks is required to ensure that all work is completed in a timely manner without excessive overtime.
- Parts inventories, because the preventive maintenance approach permits planning of which parts are going to be required and when, those material requirements may be anticipated to be sure they are on hand for the event. A smaller stock of part is required then a stock for corrective maintenance.
- Safety and pollution, if no preventive inspections or tests are carried out, equipment can deteriorate to a point where it is unsafe for man and machine.
- Reliable, Most breakdowns occur as a result of wear and tear (Corrective versus Preventive Maintenance), when the history of these parts are known these breakdowns can be prevented and therefor save valuable time, money or prevent dangerous situations from happening.
- When less (or none) unexpected breakdowns occur the vessel will be able to maintain a fully operational condition.
- Cost can be reduced. This because many minor and major breakdowns are prevented from happening.

The disadvantages of preventive maintenance are:

- Potential damage, every time a person touches a piece of equipment, damage can occur through neglect, ignorance, abuse or incorrect procedures.
- Infant mortality, new parts and consumables have a higher probability of being defective or failing than exist with the materials that are already in use.
- Parts are not used to their limits. This means that a part is replaced meanwhile it could have been used longer.
- More labor intensive, all maintenance which can be found in the schedule has to be carried out meanwhile the system is still in good working order.
- Cost can be increased; parts are not used to their full lifespan.

6.2.2 Application

Nowadays the on board engineers are carrying out most of the preventive maintenance. Every day new tasks will pop up in the maintenance computer so the engineers know what tasks should be executed. The program will provide the engineer with a job description sometimes with a checklist or information about spare parts.

On some vessels it is already common that service teams of the manufacture will come on board to execute this maintenance to the most expensive and most sensitive machinery such as the main engine, generators, turbochargers and etcetera. However, most of the maintenance is still been done by the vessels engineers.
When sailing autonomously no engineers will be on board to carry out the maintenance. Therefore, a new maintenance program must be build. This maintenance program must focus on doing maintenance in ports.

6.2.3 Conclusion

By use of a preventive maintenance system the lifespan will extend through painting, lubricating, cleaning, adjusting and replacing of minor parts. Preventive maintenance is carried out on a time or condition base. This means that tests and periodic inspections will be carried out in order to prevent any problems that may arise.

6.3 Corrective maintenance

From the three types of maintenance corrective is the last resort of maintenance done on board a vessel or installation. This kind of maintenance is carried out after a detection of failure on a piece of machinery or equipment, so it can be restored to a condition in which it will work proper again. When restoring the equipment is impossible due to excessive damage the equipment needs to be replaced. Because almost all the equipment on a vessel is important for keeping it running a breakdown or sudden failure is not tolerated. Failed equipment will disable the vessel and will cost a lot of money. To avoid any risk of failing or losing equipment predictive and corrective maintenance is done. But when even these two types of maintenance fail to prevent damage, corrective maintenance is necessary.

In the early year’s corrective maintenance took place most of the time, due to the lack of information and knowledge about the running systems. Later on modern systems led for a large part to the replacement of corrective maintenance. In figure 1 it is highly visible that conditional and methodical repairs are dominating nowadays.

![Maintenance evolution graph](image)

Figure 1. The maintenance evolution. Curative is the corrective maintenance. (systems, 2011)

The purpose of conditional (conditional preventive maintenance) is to repair machinery or equipment as late as possible, but before any risk of wear or loss of efficiency. This relies on simple techniques such as visual inspection on board autonomous vessels (by the means of on board cameras etcetera.) or complex techniques such as vibration sensors, thermographic analysis, and oil analysis etcetera. (systems, 2011)

Systematic methodical (preventive maintenance) is intended to avoid any risk of damage or breakdown. Parts are replaced systematically after a pre-determined period, without
taking account of their actual state of wear. This is particularly recommended when a defect in the parts concerned can cause major losses or where the cost of the part to be replaced is insignificant in comparison with the cost of a break in production. (systems, 2011)

With the use of good condition monitoring the conditional and methodical maintenance will ensure that corrective maintenance will be null.

In anno 2016 hardly any machines have a breakdown on an inconvenient time such as maneuvering in port. This is because the excellent condition-based maintenance like predictive and corrective maintenance. A future goal is to achieve zero accidental failures. Because nowadays still machinery fails to work, corrective maintenance on autonomous vessels is necessary. Besides that, repairs will always be needed. The challenge is to find the optimum balance between predictive, preventive and corrective maintenance.

Figure 2. Structure of maintenance. (Kelly)

6.3.1 Applications of corrective maintenance on autonomous vessels
Nowadays corrective maintenance is done by the crew on board the seagoing vessel. When machinery suddenly breaks down man will interact to solve the problem. For example, when a drive belt from a generator snaps due to wear it needs to be replaced (table 1). (Note: predictive and preventive maintenance would have prevented this event). This is a common incident because they are of frequent occurrence in fans, blowers, engines etcetera and generate unique forcing functions. First the fault needs to be traced to the generator and its drive belt. After this an engineer needs to find the correct spare part in the storage. Then he can take repairs on the generator. All these actions will take a lot of time and between the shutdown and repair the generator will not generate any power.
<table>
<thead>
<tr>
<th>Symptom</th>
<th>Cause</th>
<th>Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>High IX rotational frequency in radial direction.</td>
<td>Unbalanced or eccentric sheave.</td>
<td>Balance or replace sheave.</td>
</tr>
<tr>
<td>High IX belt frequency with harmonics. Impacting at belt frequency in wave form.</td>
<td>Defects in belt.</td>
<td>Replace belt.</td>
</tr>
<tr>
<td>High IX belt frequency. Sinusoidal waveform with period of belt frequency.</td>
<td>Unbalanced belt.</td>
<td>Replace belt.</td>
</tr>
<tr>
<td>High IX rotational frequency in axial plane. IX and possibly 2X radial.</td>
<td>Loose, misaligned, or mismatched belts.</td>
<td>Align sheaves, re-tension or replace belts as needed.</td>
</tr>
</tbody>
</table>

Table 1. Drive belt failure: symptoms, causes and corrective actions. (Kelly)

Still when predictive and preventive fail corrective maintenance is necessary. A vessel that sails completely autonomous will lack a crew and so it on board engineers. Wherever on sea a piece of machinery or equipment will break down interaction is required. Every asset on board the vessel is needed so broken parts need to be traced and repaired or replaced. When there is no crew on board a few options stay open:

- Wait for the next port to repair.
- Redundancy: switch to other (back-up) system.
- Robotic emergency repair.

6.3.2 Repairs in the next port
Repairs on the equipment are not possible when there are no spare parts on board; mostly this is because it is not a critical system. When this system is not in use due to his breakdown the engineers on shore can decide what to do. These engineers will be stationed in strategically placed command centers all around the globe or even in one place. From here they monitor the fleet of vessels. Will a system fail they can choose the right action with all the information available in the command center. (Rolls Royce, 2016)

When found out the next port of arrival has a nearby storage depot or service center with the right part, the action of “wait for the next port to repair” could be chosen. Now the vessel will continue sailing till the next port. Here a maintenance crew will board the vessel and start repairs or replacement of the broken machinery or equipment.

6.3.3 Redundancy
Should a piece of equipment or machinery fail to work the option redundancy is also possible. The important systems of the autonomous vessel will always work with redundancy (Chapter: What are the requirements for energy supply on autonomous vessels, Low Loss Concept, Redundancy, page 12).

The engineer on shore can switch the system to its back up system if this is not done already by the vessels system itself. By this means the vessel can continue the voyage. After this action the vessels route will be examined for the first service center on the route. Here the vessel will undertake repairs or replacement by the service crew of that harbor during the loading or unloading sequence.
6.3.4 Robotic emergency repair

If a main system fails, there is no redundancy option left or waiting till the next port of arrival is no option robotic emergency repair is a must on autonomous vessels. The command center on shore can decide what to do through system information gathered on board from sensors, cameras etcetera.

In the near future robots will be more reliable and compact. Because of all the benefits and the absence of crew on board autonomous vessels during sailing robotics can easily overtake the human job. The advantages for robots are great and can be divided in two categories:

Productivity
- Robots have high-speed and accuracy.
- Robots can be outfitted with a great variety of applications.

Safety
- Robots can replace the dangerous tasks for workers.
- Robots can work in hazardous areas (such as an inert-gas engine room).
- Robots are capable of lifting heavy objects and equipment.

The disadvantage is that the initial investment for robotics on board can be significant in this time. Later production costs will be reduced.

When robotics will be implemented in the engine room this will happen by the use of a rail guided system. This rail system will be similar to the already existing rail system in engine rooms on the ceiling for the tackles. Except this system will also guide the robotic arms alongside the pathways for humans next to the machinery. With this railing system the robotic arm(s) can cover the entire engine room and reach even more places than humans can (figure 3).

![Guiding rails](image)

*Figure 3. A floor map of the engine room fixed with a guided rail system for robotic arms.*
One rail will be connected with the storage facility on board. This way the robotic arm can get spare sensors and parts without interaction by humans. A monitoring system will keep track of the used spare parts and stored parts. This way the command center knows exactly what and when the vessel needs to be restocked.

A separate chamber will hold the application modules for the robot(s). The modules will vary from:

**Welding applications modules**

- Arc welding.
- MIG/MAG welding.
- Laser welding.
- TIG welding.
- Plasma cutting or other cutting.

**Material handling modules**

- Material lifting.
- Vision inspection (by the means of cameras and multiple sensors).
- Material bending.
- Material handling.
- Grinding.
- Drilling.
- Painting.
- Lubricating.
- 3D laser vision.
- Assembly.
- Cleaning.
- Refueling.

**Safety handling modules**

As seen in the list above the applications for robotics are endless. More applications will be possible in the near future.

6.3.5 Conclusion
Corrective maintenance will always be the last resort of maintenance done aboard a vessel or installation. Instead of fully man maintained maintenance, it will shift to robotic maintenance and shore based maintenance in the near future. This means that engineers are no longer required on a sailing vessel. Instead the future engineers are stationed at shore based workstations and centers where they will go to the vessels that are in need of maintenance. This will all happen in port.

While an autonomous vessel is seagoing, emergency repairs can be made by the use of robotics or be postponed till the next port of arrival.
7 The influence on machinery space

7.1 Introduction
By removing the human factor in the technical department a few things will be different because not all the items of a common technical department will be used when sailing autonomously.

7.2 Removing or adapt machinery and equipment
The common engine room machinery that can be deleted from board is:

The sewage plant:
When deleting the human the need for a sewage system is no longer required. This means that there is a weight reduction and also saves space. Therefore the vessel will be capable of caring more cargo.

The incinerator:
The incinerator is used for incinerating garbage and oil-residues. When no garbage is produced on board an autonomous vessel no incinerator is required. An added advantage is that incinerating produces toxic fumes when in operation. In an autonomous vessel the incinerator is deleted so that there are no emissions will occurs form the incinerator

The freshwater generator:
When no cooking, showering or toilet flushing is going on the biggest consumers are gone. Therefore the freshwater generator can be reduced in side of either completely deleted. When completely taken of the vessel the ships tanks must be capable of carrying enough water for the remaining systems.

Air-conditioning:
Also the air-conditioning unit is used for other purposes and no more for crew cabin heating and cooling but mostly for the electrical cooling and ventilation of other spaces. The purpose for this item will change and so the size needs to be recalculated.

Lifesaving equipment:
Because the human factor will not be present on board during voyages, no lifesaving equipment has to be on board. This also includes the lifeboat and life rafts. This change will result in a major cost and space reduction.

7.3 Conclusion
The technical department will look different in many ways, the human factor will disappear and the systems will adapt to good use in autonomous vessels. Some systems will be deleted completely and others will be used for different purposes. This way the vessel is optimized for autonomous sailing.
8 Conclusion

8.1 Requirements for energy supply on autonomous vessels

The power supply on an autonomous vessel the best choice will be fully electrical especially the Wärtsilä LLC. This because this configuration has the highest ERN (Environmental Regularity Number) number possible and has many advantage compared to other fully electrical vessels with the highest ERN number.

8.2 The fail-safe engine room

The benefits and wide applicability of fusiotherm are perfect for autonomous sailing. After the research using fusiotherm is strongly recommend in near future. However it is better to use a combination of the systems that where examined. This is because fusiotherm is not applicable in each system, but this system has the most advantages. This makes it wise to use this system as much as possible.

8.3 Maintenance in an autonomous vessel

8.3.1 Predictive maintenance

Installing sensors that are related to predictive maintenance help with preventing unwanted issues on sea and makes it possible to organize maintenance in port. This is pre action instead of reaction on failing issues. This makes preventive maintenance essential for unmanned vessels. The seafaring engineers will not lose their jobs but work in other environments. Without predictive maintenance the planning of maintenance and the preventing of events will be much more difficult.

8.3.2 Preventive maintenance

By use of a preventive maintenance system the lifespan will extend through painting, lubricating, cleaning, adjusting and replacing of minor parts. Preventive maintenance is carried out on a time or condition base. This means that tests and periodic inspections will be carried out in order to prevent any problems that may arise.

8.3.3 Corrective maintenance

Corrective maintenance will always be the last resort of maintenance done aboard a vessel or installation. Instead of fully man maintained maintenance, it will shift to robotic maintenance and shore based maintenance in the near future. This means that engineers are no longer required on a sailing ship. Instead the future engineers are stationed at shore based workstations and centers where they will go to the vessels that are in need of maintenance. This will all happen in port.

While an autonomous vessel is seagoing emergency repairs can be made by the use of robotics or be postponed till the next port of arrival.

8.4 The influence on machinery space

The technical department will look different in many ways, the human factor will disappear and the systems will adapt to good use in autonomous vessels. Some systems will be deleted completely and others will be used for different purposes. This way the vessel is optimized for autonomous sailing.
8.5 End conclusion
The technical department in autonomous vessels will be different from manned vessels. Not only will there be more space for the systems, but they need to be further automated and the layout needs to be more general. Is it possible to sail autonomous this research says yes to that but still more research is required before this can be applied on all vessels and that will require time.
9 Recommendations

Fully electric is the best choice for autonomous vessels at the moment. This is because of developments as the Wärtsilä low loss concept. This low loss concept is the most suitable system already developed at the moment for (autonomous) vessels, because of the high ERN number and other advantages. Therefore this system should be considered on future (autonomous) vessels.

Powder coated pipes, FRP pipes and Fusiotherm pipes are all applicable on autonomous vessels and already on the market. Fusiotherm is most promising on vessels because of the wide application; this has a lot of advantages for the piping system but is not applicable on all systems on board of vessels. Therefore this should be tested in practice on board of vessels.

Maintenance is important with autonomous sailing. Therefore a recommendation is to make best use out of predictive and preventive maintenance and reduce the corrective maintenance to a minimum. Predictive maintenance creates jobs on shore and makes a plannable maintenance in port. With preventive maintenance the engineers on shore are continuously checking the systems for the operation. There are already several systems on the market with predictive and preventive maintenance. This is often brand related and the choice will be different for every vessel. The last resort will be corrective which also will be done in port or on board by robotics. More research is required for the application of robotics on autonomous vessels.

An optimal autonomous vessel will be one where all the systems are adapted to operate fully autonomous, this is still in progress and will take time and research to be implemented.
Appendix 1

Interview Wärtsilä

Propulsion

- Do you think it is possible that the Wärtsilä Low Loss Concept is applied on autonomous vessels?
- Do you think that it is achievable to make the engine room filled with inert gas? And why or why not?
- How does Wärtsilä think about the use of high quality plastic pipelines for the engine?
- What are the techniques that Wärtsilä use for making the engine failsafe?

Maintenance

- Preventive
  o Is Wärtsilä working on a new way of preventive maintenance? Not like the old one which is based on running hours.

- Predictive
  o We heard that Wärtsilä has engines onboard of vessels that sent a couple of times a day data about the status of the engine. Is this correct?
  o What kind of data is sent to your control center?
  o Gives this information from the vessels a better vision on the engines performance and wear and tear?
  o Has this way of distance monitoring big advantages on the lifespan of the engine? If so, why?
  o We are trying to bring down the corrective maintenance by the use of vibration and temperature measurement. Is Wärtsilä involved in research at measuring the state of the engine parts?

- Corrective
  o When a vessel is sailing autonomously and there is a small brake down. Is it than possible that robots can be used for this small maintenance like replacing sensors or lubricating?
  o Is Wärtsilä doing research at 3D-printing of spare parts at the moment?

General

- What is the vision of Wärtsilä about autonomous sailing?
- Is Wärtsilä doing research at autonomous sailing?
- Do you think that it is possible that there will be an engine that needs now maintenance at sea whit in 10 years from now? This engine will then be monitored and maintenance will be done in port.
- What is the future of the technical seafarer in your opinion?
- Do you have any questions/comments for us?
## Appendix 2

### Properties of the tube

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<th>Weight</th>
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*Table 1 (aquatherm belux, 2016)*
### Appendix 3

**Fusiotherm type SDR11**

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<th>Temp.</th>
<th>Years</th>
<th>SDR11</th>
<th>SDR6 Stabi</th>
<th>SDR7,4 Faser</th>
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## Appendix 4

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Appendix 5

Design turbo and starting air system

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## Appendix 6

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Appendix 7

Scrubber tower
Bibliography


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