A SYSTEMATIC MATERIAL SELECTION PROCESS FOR BIOGAS FEEDSTOCK SYSTEMS IN CRUISE SHIP

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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A systematic material selection process for biogas feedstock systems in cruise ship

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78 pages, 19 figures, 13 tables and 3 appendices

Examiners: Associate Professor Hemantha Yeddu, D.Sc. (Tech.) and Docent Harri Eskelinen, D.Sc. (Tech.)

Keywords: Systematic material selection process, circular economy, biogas, sewage, food waste, four-field analysis, cobweb-analysis, R5, plastic, stainless-steel.

This Master thesis conducted a systematic material selection study for the systems used as a biogas feedstock. The systems such as black water and food waste in a cruise ship were studied from aspects of their functional, environmental, manufacturing and production, and cost requirements. In the thesis assistance tools and calculations were utilised to study suitability of material properties for the systems. From the environmental perspective materials were studied utilising the R5 approach. As pre-selection of materials was used stainless-steel AISI 316L and plastic PE100. The goal of the material selection process was to find out answers to the following questions: What special features does the systematic material selection process have to include in sewage and food waste systems and why? Which assistance tools apply the best for the systematic material selection process in pipe design and why?

The results showed that materials AISI316L and PE100 are suitable for the systems, although their mechanical and physical properties differ. The R5 approach provided important environmental information on the selection from the point of view of the manufacturer and the buyer. The manufacturers of both materials have sustainability strategies, but the study revealed that there are differences such as in the use of recycled material in production. Results indicated that the assistance tools four-field and cobweb - analyse provided good insight to the material properties. The results of calculations supported the material selection by revealing the materials' behaviour in different circumstances. Results also included case study calculations of a typical cruise ship's waste streams to assess the potential energy production from waste.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Konetekniikka

Aleksi Stenberg

Systemaattinen materiaalinvalintaprosessi biokaasun syöteainejärjestelmille risteilylaivassa

Konetekniikan diplomityö

2022

78 sivua, 19 kuvaa, 13 taulukkoa ja 3 liitettä

Tarkastajat: Apulaisprofessori Hemantha Yeddu ja Dosentti Harri Eskelinen

Avainsanat: Systemaattinen materiaalin valintaprosessi, kiertotalous, biokaasu, jätevesi, ruokajäte, nelikenttä -analyysi, cobweb -analyysi, R5, muovi, ruostumaton teräs.

Tässä diplomityössä suoritettiin systemaattinen materiaalivalintaprosessi biokaasun raaka-aineena käytettäville putkistojärjestelmille. Risteilyaluksen järjestelmiä, kuten mustavesi- ja ruokajäte, tutkittiin niiden toiminta-, ympäristö-, valmistus- ja tuotanto- sekä kustannusvaatimusten näkökulmasta. Diplomityössä materiaaliominaisuuksien soveltuvuutta järjestelmiin tutkittiin apuvälineillä ja laskelmilla. Ympäristönäkökulmasta materiaalia tutkittiin R5-lähestymistavalla. Materiaalien esivalintana käytettiin ruostumatonta terästä AISI 316L ja muovia PE100. Materiaalien valintaprosessin tavoitteena oli löytää vastauksia seuraaviin kysymyksiin: Mitä erityispiirteitä systemaattisen materiaalinvalintaprosessin tulee sisältää jätevesien ja ruokajätteen systeemeissä ja miksi? Mitkä systemaattisen materiaalin valintaprosessin apukeinot soveltuvat tukemaan parhaiten putkistosuunnittelua ja miksi?

Tulokset osoittivat, että materiaalit AISI316L ja PE100 sopivat järjestelmiin, vaikka niiden mekaaniset ja fysikaaliset ominaisuudet eroavat toisistaan. R5-lähestymistavan käyttö ympäristönäkökulmasta antoi tärkeää tietoa valmistajan ja ostajan näkökulmasta. Molempien materiaalien valmistajalla on kestävän kehityksen strategiat, mutta tutkimus paljasti, että kierrätysmateriaalin käytössä materiaalien tuotannossa on eroja. Tulokset osoittivat, että aputyökalut nelikenttä- ja cobweb auttoivat vertailemaan materiaalin ominaisuuksia keskenään. Laskelmien tulokset tukivat valintaa saada enemmän selville materiaalien käyttäytymisestä eri olosuhteissa. Tulokset sisälsivät myös Case study -laskelmat tyypillisen risteilyaluksen jätevirroista, joiden avulla voitiin arvioida mahdollista energiantuotantoa jätteestä.

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I want to thank my employer Deltamarin for the flexible approach to my study leave enabling me to focus fully on the studies. I also want to thank LUT for making possible to research the subject close to my heart and the support during the process. First and foremost, and I want to thank my wife for supporting my studies on every step from the beginning.

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SYMBOLS AND ABBREVIATIONS

Roman characters

D	outer diameter	[mm]
L	length	[mm]
m	mass	[kg]
p	pressure	[bar, Pa]
T	temperature	[ºC, K]
v	specific volume	[m3]

Greek characters

ρ	density	[kg/m^3]
α	thermal expansion coefficient	[mm/m(m*°C]
λ	thermal conductivity	[W/mK]

Abbreviations

AD	Anaerobic digestion
AISI	American Iron and Steel Institute
BAT	Best available techniques
BV	Bureau Veritas
BW	Black water
DNV	Det Norske Veritas
FW	Food waste
GW	Grey water
IMO	International Maritime Organization
PE	Polyethylene

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1 Introduction

The relevance of the master thesis and its necessity to the understanding of the topic is stated in the introduction. The author's motivation and the topic's context are detailed. Research problems, questions, and methods are introduced. Finally, the introduction states the thesis' scope and its contribution to the company and to the maritime industry.

1.1 Background and motivation

Human activity disrupts the cycle of nature including the natural nutrient cycle. Among other things, the disturbed nitrogen cycle leads to the eutrophication and acidification of water bodies. Eutrophication is caused by a richness of nutrients in water bodies due to the runoff from the land. Phosphorus, an important plant nutrient and prerequisite for food production may disappear before oil. As the phosphorus reserves decrease, the price of phosphorus will increase. In addition, artificial fertilizers consume a lot of energy. Nutrients that are already in use are valuable and so, they must be recycled and re-used. The Finnish transport and communications agency stated in 2013 that heavy traffic fuel would be 70% biofuels. Biodegradable wastes and sludges are formed in communities, wastewater treatment plants, agriculture, and industry. Most of these waste products are wet, so they present challenges to convert into thermal energy. This gives them an advantage to be used as a source of biogas. Their use would also help to meet the agreed material recycling targets. (Kymäläinen & Pakarinen 2015, p.7)

Biogas technology offers one solution to the above-mentioned global challenges. Biogas technology enables the recycling of nutrients, produces renewable energy, and promotes material recycling. Biogas technology can be produced in multiple scales, and it can be integrated into a variety of future biorefinery concepts to attain the optimal use of raw materials. Biogas technology can therefore be considered as an important factor enabling the circular economy (Kymäläinen & Pakarinen 2015, p.7).

Not only maritime but all industries are under pressure to make a green transition. Emission-free energy systems and other climate and environmentally friendly solutions are at the centre of many countries and companies' climate strategies. The aim is to improve energy efficiency with a fossil-free solution. Clean energy production, such as biogas, will promote green transitions with a circular economy. The industrial circular economy solutions not only produce clean energy, but they also reduce the amount of waste released into the environment. So why not utilise the unused clean energy source? (Schumüller, Weichgrebe & Köster 2020).

Shipping is also facing new, challenging regulations to reduce greenhouse gas emissions in the coming years. The International Maritime Organization (IMO 2019) has stated that "total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008." The circular economy can be improved especially in cruise ships where waste is recycled. Cruise ships produce a lot of waste, and they need large onboard systems to purify wastewater. Even direct discharge is still possible in some areas. If energy can be produced from waste, it allows the reduction of operating emissions with a climate-friendly energy resource already onboard. The circular economy can, if implemented on a larger scale, could reduce the global carbon footprint.

The initial reason for this thesis comes from my interest in rethinking old solutions towards more sustainable and cleaner technology. The old Finnish saying "back in the days everything was better" does not fit into today's climate strategy. But effective new solutions require a circular economy and the sustainable development of materials. The current situation worldwide, with increasing population and wastes, compels the maritime segment to discover and investigate materials and new solutions for cleaner and greener consumption. Not only the operational consumption, but also the manufacturing side needs improvements. Materials form the core of these solutions. Like Georg Fischer's (2022a) climate strategy states "Sustainable solutions are only possible if the entire life cycle of the applications and products is considered." That is why this is an important research topic.

The second reason for this thesis is the dire ecologic condition of the Baltic Sea. The Baltic Sea is ecologically unique, and it is highly sensitive to environmental impacts resulting from human activities. Cruises last approximately one week, and, during that time, waste must be processed to remove environmental hazards to meet regulatory obligations (Huhta, et al. 2007, p.24-25). However, according to Kallio-Kurssi (2022), even today, cruise ships can discharge shredded food waste and grey water accumulated in kitchens and showers directly into the sea without treatments. From the beginning of the year 2022 to the summer of 2022 there have been 48,000 travellers on international cruise lines visiting Helsinki harbour. Cargo ships can discharge all their wastewater into the sea in compliance with international regulations (Kallio-Kurssi 2022). In the Baltic Sea 2000 ships operate every day, from which 95% are cargo ships (Kallio-Kurssi 2022). This gives some perspective on the current situation. Every waste into the Baltic Sea is pointless, no matter what source it comes from.

1.2 Research problem

New technologies need sustainable materials for every system. A sustainable pathway to decarbonizing needs to consider the entire vessel including materials and processes at the construction and recycling stages. It is necessary to consider how shipping fits into a wider scheme of waste reduction, better material flows, reducing and reusing less carbon intensive materials across global trade. Decarbonizing the global economy requires massive changes well beyond fuels (Lloyd's register 2022). Utilisation of circular economy may increase efficiency, give opportunity to novel solutions, and add value for cleaner and greener solutions. A more cross-sectional view of the circular flow of products, materials, and services is needed today.

This thesis will research current materials for sewage and food waste systems. Materials in these systems are under a heavy risk of corrosion and the used materials need to be re-evaluated for their operational and environmental conditions. Materials are studied to find out their functional requirements corresponding to a material property. The research is applicable to other systems and applications where the same kinds of issues occur.

1.3 Objective

The goal of this thesis is to investigate the material selection process for systems suitable for biogas feedstock. Novel and current solutions require the most appropriate material for their purpose to fulfil systems requirements, to maintain the system throughout its whole lifecycle, be easily repairable and that the material is produced in an eco-friendly way. Sustainable materials and how they are manufactured (carbon footprints of products) are essential to thinking this process through. Materials have a great potential from a circular economy point of view. Recycling of materials and the R5 approach are part of this research as well. Materials selected can provide practical benefits: extended lifespan, better materials, without forgetting environment places strict demands on systems. Wasteful methods such as single used plastics and products are no longer an option.

The purpose of this thesis is to investigate the onboard collection of food waste and wastewater to power an onboard biogas reactor. In my research I will focus on the systematic material selection process to select the best fitting material for the pipe design, which collects the previously mentioned waste streams. I see this study as necessary since this kind of solution has not been implemented yet onboard and the unused energy is still waiting to be utilised. Also, the materials in current use need re-evaluation and any possible new materials must meet the same requirements as the current materials.

1.3.1 Research questions

The research will explore the loading and environmental conditions related to the selected applications, investigate which materials suitable for the applications, and to understand how they are identified. Recycling and policy standards are also important when selecting materials and designing components for the applications. The research questions are:

1. What special features does the systematic material selection process have to include in sewage and food waste systems and why?
2. Which assistance tools are best applied in the systematic material selection process in pipe designing and why?

This thesis studies the systematic material selection to find out what special features are required by the processing of biogas feedstocks. They can be e.g., analysis of material behaviour in different circumstances supported by calculations and utilising tools that take material properties and system requirements into account. Related aspects of environmental and manufacturing are studied for a more holistic approach.

1.4 Research methods

The thesis will include a literature review of the current waste treatment and land-based biogas solution. Methods will include an overview of the systematic material selection process with assistance tools. The research is conducted with a systematic material selection process for the pipe systems utilised as biogas feedstock, analyses and calculations of the pipes, interviews, and a case study, which includes data from the organic waste and results produced on a cruise ship. Also manufacturing, environmental and sustainability aspects are taken into consideration.

1.5 Scope

The research will be limited to the material selection for the materials of pipe systems used as biogas feedstock. The thesis touches upon biogas reactors, but a closer examination of their role is omitted. The study is made with pre-selected materials taken from current typical waste handling and treatment systems. Possible new materials are not studied, although their requirements are derived from a review of systems' requirements that may be utilised in further studies. Some assistance tools are left out, for the fact that they exceed the scope of one master thesis e.g., LCA, LCC and FEM analyses of material behaviour. The focus of the thesis is on the design, environmental, and circular economy point of views.

1.6 Contribution

I see that the big picture of this thesis may bring novel value to the maritime segment. Although this thesis concentrates on systematic material selection process for pipe systems, the idea of utilising waste as energy source is worth studying. Also, both current and legacy materials need periodic re-evaluation for compliance with constantly changing regulations. Materials have great potential from a circular economy point of view, so every systematic material selection is worth studying. Extending material lifespans and the use of sustainable materials in novel solutions hold great promise in their potential to decarbonise shipping, a critically valuable target in the current worldwide situation. This study creates a good foundation for further and broader research on this subject because circular economy concerns are integral to novel solutions. Initiatives in green technology also offer social responsibility advantages to a brand.

2 Ship-generated organic waste types and handling

According to Vaneeckhaute and Fazli (2019), cruise ships are the main producers of waste materials on the Baltic Sea. Cruise ship wastes include organic wastewaters such as water from food waste, grey water, and black water (sewage). Food waste is an organic material which is categorized as part of the "garbage" waste stream. Wastewater is divided into black and grey water. Black water consists of sewage generated by toilets, urinals, and medical facilities. Grey water is divided into three main streams: grey water from accommodation (showers, wash basins, bath tubes), grey water from galleys (includes grease), and grey water from laundry (includes detergents) (Vaneeckhaute and Fazli 2019, p.14; Mäkilä 2022).

In case study section I will introduce the ship-generated nutrient-rich organic waste data of food waste, black and grey water. It will include the amount of wastewater and food waste generated per person on a typical cruise ship. Accurate data on waste flows will help inform analyses and research. The amount and type of waste will affect pipe design and material selection. Therefore, the information from cruise vessels is valuable.

2.1 Food waste – Handling and treatment

Vaneeckhaute and Fazli (2019) state that "food waste is a large fraction of ship-generated solid waste with specific characteristics that require appropriate waste management strategies." Food waste is classified into two different groups: soft organic food waste as well as hard organic food and packaging. (Vaneeckhaute and Fazli 2019, p.13.)

Food waste as a wet material is subjected to microbial activity, which can cause concern for passengers and staff onboard. In addition, food waste has plant-based enzymes which when active might accelerate the spoilage process. Since ships are isolated communities, they require strict control of their waste management to prevent the spread of disease onboard. Direct discharge of the waste into the sea is still common in the areas where not prohibited. Food waste disposed at sea can have an influence on the marine biosystem and it can create ecological disturbances due to its constituent including nitrogen and phosphorus (Vaneeckhaute and Fazli 2019, p.13-14). Besides these environmental concerns, waste discharges at port reception facilities (PRF) are costly to ship owners, making it crucial to find the best solution for the waste handling. Recently, the Baltic Sea Action Group (BSAG) has launched the "Ship/t Waste Action", where ships' toilet wastewater is discharged in port and biogas is produced from it (BSAG 2021).

According to Vaneeckhaute and Fazli (2019), up to 3.5kg/person per day of food waste can be generated in cruise ships. Cruise ships with 3800 persons onboard generate annually about 1700m^3 food waste, or 22% of the total waste produced onboard (Vaneeckhaute and Fazli 2019, p.13).

2.1.1 Design of the food waste handling system

Food waste handling is divided into wet and dry garbage. The wet garbage is collected from pantries, galleys, and sculleries with a vacuum system that leads to a garbage handling room. Solid material is removed from food waste in the dewatering units, then collected in a silo. The solid food waste is dried in dedicated dryers before final disposal by incineration. The water separated from solid food waste is collected in a food waste reject water tank and from there delivered to the advanced wastewater purification system (AWP). The solid residuals from the AWP system are collected and sent to the food waste system for drying and incinerating. The most used piping material in the food waste system is AISI 316L. (Deltamarin Ltd.)

Dry garbage is collected from restaurants, shops, pantries, galleys, and from accommodation areas and transported to the garbage handling room. Recyclable materials are unloaded from the ship in harbour, but non-recyclable and burnable material is incinerated. The incinerator burns flammable materials including bio-sludge from the AWP, waste oil, and food waste. This typical flow is presented in figure 1. Dry garbage is treated in three process lines (Deltamarin Ltd):

- Burnable garbage
- Non-burnable garbage
- Recyclable garbage

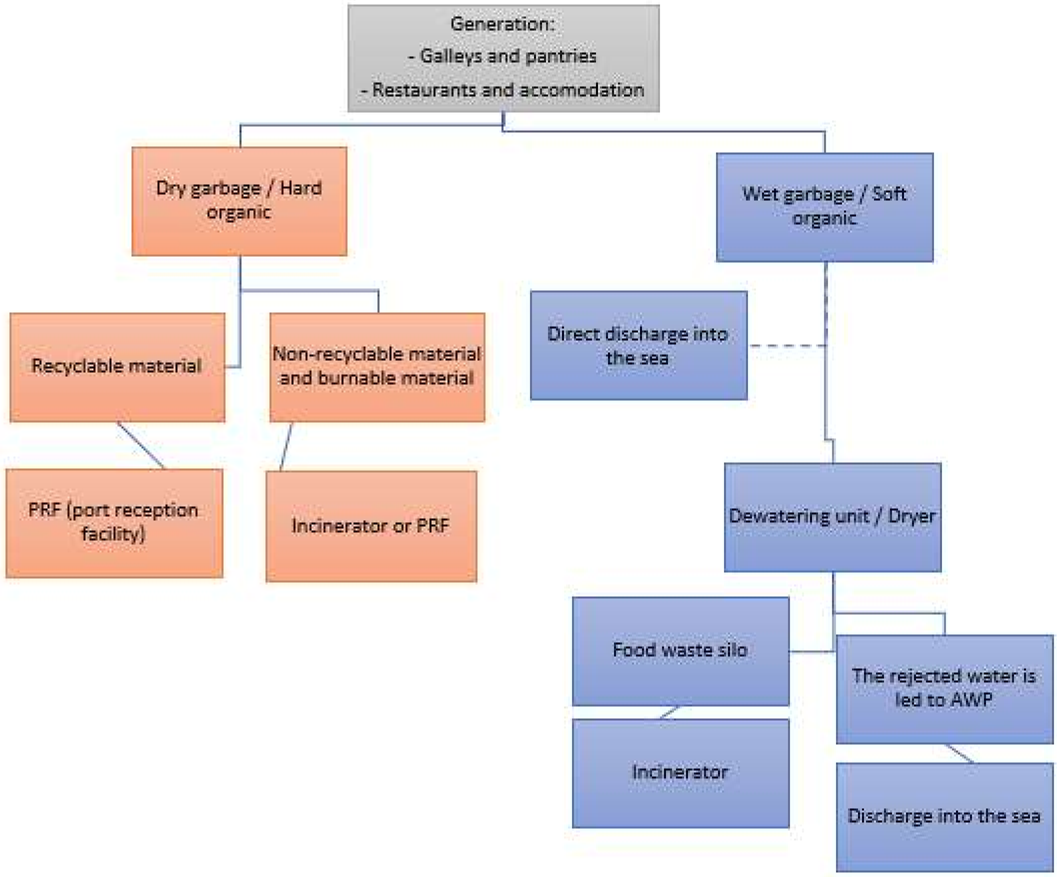

Figure 1. Typical current food waste flow diagram in a cruise ship

2.2 Black and grey water – Handling and treatment

Wastewater is divided into black and grey water. The estimated water consumption in a cruise vessel is between 200 to 250 litres per person per day. A rough estimation is that one out of five parts of water becomes sewage, and the rest becomes grey water. Onboard sewage is generally more concentrated than land-based sewage due to the onboard use of water-saving methods, i.e., vacuum collecting system. (Mäkilä 2022.)

2.2.1 Design of the black and grey water systems

Black and grey water storage is organized in dedicated water holding tanks. Sewage water storage strategies vary depending on the ship type. For cruise ships, black water from the toilets and urinals drains via a vacuum collection system and collecting tanks to the AWP system. Medical grey water from the hospital is collected with a gravity system that leads to a dedicated hospital grey water collecting tank. In case of emergency, the black water may be pumped to the sea. (Deltamarin Ltd.)

The grey water is collected from the cabins, galley, pantries, and laundry with a gravity system that leads first to the grey water collecting tanks and is then pumped from there to the AWP system's mixing tanks. In case of emergency, the grey water may be pumped to the sea. The galley grey water runs through a heated grease separator before it goes to the mixing tank. Laundry grey water is lead directly to the mixing tank. Though the black and grey water are handled differently, in the end they are collected into the same mixing tank. The flow of the sewage handling is presented in figure 2, where both handling options are possible for both systems. In both black water and grey water systems, the most used piping material is AISI 316L, but plastic pipes such as PE (Polyethylene), PPFR (PP Flame Retardants), ABS (Acrylonitrile-butadiene-styrene) and PVC-U/C (Polyvinyl Chloride) are also used (Deltamarin Ltd; Pöntiskoski 2022).

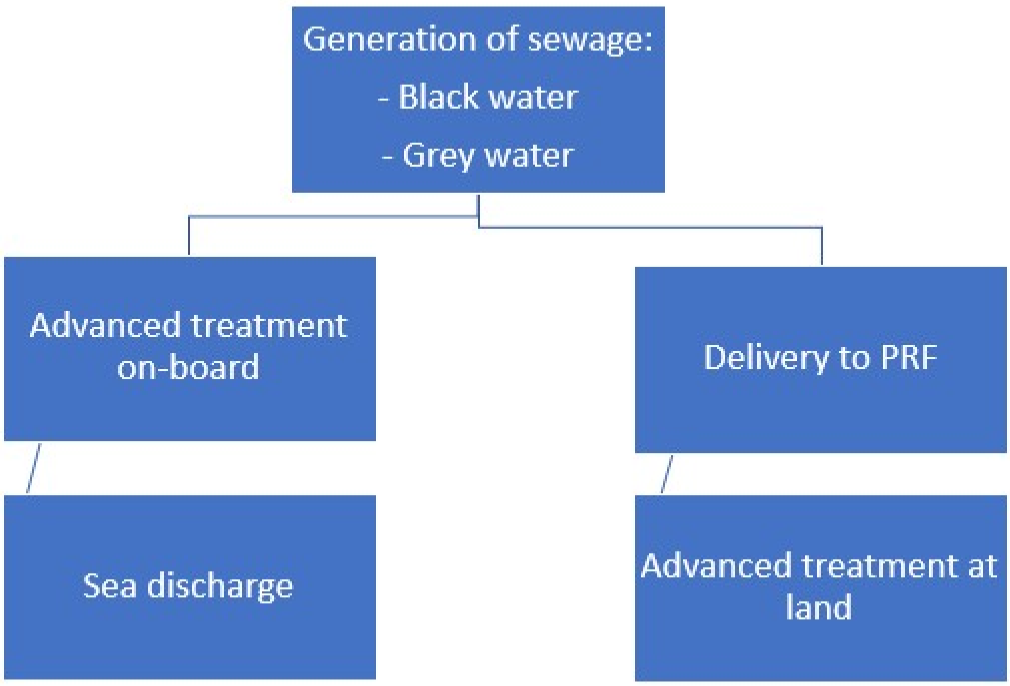

Figure 2. Flow of the sewage handling

2.3 Rules and regulations

At least two ship classification societies have set new additional environmental class notation to protect environment and to control pollution. Det Norske Veritas (DNV) established the environmental class notations Clean, Clean (Design), Clean (Tier 3) and Clean (Design, Tier 3). Also, another ship classification society Bureau Veritas (BV) created the Cleanship and Cleanship Super class notations. These notations set requirements regarding a ship's design, operation, and equipment to reduce the environmental impact from emissions to air, discharges to sea, and deliveries to shore from vessel. They require operators to improve their technical and management procedures to reduce new ships' carbon footprint and environmental impact. The notations will also increase ship's reselling capabilities, as there is a strong market demand for greener ships. (DNV 2021; Bureau Veritas 2021.)

U.S Public Health Service (USPHS) regulations apply mainly to food preparation and storage rather than food waste or wastewater systems of cruise ships. The USPHS rules cover topics such as hygienic food and beverage handling, cleaning instructions, storing food at proper temperatures (refrigeration), separation of clean and dirty dishes, transporting food between galley and serving areas, and personal hygiene (handwashing). USPHS requires pipes in the ceilings above gallies, pantries, food preparation and service areas, ECR, and switchboards rooms, to be made of stainless-steel with welded connections. Other rules deal with food preparation and hygiene, however, more detailed explorations of these regulations are not conducted in this thesis. (USPHS Manuals and Instructions.)

According to the DNV's rules, there are several testing procedures applied to the different piping systems including mechanical testing, hot tensile testing, impact toughness testing, and corrosion testing of pipes and fittings (DNV 2017a, p.107-108). The DNV's rules for piping systems establish requirements for piping materials. The materials used in piping systems must be suitable for the medium and service for which the system is intended. Depending on the type of material, service, and location there are slightly different requirements. (DNV 2017b.)

2.3.1 Plastic piping systems

The International Maritime Organization (IMO) has guidelines for the plastic pipe applications. Resolution A.753(18) covers acceptance criteria for plastic materials used in piping systems, criteria in design and installation requirements, and fire test performance criteria. The goal is to assure ships' safety and to assist maritime administrations to determine the permitted applications for such materials. It sets requirements for piping systems used in different areas based on internal/external pressure, axial strength, temperature, impact resistance, ageing, fatigue, erosion resistance, fluid absorption, and material compatibility (IMO Resolution 1993). These requirements resemble many of the criteria for a systematic material selection process.

Classification society DNV has also a criterion for plastic pipes. The criteria are similar to those of IMO Resolution A.753(18). The rules concern fire protection e.g., where coating of pipes is necessary for achieving the needed fire endurance level and penetrating of watertight bulkheads or decks (DNV 2017b p.22-23).

This is a brief overview of the rules relating to material requirements set by maritime organizations (such as the IMO) and classification societies (such as DNV). Figure 3 shows a schematic view of the various levels of maritime rules and regulations.

Figure 3. Rules in shipping (Maritime)

3 The production of biogas

The production of energy from biomass has increased along with advanced waste treatment in the past few decades. Biogas plants use renewable, biodegradable, and organic wastes to produce biogas containing methane in anaerobic conditions that, like natural gas, can replace fossil fuels (Latvala 2009, p.3). Biogas technology is a diverse, wide, and multidisciplinary subject. The production of biogas is a biological, oxygen-free decomposition process, also known as anaerobic digestion process (AD) (Kymäläinen and Pakarinen 2015, p.8). The AD is a well proven technology to treat organic wastes for biogas production in an eco-friendly way. AD is a microbial process that simultaneously reduces the amount of waste to be disposed and produces methane that can be burnt as fuel to provide energy. AD processes are implemented in various kinds of bioreactors such as conventional anaerobic digesters, sludge retention reactors, anaerobic membrane reactors, anaerobic biofilm reactors, and high-rate reactors (Tabatabaei & Ghanavati 2018, p.98-112,118).

3.1 Technical review and design principles

In the biogas reactor a microbial process occurs, where organic waste is converted into biogas by anaerobic digestion. Biogas is a mixture of methane and other components. Feedstocks containing selected waste and microbial cultures are mixed in the bioreactor to achieve a desired conversion. There are two types of digester feedstock: wet (water-rich) and dry (solids-rich). A wet feedstock contains ≤15% dry solids and typically uses a pumpable aqueous slurry whereas a dry feedstock has a dry solid rate between 20-40%. (Tabatabaei & Ghanavati 2018, p.95; Kymäläinen and Pakarinen 2015, p.82.)

The wet process usually continuously processes feedstock and dismounts the digestate to enable a steady state production of biogas. The dry process can work both as a single-input and continuous method. The single-input method works in a way that the biogas reactor will be filled at once then closed until the digestion process is done. (Kymäläinen and Pakarinen 2015, p.82.)

Tabatabaei & Ghanavati (2018) also introduce a single-stage operation and a two-stage operation. The more common single stage operation is less efficient. In the single-stage digester all the different reactions (e.g., hydrolysis, acidogenesis, acetogenesis, methanogenesis) occur in the same container under the same conditions, which are not ideal for any of the multiple reactions that occur. This also requires longer hydraulic retention time (HRT) to produce needed methanogens. The digesters of the single stage process are larger in size and the energy consumption is also greater in comparison to two-stage digesters. Two-stage digesters separate the methanogenesis steps into two treatment processes. The first reaction chamber focuses on maximizing hydrolysis and production of volatile fatty acids. The second focuses on optimizing the production of methane. As a result, the two-stage digestion is more efficient compared to a single-stage process. (Tabatabaei & Ghanavati 2018, p.98.)

As mentioned, the digester type depends on waste input; the process can include either a single or multiple feedstocks. The input method can be either single charge or continuous. Biogas production may require different types of feedstocks to be blended to obtain a suitable composition that subsequently needs to be stored. Various pre-treatments may be needed (e.g., reduction of size) to facilitate the desired digestion process. (Tabatabaei & Ghanavati 2018, p.96; Kymäläinen and Pakarinen 2015, p.82.)

According to Tabatabaei & Ghanavati (2018) there are two types of digestion processes: mesophilic and thermophilic. Mesophilic processes operate at a temperature between 30–42 °C, while thermophilic processes operate in a higher temperature range of 50–62 °C. The choice of type used depends on the different groups of microorganisms. If the feedstock which is used in the digester process contains either waste from human (e.g., municipal wastewater) or waste from animals (e.g., manure or slaughterhouse waste) the thermophilic digestion process is preferable since it kills pathogens more effectively. This digestion process is rapid, but also more expensive and harder to control. However, if the thermophilic digestion process is used, the dewatered solid residue from the digester can be directly applied to soil as a compost without risk of spreading diseases or parasites to the environment. (Tabatabaei & Ghanavati 2018, p.96.)

3.2 The production steps of biogas

To find best available techniques (BAT) for biogas production, it is necessary to consider all the facts relating to the environment, technical applicability, and economy. The BATs in an individual biogas plant are estimated according to the specific features of its activity. The biogas plant's location must be evaluated for the environmental impact of its activity on any special characteristics of the area. The environmental impact consists of emissions to air and waters, the quality and number of wastes produced, the use of chemicals and raw materials, storage, waste recovery, and energy efficiency. When estimating technical feasibility, production methods, process technologies and their management, risk reduction and casualty prevention, education of personnel, and the age and location of the facility all must be considered. This thesis considers only the matter of technical applicability since a full consideration of this multidimensional topic would exceed its scope. (Latvala 2009, p.69-72.)

Latvala (2009) presents BAT methods used in designing biogas production. The main concern is to estimate the best location while considering the transport of the process input and digestate, the use of biogas, the capacity of the wastewater treatment, and odor nuisance. In the case of locating the biogas reactor in a cruise ship, the final location requires a detailed efficiency evaluation. Another design aspect involves selecting the most appropriate biogas process and reactor for the given waste type. When the type and quality of the waste is known in advance the process can be purposely designed. The waste input's characteristics should be considered early in the design phase. To maintain a steady operating level, the use of biogas reactor needs to have minimum amount of interruption for operation. In demanding sea-going conditions corrosion, durability, strength, and the age of use of the structures and equipment should also be considered. (Latvala 2009, p.69-70.)

To clarify what are the main BAT methods in designing the biogas process, the following list will summarize the main steps:

- Choose the best fitting location for the plant.
- Choose the waste input and process so that the biogas and other treated waste can be utilized.
- To choose the best fitting process according to waste input.

- To design the process so that the biogas plant can be operated without interruption and without any problems.
- Observe the sustainability requirements for the materials and equipment.

(Latvala 2009, p.69-70.)

Tabatabaei and Ghanavati (2018) represent the following important considerations in the selection and operation of an anaerobic digester:

- Installation and operation costs
- The necessary residence time or hydraulic retention times (HRT) of the waste in the digester
- The amount of waste to be processed
- The organic loading or strength of the waste and dry solids content
- Nature of the waste (the relative ratios of nitrogen and carbon)
- Wet or dry content or combination of these two
- Mixing requirements and pre-handling of the content
- Heating requirements (depending on whether the process is mesophilic or thermophilic)

(Tabatabaei & Ghanavati 2018, p.98.)

3.3 Different types of biogas reactors

Here are presented different types of bioreactors designed for biogas production. The reactors can be either dry or wet, batch or continuous, one-step or multi-step, or one-phase or multi-phase (Wellinger et al. 2013, p.115-116). Wellinger et al. (2013) introduces three different types of biogas reactors: dry batch reactors, continuously stirred tank reactors (CSTR), and dry continuous reactors.

Dry batch reactors use 30-40% of solid content. This type of reactor is preferred both for its design simplicity, and the relatively small amount of thermal energy input and electrical demand it requires. The digester works as a one-stage dry batch. The feedstock is applied to the digester as a single input. At the same time, half of the old feedstock is removed, and another half works as an inoculum for the next batch. The system works as a closed loop.

A continuously stirred tank reactor (CSTR) utilises a continuous wet process with a dry solid content between 2% - 12%. Many facilities around the world uses this type of reactor to treat sewage sludge, agricultural slurries, and crops. As shown in figure 4, both single-step and two-step systems can be implemented, however the two-step system is more commonly used as it is better for all bacteria groups. If the two-step system is used, then it is also able to recycle liquid digestate. A daily organic loading rate is in the range of 1-4 kg VS/m^3. (Wellinger et al. 2013, p.117.)

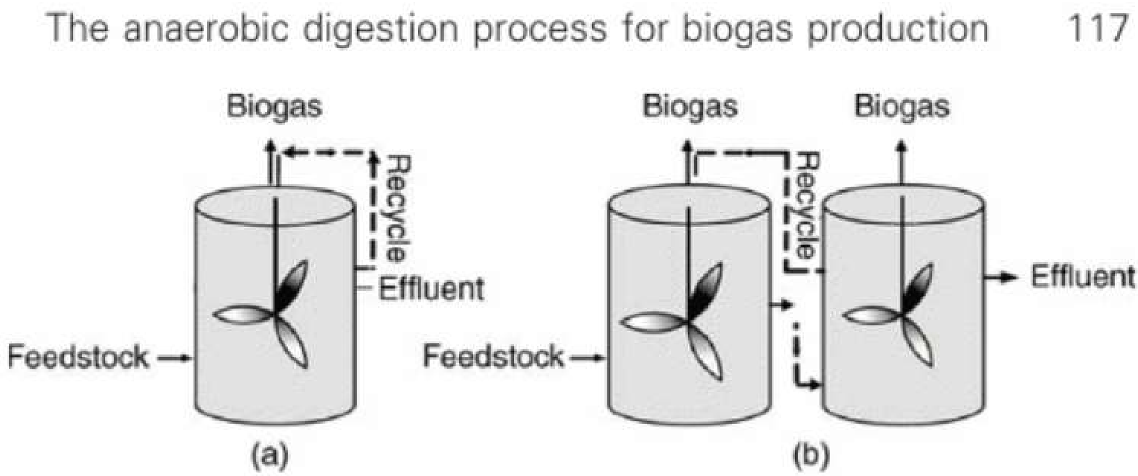

Figure 4. The design of a CSTR. (a) One-step and (b) two-step continuous digestion with recirculation of liquid digestate (Wellinger et al. 2013, p.117).

The last reactor considered is a dry continuous reactor Wellinger et al, (2013). It works as a plug flow system. In this system the substrate is fed at one end, and it flows through the reactor as a plug without mixing. The reactor can be positioned either vertically or horizontally, as shown in figure 5. (Wellinger et al. 2013, p.118.)

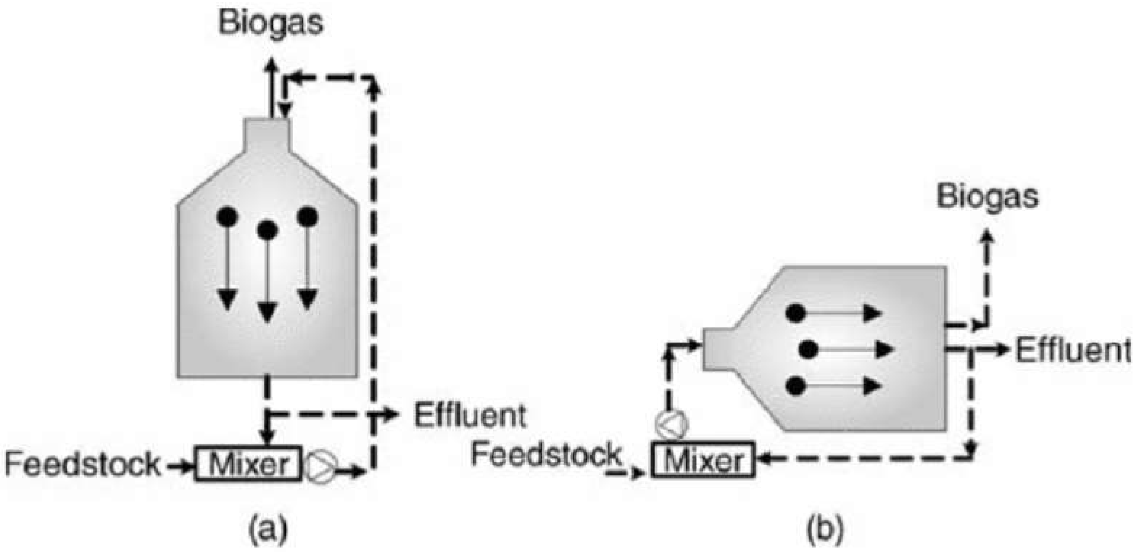

Figure 5. (a) Vertical and (b) horizontal dry continuous processes (Wellinger et al. 2013, p.118).

Tabatabaei and Ghanavati (2018) introduce five different biogas reactors. To select the right biogas reactor demands an evaluation of the type of waste, processing scenarios, and other conditions. These aspects of the biogas reactor's design and operation will influence the final selection. The five different biogas reactor types are conventional anaerobic bioreactors, sludge retention reactors, anaerobic membrane reactors, anaerobic biofilm reactors, and high-rate reactors. (Tabatabaei & Ghanavati 2018, p.95-116.)

The conventional reactor is divided into three types of reactors: Anaerobic Sequencing Batch Reactors (ASBR), Continuous Stirred Tank Reactors (CSTR) and Anaerobic Plug-flow Reactors (APFR). These reactors are commonly used due to their simple structure and operation. Figure 6 presents a reduced model of the conventional reactor concept. They use the feed from diverse sources such as food processing facilities, slaughterhouses, animal farms, and the organic fraction of municipal solid waste. The CSTR has a maximum solid content of 5-10%. The CSTR's reactor can be either rectangular or cylindrical including a mechanical stirrer. Having a variety of shape options is particularly advantageous for cruise ship applications, where space is greatly limited. (Tabatabaei & Ghanavati 2018, p.99–102.)

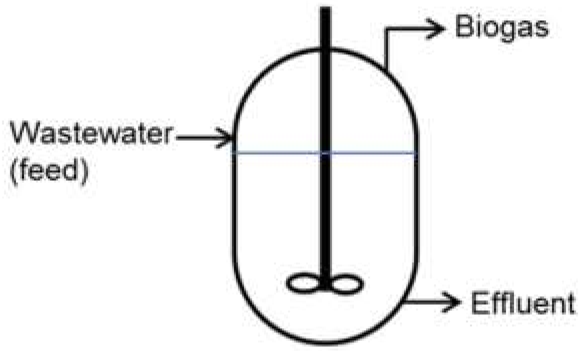

Figure 6. A continuous stirred tank type of anaerobic digester (Tabatabaei & Ghanavati 2018, p.100)

As the name describes, the sludge retention reactor is designed to decrease the time required to convert the microbial sludge into a biogas. This type of reactor has a short retention time and an increased rate of waste conversion. An anaerobic membrane reactor uses polymeric or ceramic membranes to retain the active biomass within the anaerobic wastewater treatment unit. The idea is to prevent loss of biomass to attain greater efficiency. The biomass is in contact with the waste material in an upstream tank. The anaerobic biofilm reactor has a cylindrical tank, where biofilm is used to handle organic loading. High-rate reactors aim for a better retention of biomass to maintain an active microorganism level, enhanced mixing between the wastewater and microbial solids, improve the control of temperature etc. The finer details of these reactors are excluded from this thesis. (Tabatabaei & Ghanavati 2018, p.99-112.)

Overall, the selection of different applications and reactors aims to reduce washout of active biomass, to make the start-up period shorter, to minimize operational functionality, and to respond better to the different varieties of feed compositions. The thesis does not advocate for the selection of a single suitable biogas reactor, but rather it presents the overall review of the requirements for different biogas reactor applications.

3.4 Utilising biogas as an energy source

What are some of the different applications for onboard produced biogas, both onboard and stored for later offboard use? In general, biogas can be utilised for heating, for electricity production, or as fuel. For heating, boilers with integrated circulating water systems. For electricity production several thermal power engines and fuel cell systems, such as Wärtsilä’s SOFC (solid oxide fuel cell) are used (Kymäläinen & Pakarinen 2015, p.157). There is also a possibility to produce both heating and electricity in a Combined Heat and Power -system (CHP). The CHP is a commonly used solution, as there is a need for both functions in a same location. Biogas production itself needs both heating and electricity so some of the produced biogas will be utilised to power the system itself. The biogas reactor requires heat energy as the process in the reactor requires temperature between 30-60 °C to produce gases containing methane. The mixing of a biogas reactor consumes part of an electricity. In total, roughly 10-40% of the energy produced is used for the biogas process itself. (Latvala 2009, p.44–46; Kymäläinen & Pakarinen 2015, p.150–157.)

Biogas must be refined to use as a fuel. Any carbon dioxide and sulphur compounds present must be removed from the gas. The remaining gas should contain only methane or natural gas. Biogas can be stored in gaseous, liquid, or absorbed into solid states. (Latvala 2009, p.47–48; Kymäläinen & Pakarinen 2015, p.158–161, 168–171.)

4 Systematic material selection process

This chapter presents the methods used in a systematic material selection process. This thesis answers questions as to what special features are required for the systematic material selection process in sewage and food waste systems and why? The relative merits of alternative assistance tools for the systematic material selection process in pipe designing are also examined. The assistance tool used in carrying out the research is presented in this chapter as well. The results section presents calculations that support a systematic materials selection process.

4.1 Methods of material selection process

Ashby (2011) identifies the four interactive aspects of material selection in mechanical design: function, shape, process, and material. To begin with process and shape, the shape depends on type of manufacturing process. These are e.g., forming, material removal, joining, and finishing processes. This leads us to a function. The material choice influences what manufacturing type can be used. The process itself determines shape, size, precision, and cost. Figure 7 shows well how none of these can be left out of the material selection process. As Ashby (2011) describes: “The interaction between function, material, shape, and process lies at the heart of the material selection process.”. (Ashby 2011, p.23.)

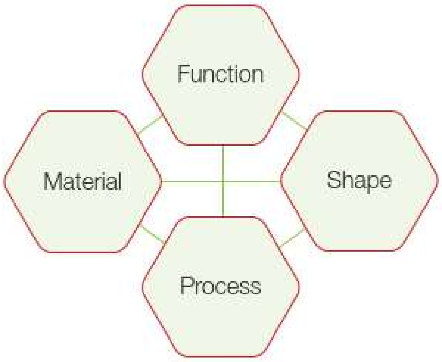

Figure 7. Interaction between functions (Ashby 2011, p.23).

Eskelinen and Karsikas (2013) also presents the material selection process from four different aspects: functions, environmental conditions, production and manufacturing, and costs. These four items form the core of material selection. Functional considerations can be e.g., wear resistance, load bearing capacity, stiffness and rigidity, and energy absorption. Process cost requirements are an important criterion, including the costs of e.g., raw materials, production and services, maintenance, quality, recycling and reuse, disposal, and life cycle assessment (LCA). The production type influences material selection as well-are the materials weldable, machinable, and easy to form and coat? Conditions and environmental aspects including humidity absorption, wear resistance, ageing, corrosion, and temperature are also important criteria. Together, all these criteria together inform the elaboration of the requirements profile presented in chapter 5. After this Eskelinen and Karsikas (2013) presents the next step of deciding the selection strategy to follow. (Eskelinen & Karsikas 2013, p.37-38.). More precise steps in material selection process are presented in Eskelinen's and Karsikas' process map shown in figure 8.

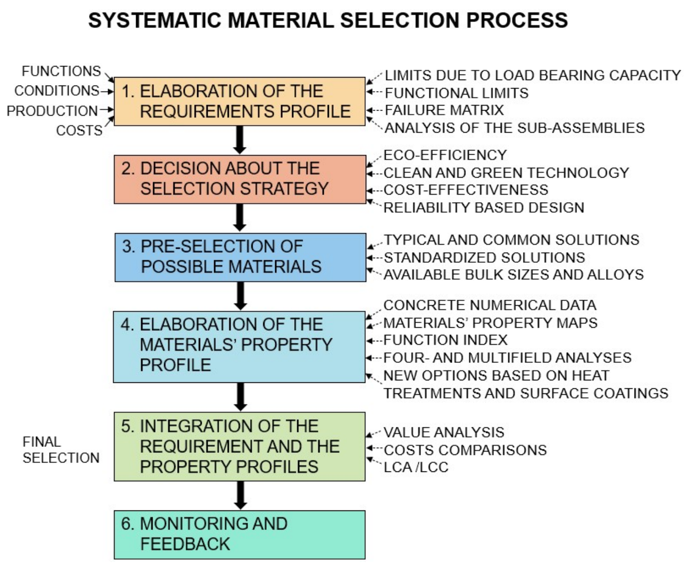

Figure 8. Systematic material selection process. Translated from (Eskelinen & Karsikas 2013, p.47)

Ashby and Eskelinen share criteria for the material selection process. Eskelinen and Karsikas (2013) include an additional step of deciding which selection strategy to follow. All these aspects of the selection process are important when developing the requirements profile. Each functional requirement may be seen as a precursor to the material selection process.

Rational material selection requires making compromises among these diverse criteria. (Eskelinen & Karsikas 2013, p.37-38.)

4.2 Tools

Ashby (2011) presents in figure 9 a design flow chart that shows how design tools and materials selection enter the procedure. Listing the varied design tools helpful in material selection, figure 9 also includes the market factors and data needs required throughout the material selection process.

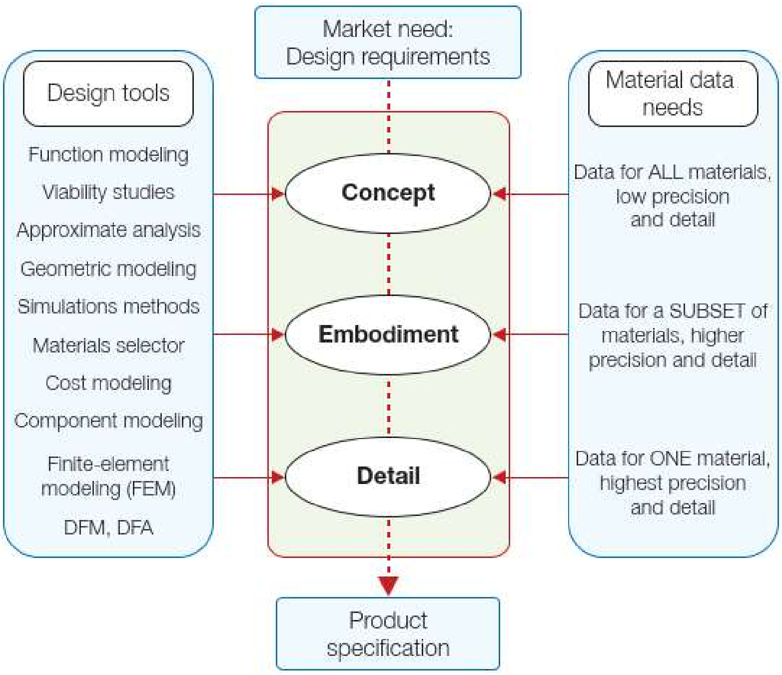

Figure 9. Design flow chart in material selection (Ashby 2011, p.21).

As shown in figure 9, finite-element modelling (FEM) and computational fluid dynamics (CFD) are useful tools in design tool packages. These tools allow a more detailed study of pipe behaviour. They allow more precise mechanical and thermal analysis predicting the occurrence of material deformations. As Ashby (2011) mentions, design tools play an important role throughout the material selection process.

The three stages presented in figure 9 show the natural progression of design tools. In the concept stage the modelling and analytic parameters are approximate estimates. All options remain open and so the range of materials is wide. Low-precision and -detail data is used for all materials. In the embodiment stage materials optimization is more sophisticated. In this stage there is a risk of excessively narrow thinking that may exclude materials prematurely. Data of a higher level of precision and detail is needed for a subset of materials. In the final stage of detail, the analysis is exact. Only one or a few materials remain under consideration requiring precise and detailed investigation. Materials' distinct properties can be found in datasheets provided by material or equipment suppliers and from detailed datasheets of material classes. (Ashby 2011, p.22.)

Ashby (2011) adds an important consideration following the material selection process: "The materials input does not end with the establishment of production. Products fail in service, and failures contain information." The analysis of product failures can provide valuable information and data that can lead to a redesign or reselection of materials. Therefore, the material selection process needs continuous monitoring and re-evaluation.

Eskelinen and Karsikas (2013) present the material selection as consisting of three phases: vision, prototype, and in real use. In the vision phase, product components are made of different material groups with simplified and typical geometries. The geometry is user friendly and aesthetic. In the prototype phase, the product's materials are preliminarily selected for testing. A 3D-model of the prototype is made to allow a more visual understanding of how the product will appear utilising various materials. During the "in real use" phase the constructional material is selected, and technical requirements are specified for production trials. Both product and production development has started. When comparing Eskelinen's and Ashby's material selection processes, many similarities can be found. Yet while the procedures they consider are similar, there remain some differences in the finer details.

4.2.1 Assistance tools

Assistance tools used to find relevant material properties include four-field analysis, cobweb-analysis, material property mapping, and R5.

The four-field analysis examines material properties by placing them into the coordination field (figure 10). The box surface areas define the four properties to be compared. The focus of the "boxes" works as an indicator as well (Eskelinen & Karsikas 2013, p.50-51). The box is determined with material properties, which can be up to four or alternatively three, where on x-axis is operating max and min temperatures evaluated. Especially with plastic, it is important to take into consideration temperature, since the many mechanical properties of plastics depend considerably on the operating temperature (Eskelinen & Karsikas 2013, p.208). Obviously, larger the box area is, the better material properties it has. That is how, the material properties can examine, however it is valuable to also estimate the system requirements on later phase.

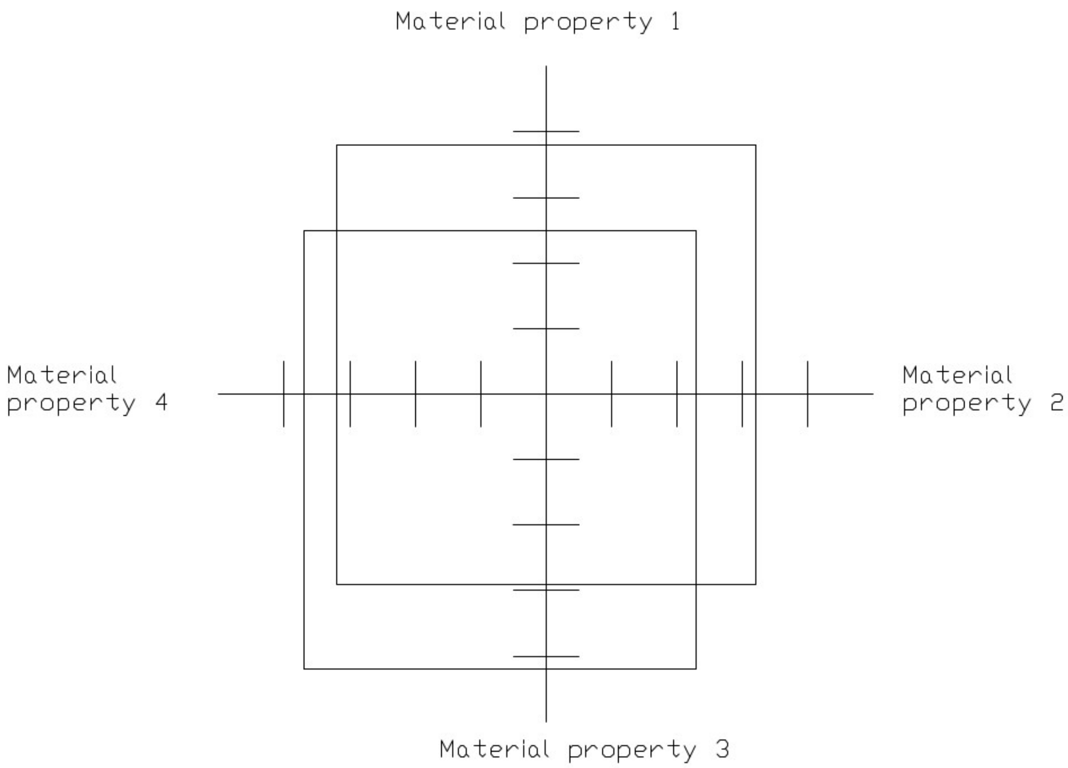

Figure 10. Four-field analysis. Translated from (Eskelinen & Karsikas 2013, p.51)

The COBWEB analysis (figure 11) allows more material properties to be examined in one analysis map. Each property is given a numerical value for comparison to the other properties. A larger number indicates a better material property. This analysis map gives a holistic view of the material properties that can be used as one way of finding a relevant material property according to requirements. The COBWEB comparison of material properties to component requirements can support further examination of the material's suitability for the selected product.

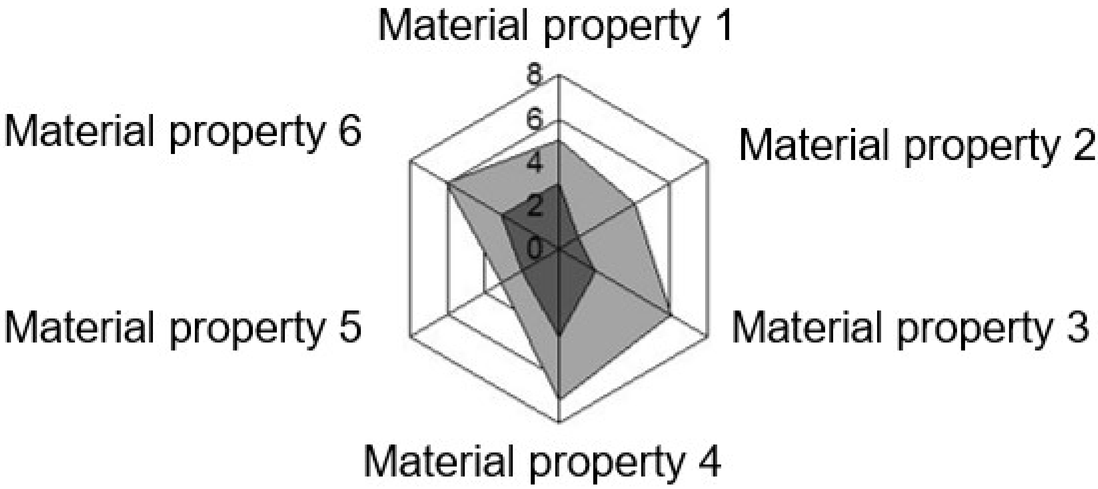

Figure 11. COBWEB-analysis. Translated from (Eskelinen & Karsikas 2013, p.51)

The material selection map shown in figure 12 places materials into a two-dimensional map with each axis representing a property of the materials. The x axis represents the modulus of elasticity, and the y axis represents the material's density value. This mapping technique allows a visible comparison of multiple materials values for those two properties. In this example, the goal is to find a material which has both high stiffness and a low weight (density). Material 1 has the higher density and higher elasticity modulus. Material 2 has a lower density but also a lower elasticity modulus. The best material for this purpose would have a low density, but high modulus of elasticity, placing it in the map's upper left corner. The boundary conditions are set by the functionality index that meets the requirements. Selection guidelines help to eliminate the materials that do not meet both requirements. (Eskelinen & Karsikas 2013, p.52-53.)

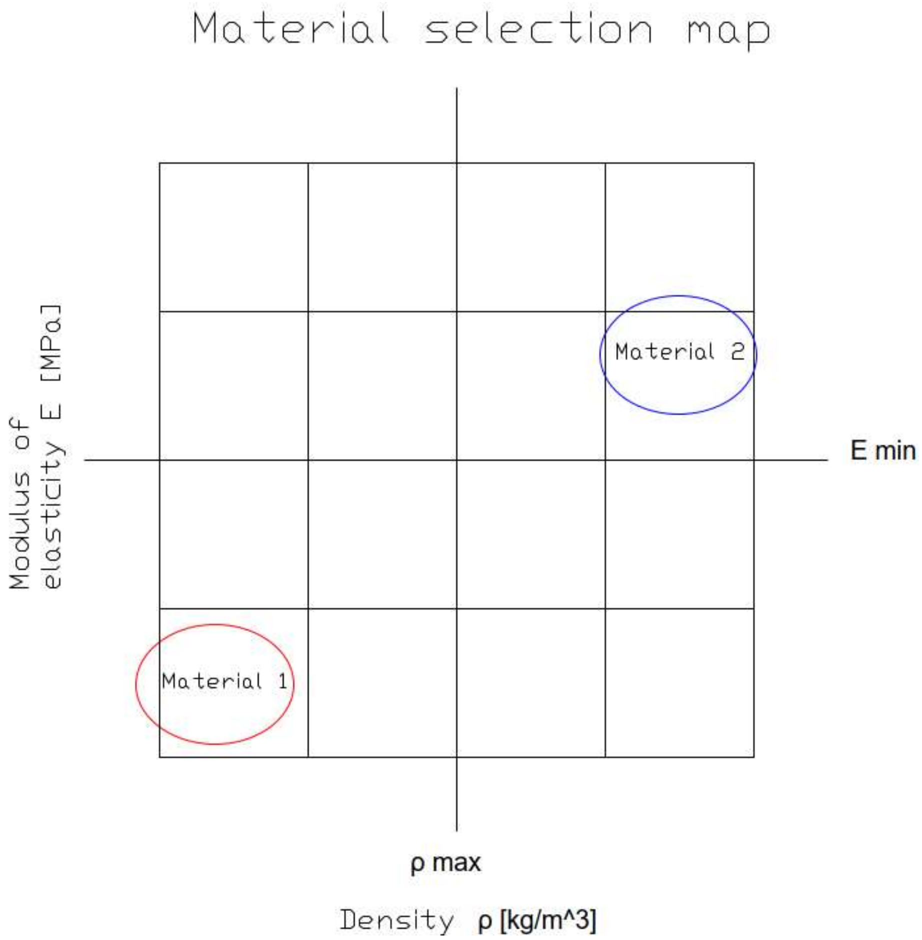

Figure 12. Material selection map. Translated from (Eskelinen & Karsikas 2013, p.53)

The R5 approach considers the material selection process from the aspect of green technology and sustainability, which has a huge demand in the current global market. As shown in figure 13, there are five key requirements related to eco-efficiency. The idea is to minimize the material used in production (reduce), to utilise waste material in energy production (recovery), to reuse the materials again by restoring the product to its initial use, and purpose, and to recycle the material from old products in reproduction. This thesis considers the recovery of cruise ship waste to produce energy for operational use in a biogas reactor.

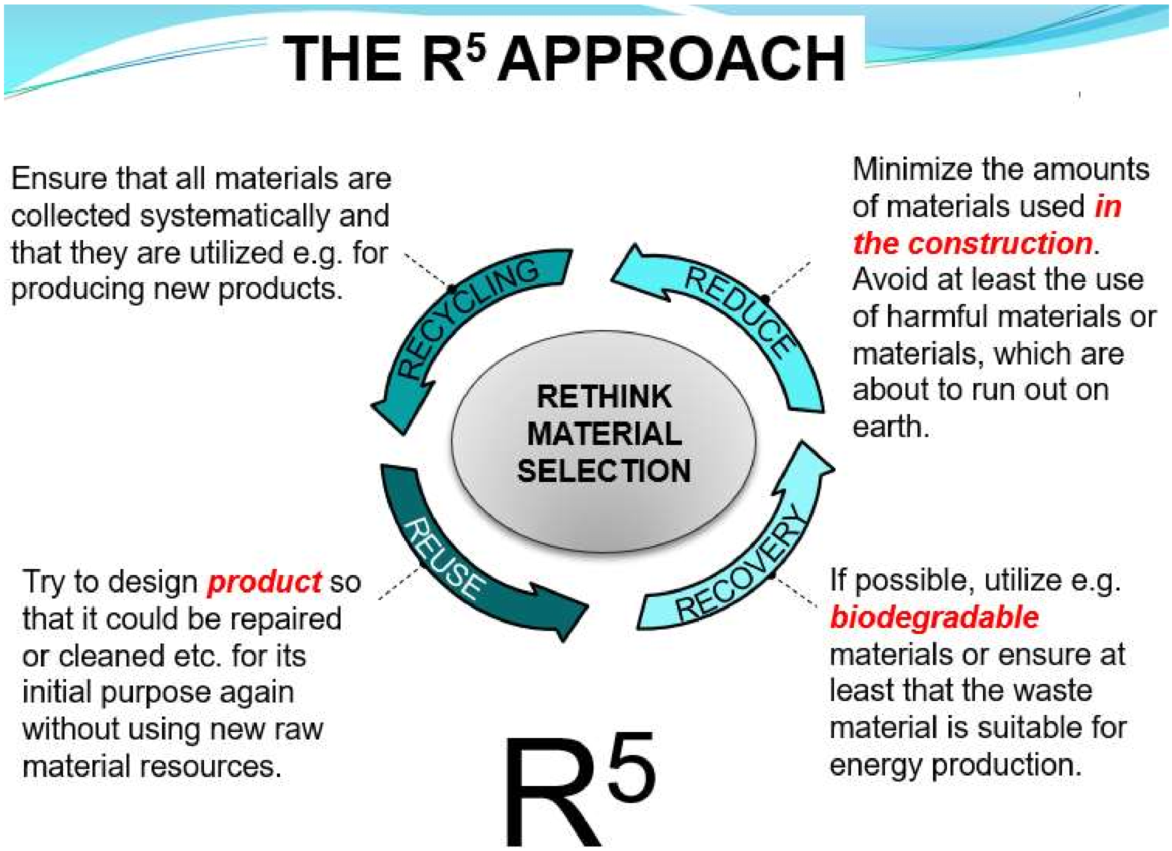

Figure 13. The basic approach R5. Translated from (Eskelinen & Karsikas 2013)

5 Integration of the requirement and the property profiles

Chapter five includes the requirements and property profiles. The requirements profile is formed using two tables: functional requirements and corresponding material properties. In these tables, the criteria of requirements and properties are displayed according to four different aspects: function, environmental conditions, manufacturing and production, and costs. The tables data was collected through interviews with experts from both the maritime segment and land-based biogas equipment suppliers and by reference to available piping system product catalogues. The material requirements list might include self-evident material aspects, but they are still examined to allow for a comprehensive consideration of the systematic material selection process.

The biogas reactors' and waste pipes' material requirements profile can include the following: the weight of the waste that the biogas reactor and specifically pipes should support, the pressure, temperature, and velocity of waste flowing through the pipes, inner surface wear, strength, fatigue, and fracture aspects, and necessary corrosion resistance.

The integrated biogas reactor system demands several materials' requirements. The requirements are compiled by investigating both the piping and reactor systems. Pipes containing waste and the feedstock supplied to the reactor require special protection against corrosion and wear resistance. The following chapter presents in more detail the functional requirements and corresponding material properties tables.

Ashby (2011) defines the main idea of a requirements profile: "The functional requirements of each component are the inputs to the materials selection process." (Ashby 2011, p.26). As mentioned, the requirement's profile consists of all the things which relate to a material requirement of the functional system.

5.1 Functional requirement's profile

To develop a requirements profile, it is important to consider questions concerning the functional requirements that must be taken into account to select the best fitting material for a particular purpose. In waste treatment systems it is critical to have a good corrosion resistance. Other concerns include: What is a life cycle of a cruise ship? How long should the pipes be designed to last? Most cruise ships are designed to last more than 30 years. How thick should the pipe walls be meet the system requirements? Next would be the weight. Every kilo adds to the ship's total weight, the system's installation time and manufacturability. Is it easy or even possible to manufacture? What are the environmental impacts of manufacturing the pipes with a selected material? Is it an eco-friendly choice or merely the cheapest and consequently the most harmful to the environment? The selection will also have an impact on emissions and a climate friendly material must be durable as well. That will also affect the cost of the pipes and the methods of the design process. The current price of steel has increased significantly. The design requirements need to define how to select materials so that their performance meets all the previously mentioned requirements. The challenges vary depending on the ranges of stress, temperature, environment, and fluid flows inside the pipe. This will have both performance and cost implications. (Ashby 2011, p.16-18.)

Ashby (2011) defines adaptive design as follows "Adaptive design takes an existing concept and seeks an incremental advance in performance through a refinement of the working principle." This underlines the goal of this thesis, as the principles of both former and today's pipe materials are well known.

Chapter 5.2 presents the material properties and functional requirements in the same table to illustrate the important relation between these profiles.

5.1.1 Requirements set on rules and regulations

The following requirements are collected from IMO Resolution A.753(18), which is applicable to all piping systems:

General: "The piping should have sufficient strength to take account of the most severe coincident conditions of pressure, temperature, the weight of the piping itself and any static and dynamic loads imposed by the design or environment."

“For the purpose of assuring adequate robustness for all piping including open-ended piping (e.g., overflows, vents, and open-ended drains), all pipes should have a minimum wall thickness to ensure adequate strength for use on board ships, also to withstand loads due to transportation, handling, personnel traffic, etc. This may require the pipe to have additional thickness than otherwise required by service consideration (e.g., pipes for vacuum and pressure systems).”

Ageing: “Before selection of a piping material, the manufacturer should confirm that the environmental effects including but not limited to ultraviolet rays, saltwater exposure, oil and grease exposure, temperature, and humidity, will not degrade the mechanical and physical properties of the piping material below the values necessary to meet these guidelines. The manufacturer should establish material ageing characteristics by subjecting samples of piping to an ageing test acceptable to the Administration and then confirming its physical and mechanical properties by the performance criteria in these guidelines.”

Fatigue: “In cases where design loading incorporates a significant cyclic or fluctuating component, fatigue should be considered in the material selection process and taken into account in the installation design.”

Material compatibility: “The piping material should be compatible with the fluid being carried or in which it is immersed such that its design strength does not degenerate below that recognized by these guidelines. Where the reaction between the pipe material and the fluid is unknown, the compatibility should be demonstrated to the satisfaction of the Administration.”. (IMO Resolution 1993, p.5-7.)

5.2 Material properties profile

Materials have distinct profile properties that meet different design needs. According to Ashby (2011) materials are divided in six different families: metals, polymers, elastomers, glasses, ceramics, and hybrids. The corresponding table of material properties is needed, so that the functional requirements of a product (in this case pipes and reactor) can be investigated in more detail. To fulfil the product requirements, the material properties need to meet the functional requirements. Although this thesis will focus more on pipes than biogas reactor materials, the following subsections show tables for both.

5.2.1 Profile for pipes

Table 1 presents the requirements and material properties profile for pipes, showing four different aspects of the systematic material selection process: function, environmental conditions, manufacturing and production, and costs. Functional requirements relate to items such as wear resistance, stiffness and rigidity, and load bearing capacity. The piping system needs to withstand dynamic pressure variations and dynamic loads. Waste streams used in biogas production contain aggressive and concentrated substances, which present a challenge to pipe's inner surface. This sets demanding wear resistance requirements. Although pressure is generally expected to be low, it is dynamic and varies depending on a system (even dropping to minus bars in vacuum systems). This will determine requirements for the load bearing capacity as well, since the loads are dynamic, and the contents of the pipes can sometimes remain in place. Also, the effects of vibration should be considered to assure that piping systems continually remain stiff and rigid throughout the process. The material's inner surface needs to be sufficiently hard to endure friction. Overall, the material must remain stiff and rigid during operation to avoid failure and leakages. (Appendix 3.)

Environmental considerations include resistance to the effects of ageing and corrosion, extreme and changing temperatures, and humidity absorption. The pipes' outer surface material must have sufficient thermal strength to remain durable in case of the high temperatures associated with fire. Ageing and corrosion of the materials surrounding pipe systems can also affect the outer surface of a pipe. The pipes' outer surface must be hard enough to withstand impacts. A ship's systems are designed to last +30 years, so the material needs to withstand that amount of ageing and the corrosive surrounding environment of salty ocean air.

The third aspect of the materials selection process concerns manufacturing and production. These criteria include requirements for both materials manufacturing and production of the product. The production of both metallic and non-metallic pipes must be considered. The melting temperature will have an influence on the pipe's machinability and formability. The formability corresponds to how effectively the material can be bended, which affects the manufacturing process. Recycled raw material should be used if it is available to reduce emissions.

The final aspect includes minimizing costs through recycling, reuse, and maintenance. As mentioned before, the biggest current challenge to industry is the need to deal with increased component prices while reducing the carbon footprint of processes. Together with increased prices and demand for building a ship within a budget, sets huge requirements for the material. Not only must we consider the production costs of raw materials, but also the system's manufacturing, service, and maintenances costs. Additionally, today's climate actions demands that materials are recycled and reused, a measure of which is expressed in the recycling rate. Finally, eco-efficiency is required throughout the system's lifetime, as evaluated with the R5 process or MI and MIPS-values.

Table 1. Functional requirements and corresponding material properties for piping systems

Function	* Wear resistance (Material should withstand aggressive and concentrated substances).	->	* Hardness of the (inner) surface
	* Should remain stiff and rigid in operation.	->	* Modulus of elasticity
	* Enough load bearing capacity is required against dynamic loading and vibration under varying temperature (Pressure varies between -0,5 - 6 bars. The pressure is dynamic and it can vary depending on system).	->	* Yield strength and fatigue strength
Environmental conditions	* Should remain durable in case of external damage.	->	* Tensile strength and impact strength
	* Temperature: In case of fire should withstand higher temperatures.	->	* Melting temperature
	* Ageing and corrosion: Functionality to last +30years and to withstands salty ocean air.	->	* Corrosion resistance
Manufacturing and production	* Good formability and weldability. Should also be cost-effective in mass production.	->	* Melting temperature
Costs	* Recycling, reuse costs and low maintenance.	->	* Recycling rate
	* Eco-efficiency throughout the lifetime is required.	->	* MI- and MIPS-values

5.2.2 Profile for biogas reactor

As mentioned, similar table was designed for biogas reactor, which is seen in table 2. The functional requirements and the corresponding material properties follows the same aspects than in previous mention list for pipes. The feedstock of a biogas reactor also includes aggressive and concentrated substances, which might wear the inner surface of a reactor. In addition, the list of pipes, the material of a reactors must ensure the tightness of a gas and liquids. This sets requirements for the material properties at least in hardness and wear resistance. Digestion and gas set different requirements for the material, which need to be considered in the process of a material selection for biogas reactor. A further research of biogas reactor has been omitted from this work.

Table 2. Functional requirements and corresponding material properties for a biogas reactor.

Function	* Wear resistance (Should withstand aggressive and concentrated substances. Waste includes both fluids and solids).	->	* Hardness of the (inner) surface
	* Should withstand corrosion triggered by various types of waste.		* Corrosion resistance
	* Should remain stiff and rigid in operation (Tightness of gas and liquids must be ensured).	->	* Modulus of elasticity and thermal expansion
	* Enough load bearing capacity is required under varying dynamic pressures variations.	->	* Yield strength and fatigue strength
Environmental conditions	* Good wear and corrosion resistance is required (To withstand hydrogen sulfide and corrosive digestate). Ageing and corrosion: Functionality to last +30 years.	->	* Hardness
Manufacturing and production	* Good weldability, machinability and formability.	->	* Melting temperature
Costs	* Eco-efficiency throughout the lifetime is required.	->	* Recycling rate, MI- and MIPS -values

5.3 Numerical values of properties

Here the goal is to construct a numerical value for material property profiles. With these numerical values, further research can be done utilising assistance tools such as four-field and cobweb analyses. Once the most important properties are selected, a third table should be added including the profiles' numerical values. Corresponding properties need to consider the selected requirements (such as corrosion resistance). The third table presents the grades of material properties. Where section 5.2.1 introduced functional requirements and corresponding material properties, now the numerical values are presented in table 3. This process is needed to analyse component properties as numeric value.

Table 3. Corresponding numerical values for pipes.

* Hardness: 215 Max HB or 95 Rockwell * Modulus of elasticity: 2*105 N/mm^2 * Yield strength: 240 Mpa, Fatigue strength: 22 kg/mm^2
* Tensile strength: 500 - 700 Mpa, Impact strength min. 80 kJ/m^2 * Melting point: 1000 C° * Corrosion resistance: 0.1 mm/year or PRE 24
* Melting temperature: 1000 C°
* At least 80% * MI- and MIPS-values

Table 3 introduces the numerical data for selected properties. This table presents the required and desired values of the properties selected previously in tables 1 and 2. Hardness has been selected in either HB or Rockwell scales. Modulus of elasticity at 20C^{o} is 2x105 N/mm^2, yield strength 240MPa and fatigue strength 22 kg/mm^2. For the environmental conditions numerical values for tensile strength, impact strength, melting point, and corrosion resistance were selected. Tensile strength was selected to be in a range of 500-700 MPa. The value for impact strength at room temperature was selected to be min. 80kJ/m^2. The melting point is as high as 1000C^o and corrosion resistance either 0.1 mm/year or PRE 24. For the manufacturing and production material property the melting temperature was selected. For the cost was selected the rate of recycling and MI- and MIPS -values. The minimal recycling rate should be 80% of the original material.

The aim of establishing these properties is to use them in the following chapter concerning assistance tools. The goal of these properties is not only to find relevant materials, but also to support the greener and cleaner choice of materials. For manufacturing with eco-friendly production methods that reduce carbon footprint needs to rely on materials produced with low emissions without excluding the consideration of whole-process sustainability and R5 principles.

6 Results

The materials investigated here, stainless-steel AISI 316L and plastic (Polyethylene, PE) are typically found in pipes built for industrial marine sewage and food waste systems. Since these materials are widely used and they are standardized solution in similar systems, they are useful and reliable to be compared despite their differences (Appendix 3). According to Saalasti (2022), stainless steel is well-suited for biogas reactor construction as well.

6.1 Analysis of the assistance tools

Next is a review of assistance tools used to examine relevant material properties. The values used here are collected from supplier catalogues and from interviews of supplier representatives. The plastic material PE100 is offered by Georg Fischer Ab in their ecoFIT product. Stainless steel AISI 316L products are produced by Blucher.

Figure 14 shows a four-field analysis of three different material properties. The blue colour indicates material PE100 and red indicates AISI316L. The x-axis depicts minimum and maximum operating temperatures. For both materials the range of operating temperature is good and wide. Both materials are functional also in lower temperatures (PE100 down to -50 °C). The only significant difference is that AISI316L is more suitable at higher temperatures (+60 and above). For PE100 the maximum operating temperature is just +60 °C. However, the systems discussed here are not required to operate at higher temperatures therefore the higher operating temperature of AISI316L does not offer additional benefits under normal operating conditions. On the other hand, the stainless-steel materials would likely better withstand fire conditions.

Yield and tensile strength are aligned along the y-axis. As can be seen in figure 14, the yield strength is much higher for AISI316L than for PE100. The yield strength of AISI316L is approximately 200 MPa, whereas for PE100 it is only 25MPa (both values are given at 23 °C). Therefore, PE100 will most likely yield lower loads than AISI316L. PE100 has a better tensile strength property with 900 N/mm^2. Tensile strength of AISI316L has also a quite good value of 490-690 N/mm^2. (Appendix 1; Appendix 2.)

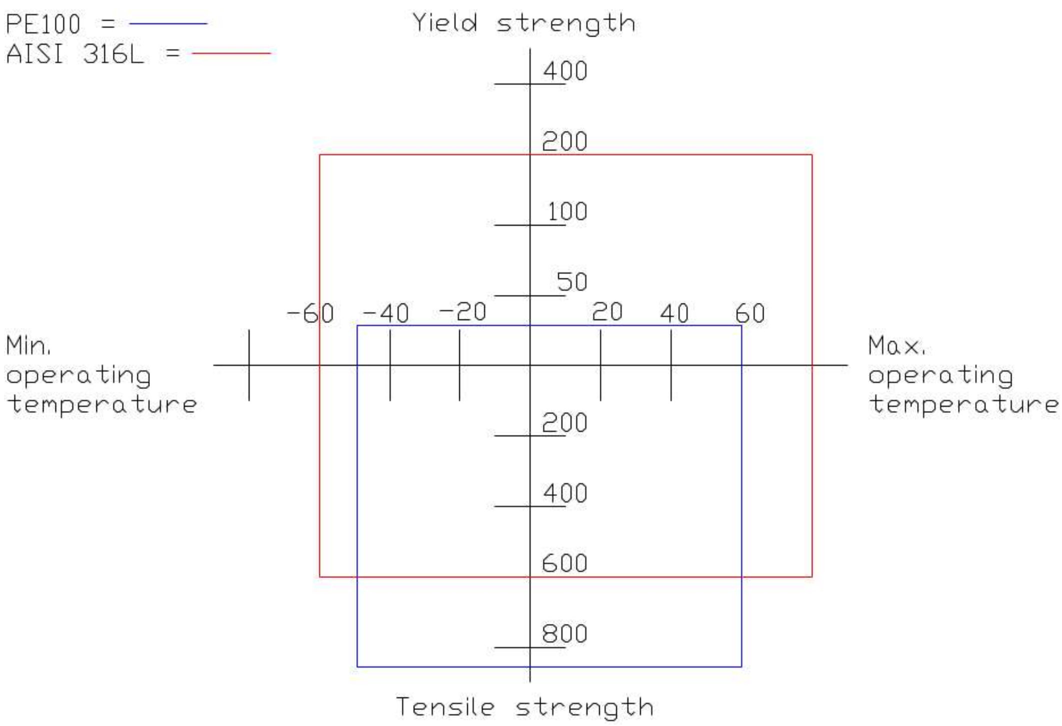

Figure 14. Four-field -analyses

The Cobweb analysis shown in figure 15 allows several values to be examined at once. The blue and orange lines represent PE100 and AISI 316L, respectively. In comparing values, there is a significant difference in melting point temperatures. Plastic welding temperatures are approximately 220-240 °C, the same as their melting point. According to a Deltamarin report (2005), PE100 ignites at temperatures of 350 °C. For AISI 316L the melting point is at 1400 °C, which makes it more durable against higher temperatures (e.g., fire). However, rubber seals (e.g., EPDM-type) used in Blucher's plug-in connection have maximum temperature range between -40 to +100 °C. The maximum temperature limit for silicone seal types is +200 °C (Blucher 2022a). The other difference to be mentioned is heat expansion, which for PE100 is about 12 times higher than it is for AISI 316L. Expansion properties are further examined in the calculations section.

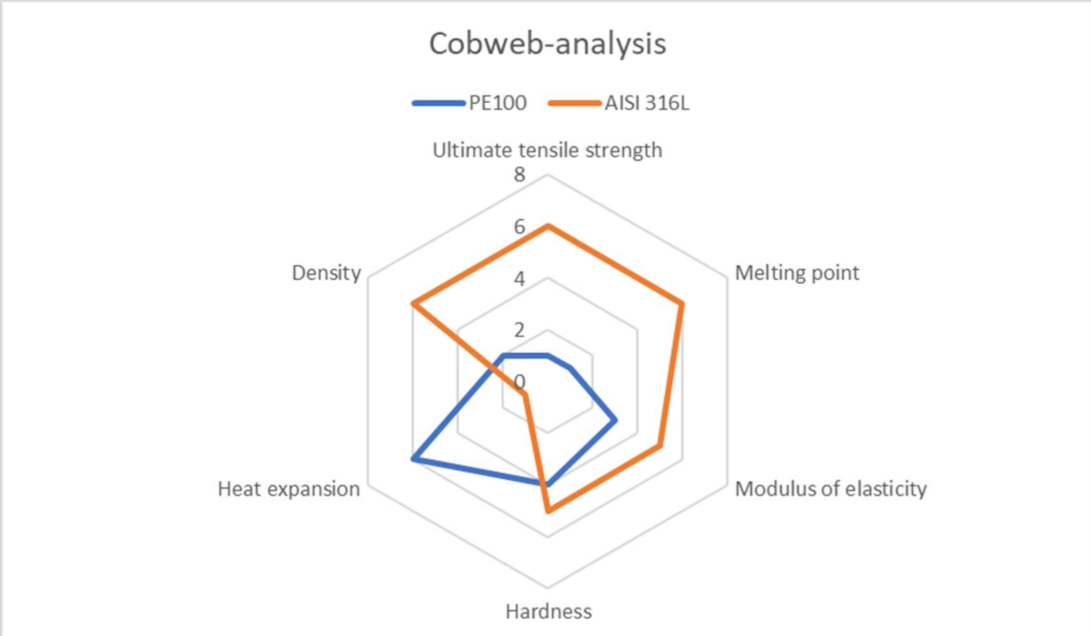

Figure 15. Cobweb -analyses

The material selection map is finally shown in figure 16. There the modulus of elasticity and density properties are represented by the placement of the material on the map. For PE100, the density is 950 kg/m³ and for AISI316L it is 7980 kg/m³. This makes the plastic lighter, even though Blucher advertises their steel products as light weight products due to their thin-walled pipes optimization of the material's high strength to weight ratio. Due to the thin wall thickness, Blucher's weight is close to PE100. Even though the difference is significant, both materials are used for same systems.

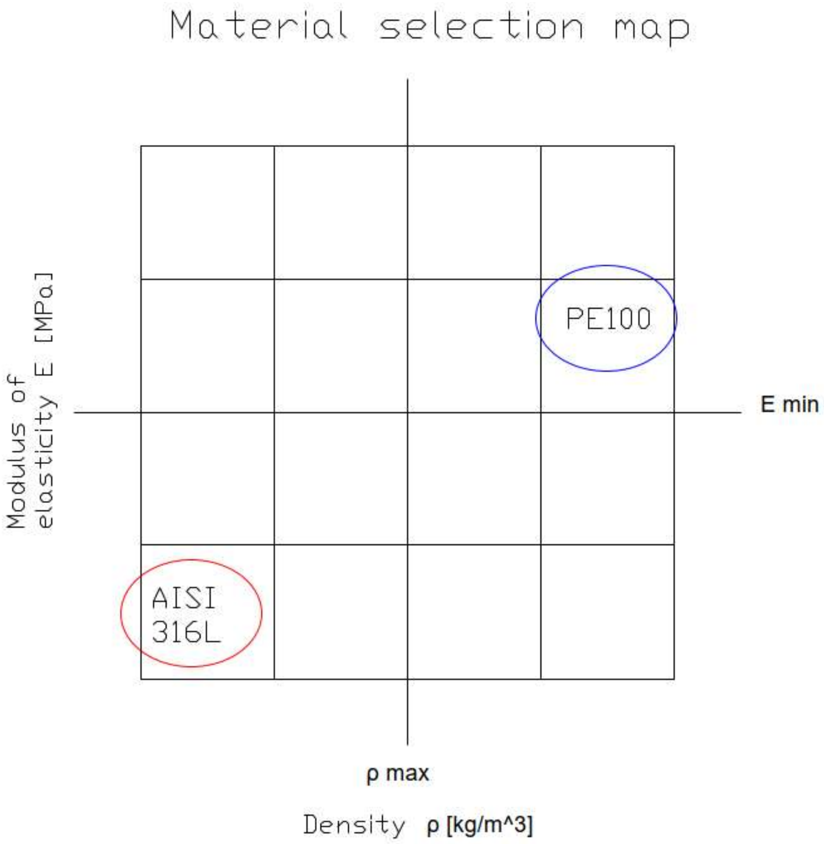

Figure 16. Material selection map

6.2 Calculations

This chapter includes the calculations necessary to support the systematic material selection process and presents a case study showing those calculations in use to estimate how much biogas and energy could be produced from a typical cruise ship's waste generation flow. The calculations include a study of heat expansion in different temperatures and von Mises equivalent stress.

6.2.1 Thermal expansion due to temperature changes

Plastic and stainless steel behave differently in their surrounding environments and at different fluid flows and temperatures. This is critical information to know because expansion affects the design of pipes and their support. As previously mentioned, the systematic material selection process investigates materials through four different aspects. The heat expansion of materials relates to the functional and environmental conditions. It was decided to find out and compare the expansion coefficients for plastic pipe PE100 (Polyethylene) and for stainless-steel pipe AISI316L.

Table 7 above shows the expansion coefficients for PE100 and AISI316L. Plastic has a greater expansion coefficient than stainless-steel, which means that it is more prone to expansion due to temperature changes.

Table 4. Expansion coefficients (Pöntiskoski 2022; Blucher 2022a, p.49)

Material	Expansion coefficient α, mm/(m*C)
PE100 (Polyethylene)	0.20
AISI 316L	0.0165

$$\Delta L = \alpha * L * \Delta T \qquad (1)$$

Equation 1 shows the calculation of expansion in length of a pipe, where ΔL is change in length [mm], α expansion coefficient [mm/(m*°C)], L is the original length of a pipe [m] and ΔT is temperature difference [°C].

By using equation 1, the change in length for PE100 is calculated as follows:

$$\Delta L = \alpha * L * \Delta T = 0.2mm/(m*°C) * 5m * 60°C = 60mm$$

By using equation 1, the change in length for AISI316L is calculated as follows:

$$\Delta L = \alpha * L * \Delta T = 0.0165mm/(m*°C) * 5m * 60°C = 5mm$$

For these examples the values of original pipe length and change of temperature were assigned as 5m and 60 °C, respectively.

These two calculations show that plastic has about a twelve times higher heat expansion than stainless-steel. The same length of pipe and temperature difference were used as in the previous calculation.

The behaviour of heat expansion for plastic PE100 and stainless-steel AISI 316L can be seen in figures 17 and 18. Notice the different scale used in each figure. On the y-axis PE100 is scaled up to 200mm, but AISI 316L is scaled up to 20mm. The orange line represents expansion in temperature difference of 20 °C. For PE100 the expansion for 10m pipeline is 40mm, whereas for AISI 316L the expansion is only 3mm. If the temperature difference is 100 °C, the expansion for PE100 is 200mm, whereas for AISI 316L it is 16,5mm. According to Pöntiskoski (2022), a pipe's wall thickness affects its thermal behaviour. Pipe expansion and contraction must be considered at the varied installation, operational, and surrounding environment temperatures.

High expansion coefficients are not purely negative, but it is critical when designing pipelines and systems. Shipboard spaces used for pipe systems are usually subject to very tight fits. Multiple systems' pipes made of different materials often share the same space. There must be an allowance for expansion, not only to leave a needed space surrounding of a pipeline, but also to allow for additional loops to be added to the piping system and to properly manage the pipes support systems during expansion. Also, during welding (installation) of pipelines, too fast cooling might cause stresses in the pipe materials and parts, which can cause cracks and ultimately leaking (Pöntiskoski, 2022). According to Pöntiskoski (2022), brackets (supporters) can be used to control pipe behaviour during heat expansion. With a same method pipe vibration is minimized, where rubber pipe clamps are used. According to a Deltamarin report (2005), AISI 316L Blucher pipes require less than 50% of the supports needed by plastic pipes. As mentioned earlier, the wall thickness affects how the plastic pipe behaves in temperature changes. Pipes with larger diameters also have thicker walls, so pipes with a smaller diameter need to be supported more frequently. (Pöntiskoski 2022.)

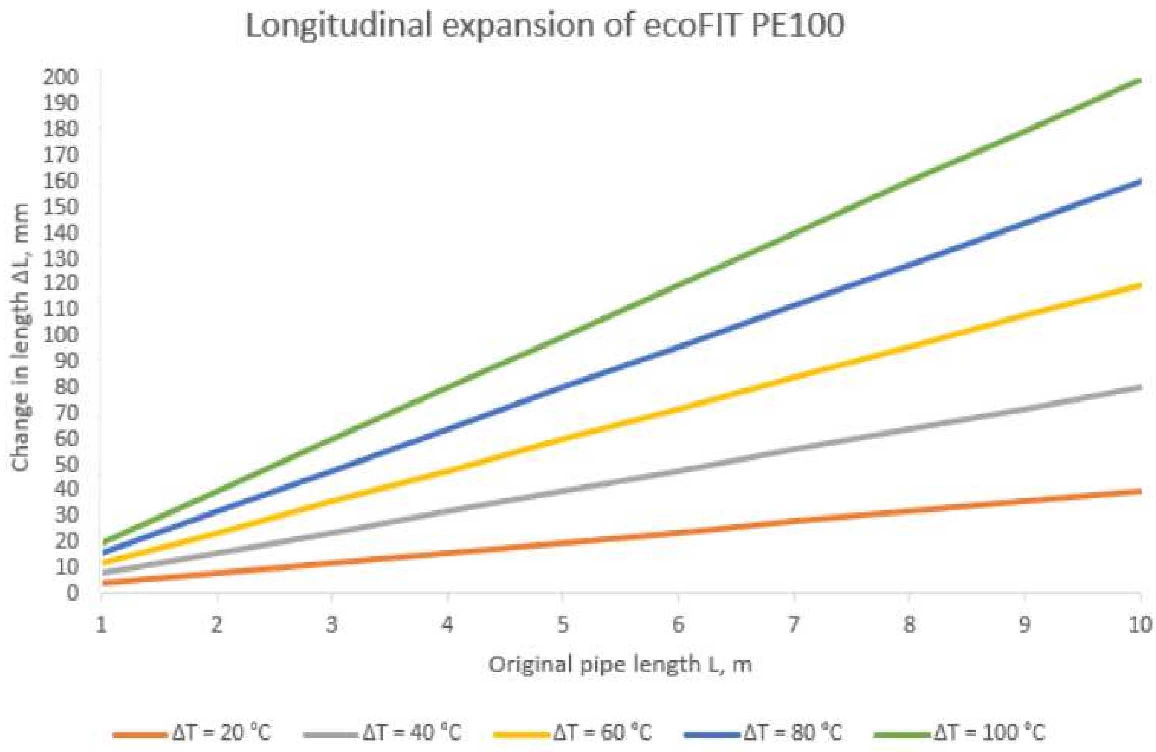

Figure 17. Longitudinal expansion of ecoFIT PE100

Figure 18. Longitudinal expansion of Blucher AISI 316L

6.2.2 Von Mises equivalent stress

With von Mises stress calculations one can estimate the internal hydrostatic pressure required to cause the wall of the pipe to yield. The von Mises yield criterion helps also to compare the materials yield stress performance. Even when the systems investigated are low pressure systems (Appendix 3), still manufactures perform leakage tests for installed pipelines. That is why the von Mises calculations are especially valuable when selecting pipe materials for systems with higher pressures.

The calculations are made for materials AISI 316L and PE100. The required material qualities for calculations are yield stress value, pipe size, and wall thickness.

$$(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 = 2\ \sigma_y^2 \qquad (2)$$

Equation 2 shows the calculation of the von Mises criterion. First hoop stress, radial stress, and axial stress are calculated. σ_1 presents the value of hoop stress, σ_2 presents axial stress, σ_3 presents the radial stress, and σ_y presents the yield stress of a material.

The Hoop stress is calculated as follows:

$$\sigma_1 = pD/2t \qquad (3)$$

where *p* is yield pressure [MPa], *D* is mean diameter [mm] and *t* is wall thickness.

The Axial stress is calculated as follows:

$$\sigma_2 = pD/4t \qquad (4)$$

where *p* is yield pressure [MPa], *D* is mean diameter [mm] and *t* is wall thickness.

Through-wall radial stress can be neglected for these calculations and therefore it is $\sigma_3 = 0$.

By using the equations 3 and 4, the hoop stress and axial stress is calculated for AISI 316L as follows:

$$\sigma_1 = pD/2t = \frac{109\,p}{2}$$

$$\sigma_2 = pD/4t = \frac{109\,p}{4} = \frac{54{,}5\,p}{2}$$

For AISI 316L the wall thickness is 1mm for a pipe size 110mm, so the inner (mean) diameter is 109mm. σ_y is 190 MPa. Substituting these stresses into von Mises criterion gives:

$$(\frac{109\,p}{2} - \frac{54{,}5\,p}{2})^2 + (\frac{54{,}5\,p}{2} - 0)^2 + (0 - \frac{109\,p}{2})^2 = 2 * 190^2$$

$$\Rightarrow\ (\frac{54{,}5\,p}{2})^2 + (\frac{54{,}5\,p}{2})^2 + (\frac{109\,p}{2})^2 \rightarrow (\frac{17821{,}5 * p^2}{4}) = 2 * 190^2$$

$$\Rightarrow\ p^2 = \sqrt{\frac{4*2*190^2}{17821{,}5}} = p = 4{,}025\ MPa$$

As 1 MPa = 10 bar, therefore, the pressure for yield is 40 bar.

The same calculation is done for PE100. The pipe's outer diameter is the same 110mm, which makes mean diameter 103,7mm with a wall thickness of 6,3mm. σ_y is 25 MPa.

By using the equations 3 and 4, the hoop stress and axial stress is calculated for PE100 as follows:

$$\sigma_1 = pD/2t = \frac{103{,}7\,p}{12{,}6}$$

$$\sigma_2 = pD/4t = \frac{103{,}7\,p}{25{,}2} = \frac{51{,}85\,p}{12{,}6}$$

Substituting these stresses into von Mises criterion gives:

$$(\frac{103{,}7\,p}{12{,}6} - \frac{51{,}85\,p}{12{,}6})^2 + (\frac{51{,}85\,p}{12{,}6} - 0)^2 + (0 - \frac{103{,}7\,p}{12{,}6})^2 = 2 * 25^2$$

$$\Rightarrow\ (\frac{51{,}85\,p}{12{,}6})^2 + (\frac{51{,}85\,p}{12{,}6})^2 + (\frac{103{,}7\,p}{12{,}6})^2 \rightarrow (\frac{16130{,}5 * p^2}{158{,}7}) = 2 * 25^2$$

$$\Rightarrow\ p^2 = \sqrt{\frac{158{,}76 * 2 * 25^2}{16130{,}5}} = p = 3{,}507\ MPa$$

Therefore, the pressure for yield is 35 bar.

The results of von Mises stress for AISI 316L and PE100 was calculated. The von Mises stress for AISI 316L is 4MPa and for PE100 it is 3,5MPa. To compare these values, they are very close to each other, even though they are different materials. The AISI 316L Blucher pipe has a greater yield stress value of 190MPa, but it also has a much thinner wall of 1mm. On the other hand, PE100's yield stress is only 25MPa, but the wall thickness is 6,3mm. This makes them very similar by these measures of their properties. Also, the pressure for yield is nearly the same for both. For AISI 316L it is 40bar and for PE100 it is 35bar.

These analysis of the results of von Mises calculations showed how pipes made of different materials behave under stress and how well they tolerate pressure. The systems here investigated also work with a vacuum. The vacuum systems are tested with the recommendations of the vacuum system supplier. For diameters (OD) bigger than 75mm, the system is tested to a maximum of -0.6 bars. Smaller pipes (OD 40-75) are tested to a maximum of -0,85 bars.

6.2.3 Case study calculations

Here is presented the case study in which the parameters of the ship and the amount of waste produced are considered. It is valuable to investigate the real potential of organic materials to be used as a source of biogas. Also, it is important to base our assessment of the viability of a Biogas system on actual waste production data to estimate potential energy yields more accurately. This study also demonstrates the real weight of the waste, its temperature, and other durability requirements that biogas reactors and specifically their pipe systems should support. This information has a critical influence on the material selection. Despite making inquiries of different ship owners to provide real data from operating ships, such data that would lead to more precise results was not obtained. Therefore, this study relies on waste generation quantities provided by the Bureau Veritas society's rules for the classification of steel ships in part F, which also contains some useful notations concerning pollution prevention.

Table 8 shows the total waste generation data for three different ship types. However, this study only considers cruise ships and the organic wastes they produce, so the other waste types are left out. Also, grey water is excluded from our analysis since it is quite neutral, containing a much higher proportion of water to organic matter. The study includes calculations according to the number of passengers. The calculations are made with 3000 passengers including crew. A cruise ship can accommodate up to 6000 passengers, so with these calculations is easy to estimate wastes produced by greater numbers of passengers by simply multiplying the results.

Table 5. Waste generation quantities (Bureau Veritas 2021).

No	Type of Waste	Unit	Quantities for			
			Cruise ships	Ro-ro passenger ships designed for night voyages	Ro-ro passenger ships designed for day voyages	Cargo ships
1	Plastics	kg/person/day	0,1	0,1	0,1	0,1
2	Paper and cardboard	kg/person/day	1,0	1,0	1,0	1,0
3	Glass and tins	kg/person/day	1,0	1,0	1,0	1,0
4	Food wastes	kg/person/day	0,7	0,7	0,7	0,7
5	Total garbage (1 + 2 + 3 + 4)	kg/person/day	2,8	2,8	2,8	2,8
6	Black water	litres/person/day	12 for a vacuum system 100 for a conventional flushing system			
7	Grey water (excluding laundry and galley)	litres/person/day	160	150	50	100
8	Laundry	litres/person/day	80	20	20	40
9	Galley	litres/person/day	90	30	30	60
10	Total grey water (7 + 8 + 9)	litres/person/day	330	200	100	200

The black water calculations included unit conversions to convert litres to kilos. The density of the wastewater needs to be known to convert from litres to kilos. These calculations relied on Dammel & Schroeder's (1991) estimate of primary sludge density at 1020 to 1060 Kg/m^3. Although our calculations are derived from Dammel & Schroeder (1991), they examined a land-based municipal solid waste system, which uses more water than the vacuum system used in ships. More accurate results would require the exact densities of the materials found in marine vessels vacuum-operated black water system.

$$v = l / 1000 \tag{5}$$

Equation 5 shows the conversion of litres to cubic meters, where v is volume [m^3], l is litres [l] and 1000 presents the rate of cubic meters to litres.

By using equation 5, the volume is calculated as follows:

$$v = \frac{12}{1000} = 0{,}012m^3$$

Next is converted the cubic meters to kilograms. The conversion is utilised with the following equation:

$$m = v\rho \tag{6}$$

Where m is mass [kg], v is specific volume [m^3] and ρ is density [kg/m^3].

By using the equation 6, the weight of the black water is calculated as follow:

$$m = 0{,}012\text{m}^3 * 1040\text{Kg/m}^3 = 12{,}48\text{Kg}$$

Table 9 shows the results of the calculated total waste generation of food waste and black water by 3000 passengers in both kilograms and in cubic meters. This information is used as an estimate for how much biogas could be produced from this level of waste flows.

Table 6. Waste generation in cruise ship with 3000 passengers

Input	Quantity	Unit	Volume	Unit2	Ship with 3000 pax	Unit3	Volume4	Unit5
Food waste	0.7	kg/person/day	0.00079	m^3	2100	kg/day	2.36	m^3/day
Black water	12.48	kg/person/day	0.012	m^3	37440	kg/day	36.00	m^3/day
					39540	**kg/day/total**	**38.36**	**m^3/day/total**

After the calculation of waste flow from 3000 passengers is obtained, it is possible to estimate how much biogas could be produced from such a cruiser's waste. From that the typical potential power available from the onboard production of biogas can be determined. For the purposes of estimation, data from a land-based company Doranova was used. Their data provided real production numbers of methane and energy to calculate the profit potential shown in table 10. These figures assume regular amount of waste is generated every day.

Table 10 shows the annual feedstock volume in tons. TS- content stands for total solids, which means the solid content of the feedstock. Organic waste such as food waste includes more solids than liquid-based sewage sludge. In terms of energy production, methane (CH_4) is useful. Its content is 60% of the biogas, which gives us in the final row the actual methane containing biogas in cubic meters. The total amount of methane is 125 901 m^3.

Table 7. Biogas profit potential calculation (Saalasti 2022)

Feedstock	Quantity, t/a	TS-content, %	TS, t	CH_4, %	Nm3/t (BK)	Nm3/t (CH_4)	Total, m3 (BK)	Total, m3 (CH_4)
Organic waste (food waste)	730	30	219	60	150.0	90.0	109500	65700
Sewage sludge (black water)	13651	2	273	60	7.4	4.4	100335	60201
Reject recycling	0	5	0	60	6.0	3.6	0	0
Sum	**14381**	**3.4 %**	**492**				**209835**	**125901**

Table 11 shows the process' energy production. The most relevant figure from the table is energy efficiency, which is calculated to be 142,3kW or up to 1246,4MWh per year. The other important figures are the volume of the reactor, 827m^3, and the estimate of biogas digestion, 14 172 tons annually.

Table 8. Dimensioning process (Saalasti 2022)

Process dimenions	Quantity	Unit
Calculated biogas yield	24.0	m^3/h
Calculated methane yield	14.4	m^3/h
Methane content	60 %	
Energy efficiency	142.3	kW
Energy production per year	1246.4	MWh
Calculated delay	21.0	vrk
Reactor volume requirement, net	827.0	m^3
VS/TS, estimate	85 %	
Organic load	1.38	kg oTS/m^3/d
Solid content of feedstock, average	3.4 %	
Estimated solids content of reactor	2.0 %	TS
Estimated amount of digestate	14172.0	t/a

Table 12 shows the energy consumed in biogas production. Heating uses 55,1% and electricity uses 10% of the total power produced by the biogas system. 35% or 50kW of the total energy production remains available to be used for other purposes. The heat demand depends on the temperature of the feedstock and the digestate's need for sanitization. Black water is estimated to have a low solids content leading to a high heat demand. This is the result of the water needing to be heated to a temperature suited to the biogas process. Also, the content and quality of solids such as fat, protein, carbohydrate, and minerals affect the estimated gas yield. (Saalasti 2022.)

Table 9. Energy consumption (Saalasti 2022)

Energy consumption	Quantity	Unit
Heat demand, heating feedstock	367382	kWh/a*
Heat demand, heating feedstock	29.5 %	From the total energy produced
Heat demand, sanitization	318689	kWh/a
Heat demand, sanitization	25.6 %	From the total energy produced
Electricity consumption	124436	kWh/a
Electricity consumption	10 %	From the total energy produced
Utilisation for ship's use remains	50	kW
*Default feedstock temperature	15	C°

According to Elg (2022) in practice, 50kW of power could be used in combustion engines with a good 48% efficiency to produce approximately 24kW of mechanical power. It could also be burned in a boiler to produce approximately 45kW of heat output. However, on bigger cruisers with 3000 passengers and more, the average electricity demand of the hotel is approximately 8MW. In this light, the energy production from biogas system is quite low, only covering a small percentage of the ship's total power requirements. (Elg 2022.)

However, in the circular economy and sustainability point of view the decarbonizing of shipping requires more holistic lifecycle approach. For this reason, every stone must be turned over to find ways to a cleaner shipping in many aspects. These calculations were meaningful to do to have more realistic view, is the idea of placing a biogas reactor in a cruiser profitable. The calculations showed, that collecting organic feedstock to the biogas reactor would not directly affect much on the ship's energy consumption. However, the case is much wider than this calculation. One way is to collect the biogas into a tank, which would be used later e.g., in a harbour and so to minimize the use of oil boiler.

As the results show, estimated amount of digestate is over 14 000 tons. To protect environment, the digestate would be needed to bunker out of the ship in the harbour for further processing. Today, there is a huge demand for nutrient recycling both in security of supply and the climate. The growth in demand for recycled nutrients accelerates the industry's development. One relevant point to raise is, would this kind of a concept idea have effect on the AWP-system on board? Could this be an alternative cleaner solution for managing the wastewater quantities? At Baltic Sea, cruise ships can discharge food waste in the sea without treatment. There need to be a change for this to save not only the Baltic Sea, but also the global marine environment from marine perspective. Overall, the goal should be to minimize the use of fossil fuels and environment pollution and to maximize idea of circular economy. That is one reason, why this thesis researched this topic.

6.3 Aspects of environmental, manufacturing and costs

This chapter explores how assistance tools inform the environmental, manufacturing, and cost comparisons necessary to generate a more holistic picture of the systematic material selection process.

6.3.1 Analysis of manufacturing and cost comparison

Eskelinen and Karsikas (2013) state that best way to consider material cost should extend over the product's lifetime from the perspective of eco-efficiency. However, the estimation of product life-cycle costs is left for further research, and this analysis relies on ready-made product price for the purposes of comparison. The rationale for this is that plastic pipes are not prefabricated pipes, whereas steel and stainless-steel pipes are. However, for Blucher, the comparison can be made with same method as plastic pipe construction is. Both Blucher and PE100 ecoFIT plastic pipes are built from parts.

There can be many things that affect material prices such as the use and type of energy, the need for fossil fuels in raw material production, and the geographical location of production. The price is also affected by the availability of raw materials used in production or the cost of oil or natural gas energy embedded in the materials. Some raw materials might not be substitutable by less costly options. It is also essential to estimate the availability of the raw materials (e.g., fossil fuels) needed in production. If there is a shortage of raw materials, recycled materials could possibly be used. Today, we live with an uncertain world situation that leads to insecurity, delivery problems, and higher prices for many materials.

Manufacturing costs are also greatly influenced by the choice of production methods including welding, casting, machining, forming (bending), and coatings. Each step of production, whether executed by human or robot, takes time, and adds costs to the end-product.

For stainless-steel pipes, inquiries were made from Polarputki Oy, a provider of steel products and services to the Finnish engineering and shipyard industry. The idea was to acquire data from the manufacturer for a pipe with a known diameter and configuration to generate more accurate estimates of pipe material prices. A similar inquiry was made to Georg Fischer AB (GF), a world-leading plastic pipe manufacturer for various industries.

The cost comparison between stainless-steel (AISI 316L) and plastic pipe (PE100) is shown in table 13. The analysis compared costs, weight, and pressure for ready-made products provided by GF and Blücher. This made for a more direct comparison, since the two products' construction methods and applications are similar. Pipes, elbows, and couplings were compared. As the table shows, the (outer) diameter chosen was 110mm. Significant differences in pressure data stand out on the chart. Blücher is mainly used in systems with low operational pressure and vacuum systems. These systems treat black and grey water, and food waste. PE100 has higher pressure tolerances making it appropriate for more demanding applications. PE100 with a pressure class of PN16 is also available. Nevertheless, since these materials are used in same systems it was reasonable to compare these materials and products. Costs are significantly affected by the volume of projects and client, discounts that can vary between 20-40% for both manufactures (Pöntiskoski 2022) (Falkesgaard 2022). A more accurate cost and weight comparison would analyse identical projects, pipe designs, and volumes.

Table 13. Cost comparison between AISI 316L (Blucher) and PE100 (ecoFIT) materials. (Falkesgaard 2022; Pöntiskoski 2022)

Material	Product	D (mm)	e (mm)	PN (bar)	Weight	Price (€/m)
Blücher 316L	Pipe D110	110	1	0.5	2,85 kg/m	86,89
Blücher 316L	Elbow 87.5°	110	1	0.5	0,67 kg/m	53,76
Blücher 316L	Coupling	110		0.5	0,45 kg/pcs	34,79
ecoFIT PE100	Pipe 110	110	6,3	10	2,1 kg/m	18,35
ecoFIT PE100	Elbow 90°	110	6,6	10	0,87 kg/m	88,8
ecoFIT PE100	Coupling	110		16	0,7 kg/pcs	45,5

6.3.2 Sustainability and eco-friendliness of the materials

The circular economy is frequently mentioned in discussions of sustainable industry and ship builders must not resist this development. The idea of circular economy requires us to reduce, reuse, refurbish and recycle, but no entity can realise that idea alone. Cross-sectoral collaboration, global regulation, and business model innovation are all essential to building a circular economy. (Garte 2022.)

While researching the subject, I decided to evaluate selection of four different product manufacturing types. These manufacturing and production options represent different combinations of energy source type (renewable or non-renewable) and whether the selected production materials are recycled or not.

A. Product, which is manufactured with a non-renewable energy resource and using non-recycled materials. (no-no)

B. Product, which is manufactured with a non-renewable energy resource and using recycled materials. (no-yes)

C. Product, which is manufactured with a renewable energy resource and using non-recycled material (yes-no)

D. Product, which is manufactured with a renewable energy resource and using recycled material. (yes-yes)

Obviously, the selection from these options will suggest how much the ship owner wants to invest in green technology whether selecting materials and products for new building or repairing older ones. Also, transparency is critical at every link of the supply chain. The sustainable shipping industry must not lose sight of environmental social governance mechanisms. Here United Nations (UN), IMO, and government entities such as the European Union (EU) must harmonise and promulgate rules governing the shipping industry's sustainable use of materials and implementing other circular economy practices. The EU's taxonomy regulations established six environmental objectives:

1. Climate change mitigation
2. Climate change adaption

3. The sustainable use and protection of water and marine resources
4. The transition to a circular economy
5. Pollution prevention and control
6. The protection and restoration of biodiversity and ecosystems

(European Commission 2022b.)

As can be seen from the EU taxonomy, sustainable economic objectives are consistent with those goals identified as critical to material selection processes and shipping in general. A successful transition to a circular economy will see pollution prevention, water and marine resource protection, and other regulatory requirements incentivising owners and investors to pursue these goals sooner rather than later.

The European Union is promoting a green deal that aims to “improve the well-being and health of citizens and future generations with several actions.” (European Commission 2022a) (European Commission 2022a). One of the green deal’s objectives is to provide “longer lasting products that can be repaired, recycled, and re-used.” (European Commission 2022a) (European Comission 2022a). This sustainability is a central component of the 5R technique used in this thesis.

According to Lloyds Register (2022), Maersk, the world’s largest cargo shipping company, has a goal of Net zero by the year 2040. The goal is to decarbonize the entire supply chain, not just fuels, but also to embrace the life cycle approach’s pursuit of reduced emissions. One goal is to recycle materials and implement the R5 approach in their strategy. (Lloyd’s Register 2022.)

Shipping faces economic pressure as well to produce their ships in a more environmentally friendly manner that supports sustainable development. According to Lloyd’s Register (2022), banks prefer to invest in low carbon technology. Economic pressure might also grow if more banks implement requirements for cleaner solutions and net zero strategies. More sustainable manufacturing methods and longer lasting products are required. However, the question remains: does the global market support the idea of longer lifespan of ships? Short term economic imperatives and long-run environmental goals seem troubled by great discrepancies. It will take time to change to a greener and cleaner fleet.

According to Lloyds register (2022), steel is the second largest carbon producer across the industry. That is why steel is an important part of a value chain. There are also “net zero steel” initiatives that aim to produce steel with zero emissions by 2050 and to offer to market zero-carbon primary steel production technologies by 2030 (Lloyd’s Register 2022). Obviously, it takes a lot of steel to build a ship, so greater gains are to be found in new building projects. Beyond the question of from what is the ship made is another: where it is made? More than 90% of ships are built in China, South Korea, and Japan (generally in Asia). More than 90% of ships are recycled in south Asia, primarily in Bangladesh, India, and Pakistan. In these areas, a lot of fossil fuels are used for energy production. There is no clear consensus on emissions policy. Sustainability strategies are touted by various ship owners and shipyards but is the effect of these claims mere green washing?

As mentioned before, the R5 approach considers the material selection through five different approaches that aim to make materials (and products) in a more eco-friendly manner. The first approach is recycling. There the aim is to collect all materials that can be utilised in the production of new products. Outokumpu, a well-known stainless-steel producer that provides raw material to Blucher, states that their recycling rate is up to 90% without any degradation of product quality (Outokumpu 2022). Blucher states in their sustainability strategy that their “…pipe products contain European steel which consists of 65-85% recycled steel.” (Blucher 2022b). According to Pöntiskoski (2022) GF’s plastic pipes are mostly produced from virgin resources. No recycled materials are used for the materials that endure prolonged contact with system liquids. Other parts, such as handles, use recycled material since the requirements are lower. Pöntiskoski also stated that recycled plastic might have some effect on a material’s quality precluding their use in system materials. That is an obvious risk to be avoided.

According to Jylhä (2020), one contributing factor to the resistance to using recycled materials is their higher production costs compared to raw materials. Product manufacturers often obtain virgin raw materials more cheaply than recycled ones. These cheaper raw materials usually come from Asia, are made under cheaper production standards, and lower costs by denying their employees good working conditions and wages. The high cost of ethical compromises and environmental effects are not included in the low prices. (Jylhä 2020.)

The next approach is reuse, which places a particular focus on designing products that can, after use, be cleaned or repaired to restore to their initial purpose, without the consumption of new raw material resources. A discussion with Pöntiskoski (2022) revealed that they have developed an alternative connection type for welding called a FastLock. There the connection can be made with a single screw, yet it still meets the demands of marine regulations. Occasionally, there might be a need to dismount a pipeline. If the pipeline's connections are made with welded connections, it needs to be cut and new material is needed to make a new connection. With a connection like FastLock, the dismounting can be done easily, and the product can be reused multiple times. Blucher's products make use of plug-in connections, as well, and they also have a solution for deck penetrations using screw connections, so that welding is not required, and dismounting is easier (Falkesgaard 2022).

The third "R" stands for recovery. The use of biodegradable material is recommended, if possible, or at least care must be taken to recover waste material that could be suitable for energy production. Obviously, materials such as stainless steel and plastic are not biodegradable and their production will always generate some waste, but production processes should be designed to maximize the recovery of waste materials.

The fourth approach is to reduce or minimize the amounts of materials used in manufacturing. The goal is to avoid the use of both harmful and non-renewable materials such as fossil fuels. The production of plastic pipes requires raw materials made of cellulose, coal, crude oil, and natural gas. Most of these raw materials derive from processed crude oil, but in some cases raw materials from renewable sources can be used.

As shown in figure 19, 6% of total petroleum consumption goes to the production of plastics. Since the production of plastic utilises the side streams of crude oil production the use of side stream is reasonable at least until fossil fuel use is discontinued. Although the goal is to reduce the use of fossil fuels, according to Kuusela (2020) over 99% of plastics are still made from fossil fuels.

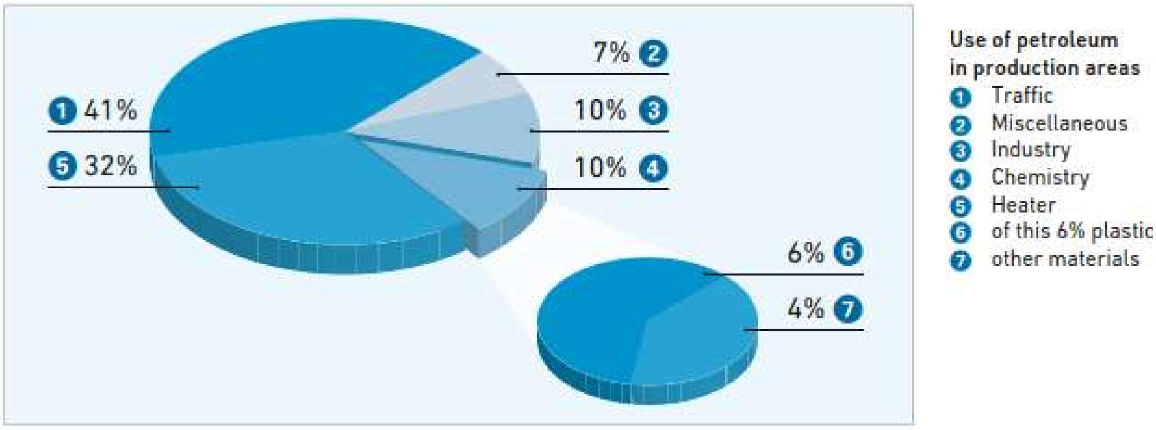

Figure 19. Use of petroleum in production areas (Georg Fischer 2022a, p.77)

Final "R" is rethinking material selection processes from a circular economy perspective. As it was shown in figure 13, the R5 approach needs continuous rethinking of processes and evaluation of the environmental effects of materials selection. Circular economy principles should inform both ship design and production. The legacy of linear take, make, and waste process models need to be transformed. Sustainability needs to operate in every sector. Finally, it is important to rethink new solutions: Is energy efficiency enough if environmental efficiency is not achieved? Or could it be other way around: Is environmental efficiency pursued at the expense of energy efficiency?

7 Discussion of the final selection

The final materials selection is made based on the functional requirements, environmental conditions, and manufacturing and cost comparisons of two pre-selected materials: AISI 316L and PE100. These were studied using three types of assistance tools: four-field analyses, cobweb-analyses, and material selection mapping. The analysis of manufacturing and costs included interviews with three product suppliers and the cost comparison of similar products. Calculations of heat expansion, a von Mises stress evaluation, and a case study supported the selection process. Finally, the sustainability and eco-friendliness of the materials was studied. There the key tool was the R5 approach, which allowed a deep analysis of the materials eco-friendliness. Sustainability was studied from a global perspective considering both government and classification societies' rules and regulations.

7.1 Comparison and connections with former research

At Deltamarin, a "black and grey water piping for ship applications" study was made in 2005 (Deltamarin Ltd 2005). There stainless steel AISI 316L Blucher and several plastic materials were studied and compared. This study should be updated, not because of any shortcomings, but since all comparisons of materials need periodic re-evaluation responsive to changes to the regulatory environment. Rules and approval criteria change frequently, e.g., according to Deltamarin's (2005) study PE100 pipes "are not approved for vacuum systems" (Deltamarin Ltd 2005), but today they are approved for vacuum systems by the DNV (Pöntiskoski 2022). This thesis was not focused on the comparison of specific materials, but rather to investigate the system requirements and corresponding material properties required to examine systematic material selection processes from functional, environmental, manufacturing and production, and cost perspectives. In my view this thesis' results could be used in future material comparison studies.

According to a study by Schumüller, Weichgrebe and Köster (2020) organic wastes may have a potential use for biogas production on cruise ships. In the case study, I found out that a cruiser with 3000 passenger generates organic waste (black water and food waste) of about

13kg per person per day, whereas the study of Schumüller, Weichgrebe and Köster (2020) calculated an average organic waste per day per person at about 9kg. According to Schumüller, Weichgrebe and Köster (2020) the energetic output for onboard biogas production is 82 W/P sufficient for 3.3% to 4.1% of the total energy demand of a cruise ship. According to my study, the total energy production after heat and electricity consumptions is 50kW and according to Elg (2022) it covers less than a 1% of energy demand. That is a significant difference.

7.2 Objectivity

The goal of this thesis was to examine the topic from a neutral aspect and with an open mind. I have seven years of experience in ship design and am aware that some materials have strong footholds in specific systems. The status of some materials has been earned over years of reliable functionality and some ship owners have strong opinions on material selection. I realise more or newer materials could have been included to this thesis, but it is more important to have developed the requirements list and material properties which may be of use in further studies.

7.3 Reliability and validity

The literature review and study of research methods used references from multiple sources. The sources used were from scientific journals (such as Elsevier and Scopus), articles from different maritime industry sources, and research on the management of ship-generated organic wastes. Deltamarin’s internal documents and interviews with product suppliers were particularly fruitful sources. Despite there being limited sources, there were sufficient materials available to validate the thesis topic.

One of the oldest sources used was from 1993, but that is the most recent regulation issued regarding the use of plastic materials in the maritime industry (IMO Resolution, 1993). Bibliometric measures (e.g., SNIP and SJR) of scientific articles (such as journals) were checked to ensure that the research materials were comprehensive and reliable.

7.4 Assessment of the results and sensitivity analysis

As mentioned, three assistance tools were utilised in this study. The four-field tool was used to analyse operating temperature, yield strength and tensile strength of plastic PE100 and stainless steel AISI 316L. Although AISI 316L has stronger properties than PE100, in systems like black water and food waste the better specifications do not make a critical difference under normal conditions. High operating temperature tolerances do matter in the case of fire. The second tool used was cobweb-analysis, where multiple different properties could be estimated simultaneously. The properties examined were ultimate tensile strength, melting point, modulus of elasticity, hardness, heat expansion, and density. Again, AISI 316L had a wider scale of properties than PE100. Material selection mapping was the final tool used. The relation of modulus of elasticity and density was studied. The small density of PE100 results in a lighter weight but smaller modulus of elasticity than AISI 316L. However, the final weights of the products are very close to each other due to the difference in wall thickness.

To support the selection process, calculations were made for heat expansion, von Mises stress analysis, and the case study of waste flows. Results from the heat expansion calculations provided valuable information regarding the materials' behaviour in different temperature changes. One key finding is that PE100 has 12 times higher heat expansion coefficient than AISI 316L. According to Eskelinen and Karsikas (2013) the material properties of many polymers are strongly temperature-related therefore it is not meaningful to make comparison without specifying a temperature indicator. The reactivity of plastic materials to heat makes the consideration of the heat expansion essential to plastic systems and pipeline designs. The availability of surrounding space, addition of loops to the piping system, temperature and cooling time of welding, the placing of brackets (pipeline supports), diameter and wall thickness must all be carefully considered.

Von Mises calculations informed the study of pressure variation tolerances. The analysis of calculations made for both materials showed that the pressure (in bar) where the pipe wall starts to yield was very close with both materials. In the case study calculations of the amount of food waste and black water waste flows were analysed. These results allowed for a more accurate estimate of the amount of energy that may be produced from biogas produced out of cruise ship waste flows. This study elaborated details of the size and shapes of biogas reactors. The research is valuable to inform new biogas reactor concepts for use onboard cruise ships.

The R5 approach was used to study the environmental sustainability concerns that arise in systematic material selection processes. R5 analysis is informed by the notion of circular economy, a key concept in the development of eco-friendliness. The study found that many parties e.g., European Union (2022a) have set regulations and goals to "provide longer-lasting products that can be repaired, recycled and re-used". However, the recycling of materials such as stainless-steel and plastics present unique challenges. Recycled stainless-steel material can be used to produce new materials, but for plastic that is rarely possible due to the reduction in quality during the plastic recycling process. The virgin material used in plastic pipe production does use fossil fuels, however the raw materials of plastic are made from the side streams of fossil fuels.

The study of manufacturing and cost comparison allowed for a true comparison between PE100 and AISI 316L products. Since similar products are used in the similar systems the comparison provided a reliable foundation for the analysis. The comparison of raw materials was ignored since the prices of raw materials vary very much and they do not contribute much to the cost of the final products. Also, the comparison of ready-made products is challenging because the final price depends on the project (volume) and who is the purchaser. Discounts varied between 20-40% from the original catalogue prices for both suppliers. The research interviews generated insights from the experts' comments on how they view current materials and their informed speculations about possible development ideas (Appendix 3).

Based on these results, I asses both materials to be appropriate for use as feedstock systems for biogas reactors. Although both materials, PE100 and AISI 316L, have unique material properties and their properties are quite different from each other, both materials are suitable for similar applications.

7.5 Key findings

This thesis focused on performing a systematic material selection process for the waste systems suitable for use in biogas production. First, the aim was to research relevant material properties suitable for the systems. Secondly, the research used assistance tools supported by calculations The most useful assistance tools from a design perspective are four-field and cobweb analyses. This study showed that a systematic material selection process depends on these analytic tools to reliably estimate materials' suitability for the systems. The cobweb analysis of many properties at same time is particularly well-suited to a holistic approach for most materials. The comparison with cobweb enables the results to be analysed from a wider perspective. The process allows a more holistic view to be developed including functional, environmental, manufacturing, costs, and sustainability considerations. This enables the results of assistance tools to be used in other systems with wider applications beyond maritime solutions.

The key for this thesis was to analyse the properties of functional and corresponding materials in table form. However, objective numerical values were difficult to obtain since the researched systems are not subject to strict requirements such as high pressure. On the other hand, these systems exposure to highly corrosive substances do lead to requirements for sufficient resistance to corrosion. The environmental approach to the systematic material selection process was particularly interesting. When the materials used in a system are not subject to strict requirements, it is even more valuable to investigate their eco-friendliness and sustainability aspects. One finding to be mentioned is the value of the R5 approach to the study of the whole material supply chain of products and in facilitating environmental social governance.

7.6 Novelty value of the results

When Deltamarin was presented with the idea of an onboard biogas reactor fuelled by ship-generated organic waste, they suggested that a systematic material selection process for such a system should be conducted. The systematic material selection was made for systems with the potential of being used as biogas feedstock. The research provided new knowledge and the list of requirements and material properties can be utilised in further studies e.g., both for new materials and, with some modifications, for other types of systems.

Besides making financial sense, the idea of placing a biogas reactor on a cruise ship to produce a portion of the energy or/and heat it creates good image for the company. Today's maritime industry including ship designing companies are eager to find alternative solutions for cleaner and greener technology both to save money and enhance their image.

7.7 Generalisation and utilisation of the results

These research results can be utilised in other systems besides sewage and food waste systems. There are many systems that use stainless-steel and plastic pipes. The systematic material selection process could be used at companies like Deltamarin as part of the development of projects and pipe design manuals. The results could also inform future research of material comparisons. The list of requirements and corresponding material properties can be generally used in other systems, applications, and industry segments besides the maritime industry. The systematic materials selection process can inform, not only the analysis of materials in current use, but also the selection of entirely new materials for emergent systems.

7.8 Topics for future research

A few additional materials could be useful to further and wider study. According to Falkesgaard (2022), PVC is commonly used for sewage systems in Asia even though its installation time is slow due to its glued connections. PVC-U and PVC-C is commonly used in European markets due to its good chemical corrosion resistance. However, in case of fire it forms toxic gases during burning (Pöntiskoski 2022). According to Mäkilä (2022) galvanized steel pipes are also used especially in the Chinese market. These are cheap but their corrosion resistance is poor and therefore their life cycle is short. It is to be noted potential new materials explored must meet the same requirements as materials in current use.

Before we can implement biogas reactors for cruise ships, the design process must be researched in greater detail. It is necessary to develop a holistic approach that takes all aspects into consideration to determine the value such a system can bring to shipping. Is it possible to replace a whole system of wastewater treatment with a biogas system? Is there still a need for wastewater treatment and, if so, on what scale? Could it save energy if wastewater do not need to be purified when it feeds a biogas system? What other equipment and applications would be needed besides a biogas reactor? What would be done with the digestate of biogas? Should the biogas be used continually e.g., as a fuel for ship, or should it be stored for later use e.g., in a harbour to avoid the use of an oil-fuelled boiler? Many questions are yet to be answered, that is why I see this topic being the source of valuable research in the future.

8 Summary

The study of the systematic material selection process included the assessment of functional requirements, environmental conditions, and manufacturing and cost comparisons of two pre-selected materials AISI 316L and PE100. These were studied using three types of assistance tools: four-field analyses, cobweb-analyses, and material selection mapping. Analysis of manufacturing and costs included interviews with three product suppliers and a cost comparison of similar products. Calculations of heat expansion, a von Mises stress criterion, and a case study supported the selection process. Finally, the sustainability and eco-friendliness of the materials was studied. There the key tool was R5 approach, allowing for a deep analysis of the materials' eco-friendliness. Sustainability was studied from a global perspective considering classification societies and government rules.

Even though placing a biogas reactor on a cruise ship will not produce a high proportion of a cruise ship's total energy consumption, I see it providing a significant ecologic value. As Gustafsson et. al. (2020) mention, "technology providers should explore the potential for developing new functional solutions that increase the value generation potential and sustainability of the ecosystem." Gustafsson et. al. (2020) also mention that "locally produced renewable fuel could provide a low-emission propulsion solution." This could upend the state of competition among technology providers. In my opinion, not every technical solution needs to be "energy-efficient" to become part of a ship's technical solution. When do economic motives overrule environmental needs? That is a question each of us should ask ourselves.

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Appendix 1. Material properties of PE100 (Georg Fischer, 2022a) (Georg Fischer, 2022b)

2.2 Characteristics of ecoFIT (PE)

Characteristics	PE80	PE100	Units	Standard
Density	0.93	0.95	g/cm³	EN ISO 1183-1
Yield stress at 23 °C	18	25	N/mm²	EN ISO 527-1
Tensile e-modulus at 23 °C	700	900	N/mm²	EN ISO 527-1
Charpy notched impact strength at 23 °C	110	83	kJ/m²	EN ISO 179-1/1eA
Charpy notched impact strength at -40°C	7	13	kJ/m²	EN ISO 179-1/1eA
Ball indentation hardness (132N)	37		MPa	EN ISO 2039-1
Crystallite melting point	131	130	°C	DIN51007
Heat conductivity at 23 °C	0.43	0.38	W/mK	EN 12664
Water absorption at 23 °C	0.01 - 0.04		%	EN ISO 62
Colour	Black		RAL	RAL 9005
Limiting oxygen index (LOI)	17.4		%	ISO4589-1

PE properties (reference values)

Property	PE 80-Value[1]	PE 100-Value[1]	Units	Test standard
Density	0.93	0.95	g/cm³	EN ISO 1183-1
Yield stress at 23 °C	18	25	N/mm²	EN ISO 527-1
Tensile modulus at 23 °C	700	900	N/mm²	EN ISO 527-1
Charpy notched impact strength at 23 °C	110	83	kJ/m²	EN ISO 179-1/1eA
Charpy notched impact strength at -40 °C	7	13	kJ/m²	EN ISO 179-1/1eA
Thermal conductivity at 23 °C	0.43	0.38	W/m K	EN 12664
Water absorption at 23 °C	0.01 - 0.04	0.01 - 0.04	%	EN ISO 62
Color	9'005	9'005	RAL	
Limiting oxygen index (LOI)	17.4	17.4	%	ISO 4589-1

Appendix 2. Material properties of AISI 316L (Blucher, 2022a)

Material Specification

Material	AISI 316 L 1.4404	AISI 304 1.4301
Analysis		
Carbon (C %)	Max. 0,03	Max. 0,07
Chromium (Cr %)	16,5 - 18,5	17,0 - 19,0
Nickel (Ni %)	11,0 - 14,0	8,5 - 10,5
Molybdenum (Mo %)	2,0 - 2,5	-
Manganese (Mn %)	Max. 2,0	Max. 2,0
Silicium (Si %)	Max. 1,0	Max. 1,0
Sulphur (S %)	Max. 0,030	Max. 0,030

Physical Properties

Structure	Austenitic (nonmagnetic)	Austenitic (nonmagnetic)
State	Non-annealed	
Specific gravity (g/cm^3)	7,98	7,9
Melting point (°C)	Ca. 1400	Ca. 1400
Decortication temperature in air (°C)	800 - 860	800 - 860
Expansion coefficient 20 - 100 °C (m/m . °C)	16,5 x 10-6	16,5 x 10-6
Specific resistance (20° C) (Ohm . mm^2/m)	0,75	0,73
Heat conductivity (20°C) (W/°C-m)	15	15
Specific heat (J/g . k)	0,5	0,5

Mechanical Properties

Ultimate tensile strength (Rm) (N/mm^2)	490 - 690	500 - 700
Yield point (Rpo2) (N/mm^2)	190	195
Modulus of elasticity (E) (20° C) (N/mm^2)	2,0 x 105	2,0 x 105
Hardness Brinell (HB) (N/mm^2)	120 - 180	130 - 180

Appendix 3. Interview of the research section

This thesis research included six interviews with experts in the maritime field. Three of the interviews are shown here, another three interview results are included in other chapters of results. First, I interviewed two project managers from Deltamarin, with years of experience in ship design especially from the perspective of mechanical engineering. An interview was also conducted with Doranova, a supplier of land-based biogas reactors to develop a wider perspective on the subject. Interviews were conducted via e-mail, and they contained almost similar questions, depending on the interviewee’s expertise. The questions related mostly to requirements of materials already in use in specific systems.

The interview with Project manager 1:

- What requirements does the waste systems have on pipe materials?

Corrosion (waste streams includes aggressive ingredients). Strength needs to withstand impacts on outer surface of a pipe (e.g., in case a tool hits a pipe, it might crack the outer surface). Pressures and temperatures are low, but the flow is dynamic. Pipes must last its entire life cycle (in the cruise ships its approximately 30 years).

- What are the pipe materials which are currently in used in waste systems?

Most used pipe material is AISI 316L. Plastic pipes are used too, but they have some features, which effects on material behavior: They do not withstand outer impacts so well than stainless steel pipes. They are sensitive for a fire (when plastic pipe crosses a watertight compartment, they need a bulkhead shut-off valve to ensure water tightness between compartments). Especially in Chinese market, they offer galvanized steel pipes (they have relatively low service life, but on the other hand they are very cheap).

- Are there some notations in rules or regulations, which could be related to this topic?

Classification society DNV-GL has a notation of a “Clean design” and USPHS.

(Mäkilä, 2022)

The interview with Project manager 2:

- What requirements are set on the pipe materials and what special features does the pipe materials include and why so?

In general, pipes are divided into three different categories I, II and III. The category where a pipe is located depends on the temperature and pressure of a system. Waste systems such as food waste and black water belongs to the category III, since previously mentioned properties are low. Rules does not have impact much on the systems either. Pipe material and joint types depends on the substance which to be transferred. More information regarding rules, can be found from LR P5 Ch12 sec2. If plastic pipes are used, not every plastic material is allowed and for that there are rules available. A suitable certificate is required and depending on the fire class of the bulkhead, the material affects the type of penetration as well.

(Bakker, 2022)

The interview with Doranova:

- Referring to the Doranova's catalogue, do you have some specific information regarding the materials, which are used in the equipment's of a biogas production?

Normally all surfaces which are in contact with biogas are made of acid-resisting steel or alternatively concrete, which is coated e.g., with polyurea to withstand mainly the hydrogen sulfide, which biogas contains. Simultaneously the gas and liquid tightness to be ensured.

Ceiling is often made of double membrane (which is HDPE plastic). The idea is to store gas in the upper part of a reactor.

Pipes are made of either from PE-plastic or stainless steel. Both are suitable for the used feedstock and are resistant to the corrosion caused by them.

- Depending on the quantity and quality of the feed mixture (food and wastewater), what material requirements have been set for the biogas reactor, pipelines, and feed devices? Does the feed mix go through pipelines to the biogas reactor, or are there used feed devices?

There are no direct material requirements for the processing systems.

Mostly, the supply and discharge piping for liquids is made of stainless steel or PE plastic pipe, which is also very resistant to corrosion.

Most of the materials are pumped into the reactor. Regarding solid feeds (food scraps, vegetables, grass, etc.), there are a few different options:

Mix directly with liquids and pump into the reactor (suitable pump according to the solids content, e.g., piston pumps also push solids forward if necessary).

The solids are fed through the feed carriage with a screw directly into the reactor, (e.g., easy feeder Solo type equipment). Here it is important to feed the digestate below the surface so that the gas does not escape through the feed screw.

If there are a lot of long fibers, as in grass, the solids can be first ground and then mixed with either compost or liquid feeds.

Easiest is if you can mix the feeds into liquid/slurry and pump everything into the reactor.

- Referring to your catalogue, there are mentioned that the biogas reactors are made from concrete, stainless steel, and acid-resisting steel. Are these materials commonly in used?

Yes, if a steel reactor is made, the surface in contact with the digestate is made of stainless steel and the upper part, where there is gas, is acid-resistant. Generally, the uppermost ~1 meter from the reactor, is made of the acid-proof steel.

If the reactor is made of concrete, the top part is at least coated to withstand gas and hydrogen sulfide. Often in this context, the entire reactor is coated, which also ensures the reactor's water resistance.

- Are there some challenges regarding some materials, which would be beneficial to investigate to find better alternative materials?

If you mean building materials, the problem with steel is not so much availability, but the significantly increased price, almost three times what it was a few months ago.

In terms of availability, the longest delivery times are for electrical and automation equipment (e.g., Siemens already gives delivery times of more than a year).

- Other to be mentioned?

As additional considerations, it is also worth looking at the use of digestion residue. That is, normally it is used as fertilizer, but for that the digestion residue must be sanitized (1 hour at over 70 degrees) and the piece size must be less than 12 mm. Usually, a macerator is used for this before the reactor or after it, before sanitizing, which ensures the piece size.

(Saalasti, 2022)