YRKESHÖGSKOLAN NOVIA

Enhancing the Accuracy of Weight Estimates for LNGPac Constructions

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Abstract

This thesis was done for Wärtsilä Fuel Gas Supply Systems (FGSS). This research focuses on improving the current method for estimating the weight of LNGPac construction. Started in fall 2023 and completed in spring 2024, this research forms part of the engineering degree in Mechanical and Production Engineering.

It had been observed that the current weight estimates for LNGPac constructions are not particularly accurate, leading to large discrepancies between the theoretical and the measured weight of the LNG-system. This discrepancy can lead to potential fines and negatively affect customer satisfaction. Therefore, it was decided to start a thesis about this topic to try to identify the flaws of the current methodology and find ways to make the estimates align with the real weight.

The methodology involves a mixed research approach, combining qualitative and quantitative methods. The qualitative method involved consultations and discussions in the form of meetings and personal contact with people within the department, this was done to identify factors affecting weight estimation. The quantitative method used data from previous projects to analyze the accuracy of our current weight estimates and variations in the thickness of the delivered plates that were suspected to affect our estimate.

The result pinpoints where the flaws are in the current estimate method, and a new enhanced version of the estimate method is created. The new version considers the deviation in the received plates, which makes the estimated weight align more closely with the real-world weight.

Language: English
Key words: LNGPac, alternative fuels, weight estimation, constructions.

EXAMENSARBETE

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Titel: Förbättring av noggrannheten vid viktestimering av LNGPac-konstruktioner

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Abstrakt

Detta examensarbete gjordes för Wärtsilä Fuel Gas Supply Systems (FGSS). Arbetet fokuserar på att förbättra den nuvarande metoden för att estimera vikten av LNGPac-konstruktioner. Inledd hösten 2023 och avslutad våren 2024, utgör denna forskning en del av ingenjörsexamen inom maskin- och produktionsteknik.

Det hade observerats att de nuvarande viktestimeringar för LNGPac-konstruktioner inte var tillräckligt precisa, vilket ledde till stora avvikelser mellan den teoretiska och den uppmätta vikten av LNG-systemet. Denna avvikelse kan leda till potentiella böter och kan negativt påverka kundens nöjdhet. Därför beslutades det att påbörja ett examensarbete om detta ämne för att försöka identifiera bristerna i den nuvarande metod och hitta sätt att få estimeringarna att bättre överensstämma med den verkliga vikten.

Metoden omfattar en blandad forskningsansats, där kvalitativa och kvantitativa metoder kombineras. Den kvalitativa metoden involverade samråd och diskussioner i form av möten och personlig kontakt med personer inom avdelningen, detta gjordes för att identifiera faktorer som påverkar viktestimeringen. Den kvantitativa metoden använde sig av data från tidigare projekt för att analysera noggrannheten hos våra nuvarande viktestimeringar och variationer i tjockleken på de levererade plåtarna som misstänktes påverka vårt estimat.

Resultatet pekar ut var bristerna finns i den nuvarande estimeringsmetoden, och en ny förbättrad version av estimeringsmetoden skapas. Den nya versionen tar bättre hänsyn till avvikelsen i de mottagna plåtarna, vilket gör att det uppskattade vikten överensstämmer bättre med den verkliga vikten.

Språk: engelska
Nyckelord: LNGPac, alternativa bränslen, viktestimering, konstruktioner

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Nimike: Painoarvioiden tarkkuuden parantaminen LNGPac-rakentamisessa

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Tiivistelmä

Tämä opinnäytetyö tehtiin Wärtsilän Fuel Gas Supply Systems (FGSS). Työssä keskitytään parantamaan nykyistä menetelmää LNGPac-mallien painon arvioimiseksi. Syksyllä 2023 aloitettu ja keväällä 2024 valmistunut tutkimus on osa kone- ja tuotantotekniikan insinööritutkintoa.

Oli havaittu, että nykyinen LNGPac-rakenteiden painonarviointi ei ollut riittävän tarkka, mikä johti suuriin eroihin rakenteen suunnitellun ja mitatun painon välillä. Tämä ero voi johtaa mahdollisiin sakkoihin ja vaikuttaa kielteisesti asiakastyytyväisyyteen. Tämän vuoksi päätettiin käynnistää tätä aihetta koskeva opinnäytetyö, jossa pyritään tunnistamaan nykyisen menetelmän puutteet ja löytämään keinoja, joilla arvioinnit saadaan vastaamaan paremmin todellista painoa.

Menetelmänä käytetään sekatutkimusmenetelmää, jossa yhdistetään laadullisia ja määrällisiä menetelmiä. Kvalitatiiviseen menetelmään sisältyi kuulemisia ja keskusteluja kokousten ja henkilökohtaisten kontaktien muodossa osastolla työskentelevien henkilöiden kanssa, ja näin pyrittiin tunnistamaan painon arviointiin vaikuttavia tekijöitä. Kvantitatiivisessa menetelmässä käytettiin aiemmista hankkeista saatuja tietoja, joiden avulla analysoitiin nykyisten painoarvioiden tarkkuutta ja toimitettujen levyjen paksuuden vaihteluita, joiden epäiltiin vaikuttavan arvioihin.

Tulokset osoittavat, missä nykyisessä arviointimenetelmässä on puutteita, ja arviointimenetelmästä luodaan uusi parannettu versio. Uudessa versiossa otetaan paremmin huomioon vastaanotettujen levyjen eroavaisuudet, jolloin arvioitu paino vastaa paremmin todellista painoa.

Kieli: englanti
Avainsanat: LNGPac, vaihtoehtoiset polttoaineet, painon arviointi, rakenteet

Table of Contents

List of Figures

List of Tables

1 Introduction

This thesis is made on behalf of Wärtsilä Fuel Gas Supply Systems (FGSS), which focuses on alternative fuel systems for the marine industry. The thesis work started during the autumn of 2023 and was finished during the spring of 2024. The thesis was carried out as a part of an engineering examination in the field of Mechanical and Production Engineering

This chapter will cover the background, purpose, and goal of this research. Furthermore, the company and department where this thesis was conducted will be introduced, and a disposition will be presented to offer a clearer preview of what's to come in the subsequent sections.

1.1 Background

Summer of 2023, I started my employment at Wärtsilä FGSS as a summer trainee. My main role has been in quality management. During my time at the department, we got a complaint about the LNG system, also called LNGPac, that the system weighed more than what was agreed on. This situation is known to have happened multiple times before, therefore it was decided to start a thesis about this topic to get to the root cause of the issue.

Deviation between the design weight and the actual weight of the system can result in penalties, and negatively impact customer satisfaction. Currently, the weight is primarily determined using data from 3D drawings. However, it has been concluded that relying on these 3D models for estimating weight is not sufficiently accurate. To address this problem a comprehensive analysis was undertaken to identify the reasons behind the weight variances and develop a solution to resolve the issue.

1.2 Purpose & goal

The primary objective of this thesis has two aspects. Firstly, it seeks to identify the underlying reasons for the weight deviation between the specified and actual weight in the LNGPacs. Secondly, it aims to develop an improved estimation method to enhance the accuracy of the weight estimations.

By bridging the gap between specified and actual weights, this research seeks to improve the accuracy of weight estimation for the LNGPac system, thereby contributing to the overall quality of Wärtsilä Fuel Gas Supply Systems.

1.3 Wärtsilä

Wärtsilä is a global leader in innovative technologies and lifecycle solutions for the marine and energy markets, emphasizing sustainable technologies and services. Wärtsilä was founded in 1834 and has today grown to an international company with 17500 employees located in 79 countries. Wärtsiläs net sales totaled 5.8 billion euros in 2022. The company is listed on Nasdaq Helsinki. (Wärtsilä, 2023)

Wärtsilä is most known for its large internal combustion engines, which provide power to both marine vessels and powerplants. In 2015 Wärtsilä was recognized by Guinness World Records for creating the most efficient four-stroke diesel engine in the world, the Wärtsilä 31. (Wärtsilä, n.d.-a)

A key element of Wärtsiläs identity lies in its commitment to sustainability. With its values, principles, and strategic goals, the company prioritizes solutions to reduce carbon emissions. Wärtsilä has a high focus on alternative fuels to power its engines, contributing to lower emissions and a more environmentally conscious future. (Wärtsilä, 2023)

1.3.1 Fuel Gas Supply Systems

Wärtsilä Fuel Gas Supply Systems (FGSS) is a department under the branch of Marine Power that focuses on alternative fuels for the marine industry. FGSS's roots go back to 2009 when the first design of the LNGPac was introduced. Since then, the department has experienced exponential growth, and as of now, there are around 100 employees.

The organization develops designs and sells fuel systems for alternative energy sources. The products offered currently are LNGPac, GVU, and MethanolPac. The organization also has two other fuel systems that are under development, HyrdrogenPac, and AmmoniaPac.

1.4 Disposition

In this section, a brief description of what the following chapters will contain is presented.

- Theory, in this chapter background theory relevant to my work is presented. This chapter provides valuable information to help understand the fundamental concepts guiding my research.

- Preliminary studies, this chapter serves as a presentation of the pre-studies that were conducted before commencing the primary research.

- Methodology, this chapter will explain the methods chosen for achieving a result. This involves analyzing old data, meetings, and planning.

- Results, in this chapter the results and findings achieved by my research are presented.

- Discussion, this chapter offers a critical analysis of my findings, my perspectives on this thesis work, and suggestions for future development based on the results.

2 Theoretical Background

In this chapter, the theoretical background of this thesis will be presented. The following subchapters will provide information about the properties of LNG, the purpose of an LNGPac, its functionality, and its components. Furthermore, computer-aided design (CAD) will be introduced alongside its applications.

2.1 Liquefied Natural Gas

Liquefied natural gas (LNG) is an efficient way to store and transport natural gas. By cooling down natural gas to about -162°C it transitions from gaseous state to liquid form. Natural gas in its liquid form occupies only 1/600th of the volume in comparison to when it is in its gaseous form. Although natural gas is a fossil fuel, it is a significantly cleaner energy source than traditional fuels. Compared to the most widely used fuel in shipping today, heavy fuel oil (HFO), LNG can reduce greenhouse gas emissions by 23%. Additionally, it almost eliminates sulfur oxide and particle matter, while nitrogen oxide is reduced by 80%. This makes LNG a more environmentally friendly energy source. (DNV, u.d.)

Natural gas is not only used for powering marine engines, but it is also a vital energy source for our industries and heating our homes. Traditionally, vast natural gas reservoirs supplied Europe through pipelines. However, recent geopolitical complexities have added complexity to this supply chain. Therefore, there is an increased interest in LNG due to its capacity for efficient overseas transportation.

LNG contains mostly methane, with composition varying from 87% mole to 99% mole methane depending on the source and how it is processed. LNG is transparent, has no smell, and is non-corrosive. The density of the fluid is relatively low, from 430 kg/m^3 to 470 kg/m^3, which is less than half the density of water. (Mokhatab, Valappil, Mak, & Wood, 2014, pp. 3-4)

LNG has a high LHV (low heat value) of 49 MJ/kg, compared to diesel at 42.6 MJ/kg. (Johnsson & Strande, 2013). The chemical symbol for methane is CH4, and the chemical transformation that occurs during combustion is as follows:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

2.1.1 LNG as a fuel for the marine industry

The demand for LNG-fueled ships is continuously increasing. The ambitious targets set by the International Maritime Organization (IGF) to reduce carbon emissions have contributed to increased popularity of LNG-fueled vessels. The aim is to reduce CO_2 emissions by at least 40% by 2030 compared to 2008 levels, and net-zero greenhouse gas emissions by the year 2050. In the year 2022, there were 222 new orders for LNG-fueled vessels, while 355 LNG-powered vessels were already in operation. (International Maritime Organization, 2023; LNGPrime, 2023)

The utilization of LNG as an energy source for the marine industry is not done without its complexities. Before the LNG can be supplied to the engines, several steps must be taken. Firstly, The LNG needs to be heated to transform it into a gaseous form. Secondly, the amount of natural gas supplied to the engines needs to be precisely regulated, this is because the gas is only flammable in a range of 5% to 15% by volume of air. Outside this range the methane is not flammable because of a lack of methane or oxygen (Mokhatab, Valappil, Mak, & Wood, 2014, p. 5). To meet these criteria an LNGPac is implemented to process and store the LNG. More about LNGPac is presented in Chapter 2.2.

Wärtsilä has two main solutions for igniting natural gas in the combustion chamber, spark-ignited (SG) engines and dual-fuel (DF) engines. Spark-ignited engines operate purely on natural gas, and the combustion process follows a normal Otto cycle, with the air-fuel mixture being ignited by a spark plug. Dual fuel engines on the other hand, can run on both diesel and natural gas. When operating in gas mode, the engine functions as the Otto-cycle principle, but in contrast to the SG engine, the DF engine´s air-fuel mixture is ignited by a small amount of diesel which is injected near the top dead center on the compression phase. (Wärtsilä, n.d.-b)

2.2 LNGPac

LNGPac is a complete fuel system for LNG-fueled ships. It serves as a solution to store and process liquid natural gas and feed it to the engines reliably. By utilizing natural gas as a fuel and integrating an LNGPac system, emissions such as nitrogen oxide particles, sulfur, and carbon dioxide can be significantly reduced. (Wärtsilä, 2020)

The system can be built with different modules and sizes based on the customer's requirements and needs. The flexibility of the LNGPac design makes it implantable in both larger and smaller vessels. From the projects that have been delivered the LNG tank capacity has ranged from 25 to 3000 cubic meters. (Wärtsilä, 2020)

Figure 1 presents an example of a complete fuel gas system which includes an LNG storage tank, tank connection space, gas valve unit, bunkering station, and heating media skid. The upcoming text will provide a detailed description of these modules and components.

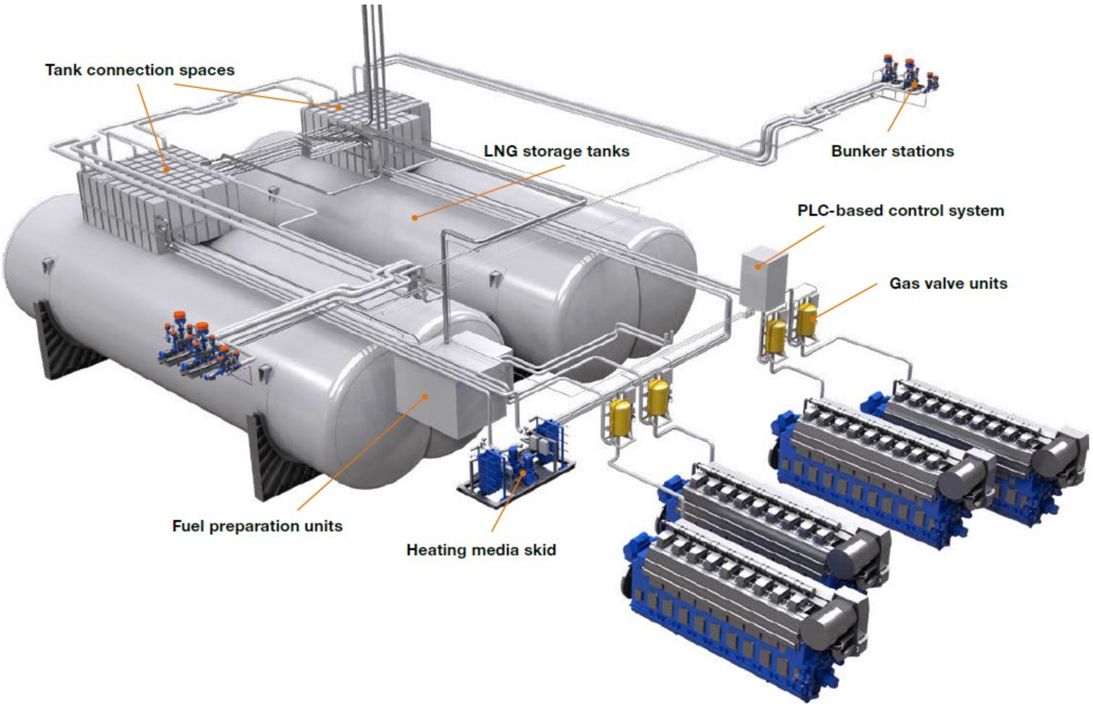

Figure 1. LNGPac system (Wärtsilä, 2020).

2.2.1 LNG storage tank

The fuel storage tank is one of the most vital constructions of the LNGPac. The LNG needs to be well isolated to maintain the cryogenic conditions. If the LNG gets too warm, the liquid will start to generate an excessive boil of gas which causes the pressure to rise inside the tank. The tank is required to be able to keep the tank pressure below safe limits for a minimum of 15 days without relieving any built-up pressure to the atmosphere, this duration is referred to as holding time. The tanks are insulated in two different forms, vacuum, and polyurethane foam (PUF). (Wärtsilä, 2020)

Vacuum-insulated tanks are constructed with two shells, one outer and one inner, in between these two shells vacuum is drawn. Vacuum is highly efficient at insulating and would in an ideal case eliminate all convection from the inner and outer shell because there is no media to transfer heat. Unfortunately, an ideal vacuum is impossible to achieve, and there will always be some degree of heat transfer, although it is minimized. There is also an additional insulation used in the vacuum-insulated tank called evacuated perlite, whose purpose is to reduce thermal radiation (Wärtsilä, 2020). Perlite is a volcanic rock that has been crushed, heated above 870°C, and then combined with water, causing the perlite to expand four to twenty times its original size. (Perlite Institute, 2018)

Polyurethane-insulated tanks, also called single-shell tanks, are cylindrical tanks with polyurethane foam coating. The insulation is applied either by installing prefabricated panels or by directly spraying polyurethane foam on the outer surface of the tank. The typical insulation thickness is 300 mm. The thickness can be increased to improve the performance, but thicknesses over 450 mm are not advisable because of an increased risk of the insulation collapsing due to the shrinkage of the tanks during bunkering. (Wärtsilä, 2020)

The choice of insulation type is usually dependent on the storage volume and holding time. Vacuum-insulated tanks are usually used for tanks with a capacity smaller than 300 m^3 while polyurethane-insulated tanks are selected for volumes larger than 300 m^3. Vacuum insulated have the most extensive holding time, estimated 10 times longer than a polyurethane tank in similar dimensions. However, they are more expensive to build and are heavier than a similar size polyurethane tank. Holding time for polyurethane insulated tanks is satisfactory when it has a larger capacity volume due to the large amount of volume of media keeping the LNG cooler for longer. (Wärtsilä, 2020)

2.2.2 Tank Connection Space

Tank connection space (TCS) is a module where all pipes are connected from the tank. The main functionality of the TCS is to measure, control, and regulate the condition of the tank and to process the LNG, making it ready to be delivered to the engines.

The TCS is equipped with components such as process- and emergency shut-down valves, instruments, LNG pumps, and evaporators. Process valves control the flow of the media within the system, and emergency shut-down valves activate in cases of emergencies to prevent hazards and to maintain the integrity of the system. The instruments measure parameters such as temperatures, flow rates, and pressures, ensuring a safe and reliable operation. LNG pumps, which are used in a pump-based system, provide the evaporators with the right amount of LNG. The evaporators heat the LNG causing it to transform to a gaseous state which is later delivered to the gas valve units. (Wärtsilä, 2020)

The module is constructed in different configurations depending on the specific project. The TCS can be positioned on the top, side, or at the end of the tank and can either be enclosed or open construction. For installation on deck, the TCS could simply be an open dome arrangement without enclosure. For installation below the deck the TCS is enclosed in a gastight structure to limit the gas escaping in case of a leakage. The interior is equipped with a variant of equipment depending on the complexity of the system and which modules are used within the system. Some TCS have a gas valve unit integrated, while some lack this feature. A similar case is with the LNG pumps which are only used in a pump-based system. (Wärtsilä, 2020)

2.2.3 Gas valve unit

The gas valve unit (GVU) regulates the gas pressure fed to the engine. GVU ensures a fast and secure operation, with fast shutdown time. The gas pressure is precisely controlled depending on the engine load and is roughly 1 bar higher than the charge air pressure.

The GVU can be an open, closed design or integrated inside the TCS. The open design is only used when a separate designated room is available next to the engine room. The enclosed design has its own gastight capsule and can be placed directly in the engine room. If the LNGPac is close to the engines, the GVU can be integrated into the TCS. To achieve a fast response of the GVU output, the maximum allowable pipe length from the GVU to the engine has been limited to 10-30 meters, depending on the specific engine model. This limitation applies to all GVUs (Wärtsilä, 2020; Wärtsilä, n.d.-c)

2.2.4 Bunkering station

A bunkering station is used to transfer LNG from an external source to the storage tank. The system is equipped with valves, pressure gauges, filters, and relief valves to ensure a safe and efficient bunkering operation. The fuel receiving stations are usually placed at upper deck level for easy accessibility and the LNG is bunkered via trucks, bunker vessels, or LNG terminals (Wärtsilä, 2020).

2.2.5 Fuel gas preparation unit

In some installations, there is not enough room for all the process equipment to be installed inside the TCS. Therefore, equipment such as buffer tank and gas heaters are installed in the additional module called fuel gas preparation unit (FGPU). This module is installed downstream of the TCS and upstream of the GVU. Often the evaporation of the LNG is segregated to the TCS and leaves only gas heating to the FGPU, meaning that FGPU is only in contact with natural gas and limiting the cryogenics hazards to the TCS only. Similarly, to the GVU, the FGPU can be either built in an open or gas-tight construction, adhering to the same safety protocols. (Wärtsilä, 2020)

2.2.6 Heating media skid

A separate heating media skid (HMS) is installed in some projects, and its purpose is to supply the heat exchanger with warm liquid to gasify the LNG. The heat is usually extracted from the engine's coolant water via circulation pumps, which pump coolant through the LNG heat exchangers. Inside the HMS there are components such as circulation pumps, heat exchangers, distribution valves, instruments, and a expansion tank. (Wärtsilä, 2020)

Wärtsilä also developed a cold recovery system solution which is patented. The system utilizes the coldness of the LNG for cooling purposes, such as powering fridges and AC systems. The cold recovery system contributes to a fuel saving of 3-4%, which usually gives a return on investments of less than two years. (Wärtsilä, 2020)

2.3 Computer-aided design

Computer-aided design (CAD) is used to create two or three-dimensional designs in a virtual environment. This tool is used by engineers and designers and has replaced the manual method of drawing designs, with pen and paper. (Siemens, n.d.)

The first use of what can be recognized as a CAD program was developed by Patrik Hanratty at General Motors in 1957, this program involved interactive graphic and numerical control programming. Although the software was not efficient, the ground was set for future development. It was not until 1982 that CAD programs became more mainstream with designers, with the introduction of AutoCAD. The initial version enabled users to draw in 2D, and three years later, 3D modeling was launched. Today AutoCAD is the industry leader, with many millions of users. (Geddes, 2020)

CAD programs enable the designer to flexibly create or modify all aspects of a product, component, or assembly, making it far more efficient than drafting designs the traditional way. Modern CAD software makes it possible for engineers to simulate, optimize, and refine the design before it reaches the manufacturing line. (Siemens, n.d.)

CAD simulation software allows virtual tests to be conducted on a designed object without needing the physical product or part. This makes the designing process more efficient and saves both time and money. By conducting simulations, the designed object can be tested on diverse factors regarding how the design behaves. These simulations can for example be structural stress- or flow simulations. Structural simulations ensure that models can withstand loading conditions while flow simulations help improve elements like optimizing cooling systems or testing pressure dynamics. (CADimension, n.d.)

CAD software makes it possible to easily determine the weight of a part or assembly. The software can determine the volume of the object, and by assigning a material with a specific density to the designed object, the software can calculate the theoretical weight of the item. The software uses the following equation when determining the theoretical weight:

$$m = \rho \times V \qquad (1)$$

Where m is the mass, ρ is the density of the material, and V is the volume of the object.

3 Preliminary studies

Prior to commencing the primary research, preliminary studies were undertaken to investigate the construction design and manufacturing processes of LNG tanks. This groundwork was essential for gathering the necessary information to formulate a solution to the problem. This chapter provides information about details regarding tank design and manufacturing process.

3.1 Tank construction design

This study was aided by the department's design engineer Koczur, with whom I had a meeting and maintained communication with. This chapter will give an overview of different kinds of tank designs, including single-shelled and double-shelled tanks. Additionally, factors determining the shell thickness will be presented.

The design of the tank configuration is very flexible to meet the customer's demands. To fit the tank in the designated construction space, the tank can be placed vertically or horizontally and comes in five main construction configurations. Vacuum-insulated tanks can only be constructed as a single cylindrical structure, while polyurethane tanks come in forms such as single cylindrical, bilobe, multilobe, and membrane configurations. In Figure 2 a bilobe tank is presented. (Koczur, 2023)

Figure 2. PUF-insulated bilobe tank (Wärtsilä Internal Document, 2018).

3.1.1 Single shell

Single-shelled tanks are usually constructed with low-carbon nickel alloy steel or occasionally stainless steel. These materials are chosen because of their experiential durability, corrosion resistance, and suitability for holding cold LNG. The single-shelled tank consists of parts such as stiffening rings, tank foundation, vacuum rings, and anti-floating devices as illustrated in Figure 3. (Koczur, 2023)

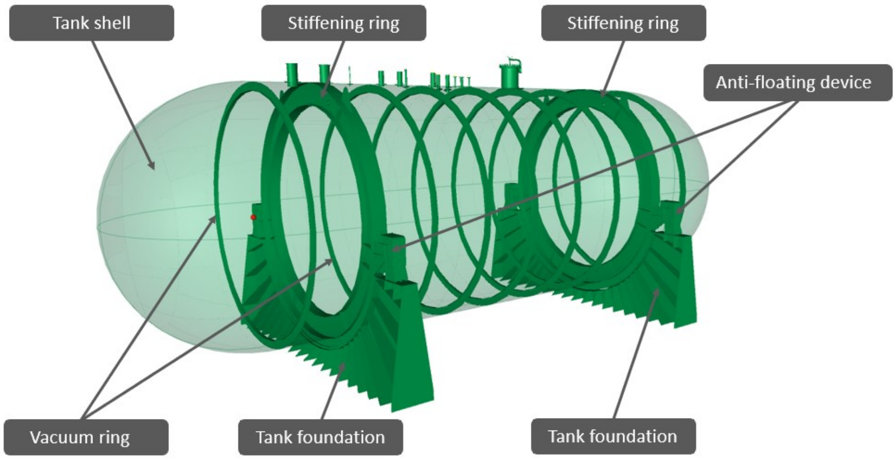

Figure 3. Single shell tank construction (Wärtsilä internal document, 2023)

These tanks consist of a cylindrical structure, with the ends of the tank referred to as dish ends. The thickness of the shell is determined based on multiple factors which are presented in Chapter 3.1.3. The thickness usually ranges between 12-18 mm depending on whether the LNGPac is situated on an open deck or below deck. (Koczur, 2023)

The tank is positioned on top of two tank foundations, one of the foundations is fixed to the tank while the other one allows movement. The sliding foundation allows the tank to move during heat changes, which is crucial during bunkering when rapid heat changes occur. In between the foundation and the shell, there are wooden blocks whose purpose is to minimize heat transfer to the ship floor and allow the structure to slide. (Koczur, 2023)

Stiffening rings transfer the load of the tank to the foundation. It also reinforces with outer shell with the help of the vacuum rings, making the structure withstand pressures and load from the liquid pressing against the shell and liquid movements during rough seaways.

The anti-floating device is mounted after the tank has been positioned onto the foundation, keeping the tank in its position. The purpose of this component is to secure the tank and to prevent it from moving in a vertical direction. (Koczur, 2023)

3.1.2 Double shell

The double-shelled tank has a similar design as the single-shelled tank, but with some distinguished features as seen in Figure 4. The construction has two shells, with the annular space containing the vacuum and perlite. The shells are constructed with stainless steel (SS 304) and have a typical thickness of 12 mm if positioned under the deck, and 18 mm if positioned on deck, but this value varies with design. (Koczur, 2023)

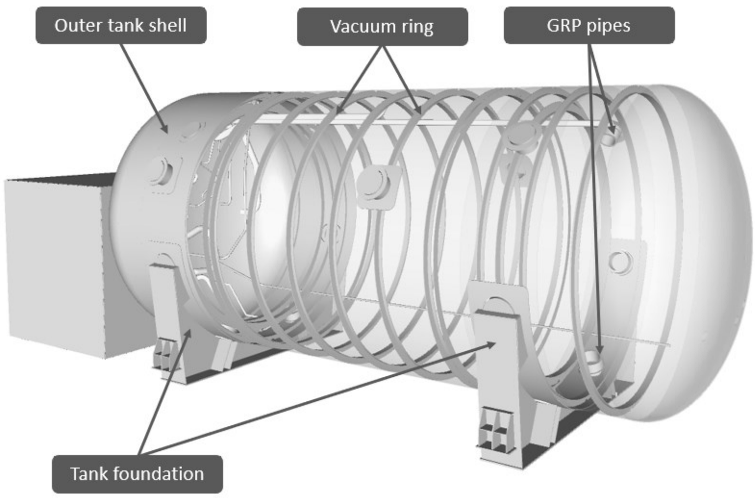

Figure 4. Double shell tank construction (Wärtsilä internal document, 2023)

The glass reinforces plastic (GRP) pipes keeps the inner shell positioned in the right position with regards to the outer shell. The inner shell is positioned evenly approximately 200 mm from the outer shell. The GRP pipes holds the weight of the inner shell tank and copes with all the forces created by the liquid's movement. Usually, four GRP pipes are installed in the bottom section of the tank while two pipes are installed on the sides. GRP material is used because of its ability to withstand the load and forces exhibited on the tank, while also minimizing the transfer of heat. GRP is a lightweight and extremely strong material while it significantly transfers less heat than if a metallic material were used. (Koczur, 2023)

Vacuum rings in double-shelled tanks have one additional purpose in comparison to the single-shelled tanks. Due to the vacuum being present between the outer and inner shell, the atmospheric pressure creates a force on the outer shell. To cope with the additional external pressure, there are additional vacuum rings installed, which are more closely distributed throughout the tank. (Koczur, 2023)

3.1.3 Influential factors in tank shell thickness

The thickness of the shell has a great impact on the weight of the system. Extensive calculations are made to calculate the appropriate shell thickness. The main factors determining the tank shell thickness are:

- **Accelerations**: The accelerations are determined by the LNGPac location on the vessel.
- **Internal Pressure**: Single-shell tanks are built for internal pressures ranging from 4 – 6 bar, while double-shell tanks are constructed for higher internal pressures, approximately 9 bar.
- **External Pressure**: Atmospheric pressure forcing on the outer shell of a vacuum-insulated tank. Additionally, forces such as hit from waves, and other environmental forces needs to be considered if placed on an open deck.
- **Mechanical Properties of Material**: Single-shell tanks often use nickel steel, which has better mechanical properties than stainless steel, resulting in the use of thinner plates in comparison to stainless steel tanks.
- **Type of Dished End**: Hemispherical dished ends are much thinner in comparison to elliptical, often requiring only half the thickness.

3.2 Manufacturing Process

In this chapter, a presentation about the manufacturing process for the steel construction of the storage tank and TCS will be presented. This study was aided by the department's production manager Xu, who is located on-site where the tanks are manufactured in China. The manufacturing process is a long and complicated process, therefore, only the most relevant process steps will be presented.

Before the construction phase begins, all material supplied by the subcontractors needs to be validated. Plates that arrive at the shipyard are required to have material certificates to verify that they meet the required specifications. These certificates are supplied by the plate manufacturer and outline parameters such as dimensions, chemical composition, and the mechanical properties of the material. All tests performed by the plate manufacturer are conducted according to the relevant standards and are witnessed by a third-party inspector. (Xu, 2023)

Additionally to the material certificates, internal in-house testing is also performed. The plates are visually inspected to ensure that no abnormalities are found on the surface of the plates, such as cracks, porosity, and planeness. Furthermore. dimensional measurements are taken to ensure that the dimensions are within tolerances. (Xu, 2023)

The manufacturing process for the shells starts with cutting the plates to the correct sizes in adherence to the drawings. The plates are then cold rolled to a cylindrical shape and then the two plate ends are welded together (see Figure 5). Multiple of these cylinders are constructed and welded together to attain the desired tank length. During the welding of the cylinders, additional elements such as stiffening rings and vacuum rings are inserted and welded to the inner shell. (Xu, 2023)

The fabrication of the end dish begins by cutting multiple plates into the desired shape and welding them together to form a circular disc structure. To achieve a hemispherical shape the plates are subjected to a cold rolling process that forms the sheet metal. If the tank is constructed with stainless steel, the tank needs to be subjected to a pickling and passivating process before the tank is sealed. This is conducted to remove any contaminants from the tank surfaces. Once the end dishes and shell are free of contamination, they are joined together with the cylindrical form of the shell. (Xu, 2023) In Figure 6 an illustrative picture of the initial construction phase is presented.

Figure 6. Shell manufacturing (Wärtsilä 2022).

Figure 5. Dish end installed (Wärtsilä 2022).

If the tank is vacuum insulated, an additional shell is constructed in the same principle as described above. The inner shell is then inserted into the outer shell with the help of a crane and a temporary rail to guide it, as seen in Figure 7. Afterwards, the inner shell is adjusted so it is spaced evenly in correspondence to the outer shell. When it is correctly positioned, the GRP pipes are inserted and secured by welding the end of the GRP pipe to the outside of the shell. After this stage, the outer shell dish ends are installed. When the tank has been sealed, a pressure test and helium leakage test are conducted to ensure that the tank is completely airtight and capable of withstanding the internal pressures. (Xu, 2023)

The manufacturing of a squared and enclosed TCS starts with constructing the outer frame by welding together square tubing. Next, plate panels are welded onto the frame, and service doors are mounted to enclose the structure, making it airtight. Subsequently, the interior of the TCS is assembled with equipment such as valves, instruments, and piping before joining it to the tank (Xu, 2023). The pipe penetrations on the tanks are prepared and then the whole TCS structure is welded onto the tank, see Figure 8.


Figure 7. Assembly of Inner shell (Wärtsilä 2023).


Figure 8. Assembly of TCS (Wärtsilä 2023).

During the progression of fabrication operation, each weld is systematically tested for cracks, improper penetration, and porosity. This involves visual inspection, dye penetrate testing, and ultrasonic or radiographic testing. Radiographic testing is conducted on all critical welds, such as the plate welds that hold the cryogenic liquid. Additionally, dimension measurements are taken to ensure that it is within tolerances. (Xu, 2023)

Before the LNGPac can be delivered to the customer the complete system is inspected, a so-called factory acceptance test (FAT) is conducted. During the test, all instruments, cabling, and valves are inspected to ensure that everything is in order. Additionally, certificates of prior testing are reviewed, such as pressure tests and weld test certificates. The final step before delivering the tank is the weighing of the tank. This is conducted using cranes equipped with built-in weighing scale. (Xu, 2023)

4 Methodology

This chapter will clarify the approach and methods used during the thesis to achieve the desired outcome. First quantitative, and qualitative research method will be presented, along with an explanation of why the given method was chosen, and how these methods will be implemented in my research.

4.1 Choice of research method

According to (Douglas;Borrego;& Amelink, 2014), there are three main research approaches used in academic studies, qualitative, quantitative, and mixed methods.

The quantitative method is used to analyze numerical data to achieve a conclusion. From an engineering standpoint, these kinds of studies often use descriptive statistics, such as measures of central tendency and variability, along with statistical analyses to identify patterns, trends, and relationships. (Douglas;Borrego;& Amelink, 2014)

Qualitative research involves studying and gathering information from sources such as surveys, interviews, and observations. It aims to answer questions such as: What is occurring? Why does something occur? How does one phenomenon affect another? (Douglas;Borrego;& Amelink, 2014)

In a mixed research method, the researchers gather and analyze information from both quantitative and qualitative methods within the same project. These two methods can be used simultaneously or in sequence and the information gets integrated in one or more stages in the research process. This approach allows for a more comprehensive and refined understanding of the research questions and objectives. (Douglas;Borrego;& Amelink, 2014)

For my research, it was concluded that a mixed research approach would be the most suitable. The goal with the qualitative research method is to identify the reasons why our estimates are not accurate. Once these reasons are identified and documented, a more thorough analysis of these reasons can be performed using a quantitative research method. After these two research methods have been conducted, the planning of the new weight estimation method can begin.

4.2 Implementation of research methods

This section outlines how the research methods are planned to be implemented throughout the progression of my thesis.

The research will start with the qualitative method, which will focus on gathering information about factors that can affect weight estimations. Information will be gathered from various sources within the department through meetings, e-mails, and personal conversations with team members, design engineers, and the manufacturing engineers for FGSS. By gathering information, the goal is to achieve a better overview of the situation, which will enable further planning towards developing a solution to the problem.

The quantitative research part of this thesis will involve data analysis to further investigate the factors affecting the estimations obtained from the qualitative research method, and to determine the accuracy of our current weight estimates. The primary goal is to gain insights into the extent to which these factors impact the weight estimation and to identify potential areas for improvement in the estimation process.

5 Results

The following section will present the result of the thesis work. The results section consists of graphs, tables with data, and a textual analysis of the findings. First, a summary of the factors affecting the weight estimates is presented, followed by a data analysis where some of these factors are further researched, and finally, the new weight estimation approach is presented based on the findings of the data analysis.

5.1 Summary of factors affecting the weight estimation accuracy

In this subchapter, a summary of the factors affecting the weight estimation accuracy is presented. The following list is organized with the factors with the most contributor factors listed at the top, followed by the lesser contributed factors. This result was achieved by using the qualitative method presented in Chapter 4.2, as well as own reflections after studying the design and manufacturing process.

- Thickness of delivered plates: Plate thickness deviation between ordered and received plates.
- Documentation and CAD errors: Design changes during the progression of the manufacturing process, which are not updated to the new drawings and missing equipment or features in the CAD drawing, resulting in lower theoretical weight.
- Dish ends manufacturing: The plates used for the dish end manufacturing needs to have a thickness buffer of approximately 1 mm, due to the thickness decreasing during forming.
- Inconsistency in manufacturing: Dimension deviations, amount of welding material, and additional material added to some areas, can all have an impact on the final weight.
- Material density variations: Differences in material density in the delivered plates in comparison to theoretical density.
- Scale accuracy: The scale used for weighting the tanks can deviate from the actual weight. The scale weighing accuracy, and its measurement tolerance are factors that need to be considered.

Plate thickness discrepancies between the ordered and received plates are the largest contributing factor to the current weight estimation error. Since the tanks are almost completely constructed using sheet metal, making small thickness deviations of the plates results in a lot of added weight. For example, one percentage thicker plates make the whole construction weigh approximately one percentage more, which stands for a couple hundred to even over thousand kilograms weight increase. This topic is researched further in Chapter 5.2.1.

In some cases, there have been situations where the construction weight has not been updated after design changes. This can happen both during the manufacturing process or during the time between the construction of two identical tanks. Often an identical LNGPac design is used for multiple vessels, for example in case fleets of similar vessels are constructed. If there has been a design change during the time between these two projects, it is often forgotten to update the weight to the new drawing. There can also be cases where small features and components are not detailed in the CAD drawing, resulting in a lower weight estimate.

The sheet metal used for constructing the dish ends needs to have an additional thickness buffer of approximately 1 mm. This is because during the forming of the sheet metal to a hemisphere shape, the metal is cold rolled. This makes the material stretch and makes it thinner in some places. To ensure that the plate thickness does not get thinner than the specified thickness, the buffer is added. This is not considered in the weight estimation, which makes the actual dish end weigh heavier than estimated.

Inconsistency in the manufacturing process can have some effect on the final weight. There can be potential variations in dimensions, material usage, and assembly techniques, which can overall impact the mass of the construction. This factor is further researched in Chapter 5.2.3.

Variations in the material density is a factor that can affect the final weight. Although material composition is checked at site, no actual material density is controlled. The acceptable material composition deviation is quite small, but it could still affect the density of the material to some degree.

The accuracy of the scale directly affects the noted weight of the construction. Although the scale is calibrated each year, there can still be a deviation between the measured weight and the actual weight, because of the accuracy tolerance of the equipment.

5.2 Result from data analysis

In this subchapter, the data analysis conducted within this research is presented. This includes data analysis of the plate thickness discrepancies and manufacturing consistency which are key factors affecting weight estimation as identified through the qualitative research. Additionally, the data analysis conducted to determine the accuracy of our current weight estimation method is presented.

5.2.1 Plate thickness discrepancy

During the qualitative research, it became clear that the steel plates used in the construction have a heavy positive tolerance on thickness. This is because, according to the class rules, the thickness of the finished formed plate can not be thinner than what is specified in the drawings. The thickness of the plates has only positive tolerances and no negative tolerance is allowable. The steel mill follows standard EN10029, class C, see table 1 below.

Table 1. EN10029 manufactured plate thickness tolerances.

Nominal thickness t	Tolerances on the nominal thickness (see 6.1.1)							
	Class A		Class B		Class C		Class D	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
$3 \leq t < 5$	−0,3	+0,7	−0,3	+0,7	0	+1,0	−0,5	+0,5
$5 \leq t < 8$	−0,4	+0,8	−0,3	+0,9	0	+1,2	−0,6	+0,6
$8 \leq t < 15$	−0,5	+0,9	−0,3	+1,1	0	+1,4	−0,7	+0,7
$15 \leq t < 25$	−0,6	+1,0	−0,3	+1,3	0	+1,6	−0,8	+0,8
$25 \leq t < 40$	−0,7	+1,3	−0,3	+1,7	0	+2,0	−1,0	+1,0
$40 \leq t < 80$	−0,9	+1,7	−0,3	+2,3	0	+2,6	−1,3	+1,3
$80 \leq t < 150$	−1,1	+2,1	−0,3	+2,9	0	+3,2	−1,6	+1,6
$150 \leq t < 250$	−1,2	+2,4	−0,3	+3,3	0	+3,6	−1,8	+1,8
$250 \leq t \leq 400$	−1,3	+3,5	−0,3	+4,5	0	+4,8	−2,4	+2,4

To get an insight into how consistent the plate manufacturing is, and what the average thickness deviation is a data analysis was conducted. The data was collected from previous projects, where the plates had been controlled measured, and documented.

In the following section, the results from the data analysis of the received plates from the steel mill are presented. In Figure 9 and Table 2, the results of the X7NI9 plates used in single-shelled tanks are showcased, and in Figure 10 and Table 3, the results for the SS 304 used in double-shell tanks are presented. The figures visually showcase the deviation between ordered and received plate thickness alongside its trendline. The figures are complemented by tables showcasing the average received plate thickness, its deviation from ordered thickness (expressed both in percentage and millimeter), and the standard deviation of the received plates, to determine how consistent the plate manufacturing is. The complete data sheet from which the result was gathered can be seen in Appendix 1 and Appendix 2.

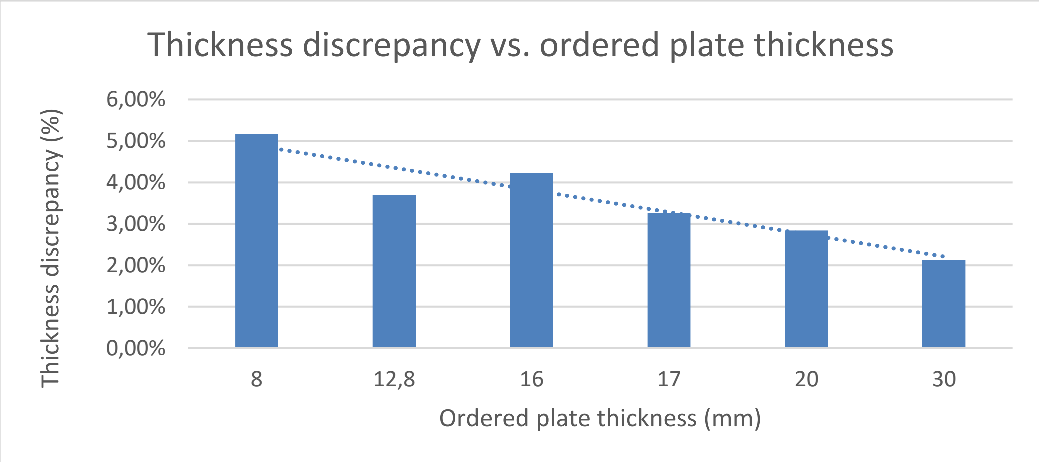

Figure 9. Percentage of deviation in thickness from ordered X7NI9 plates.

Table 2. Plate thickness discrepancy analysis of X7NI9 plates.

Ordered plate thickness (mm)	Average received plate thickness (mm)	Average discrepancy ordered/received	Standard deviation of received plates (mm)
8,00	8,41	5,16%	0,01
12,80	13,27	3,69%	0,03
16,00	16,68	4,22%	0,03
17,00	17,55	3,26%	0,05
20,00	20,57	2,84%	0,03
30,00	30,64	2,12%	0,04

The received X7NI9 plates are moderately thicker in comparison to what had been ordered. The average discrepancies between the ordered and received thickness, expressed as a percentage, range from 2,1% to 5,2%. It can be noted that the discrepancy decreases as the plate thickness increases. The standard deviations of the received plates are low, ranging from 0,01 to 0,04 mm.

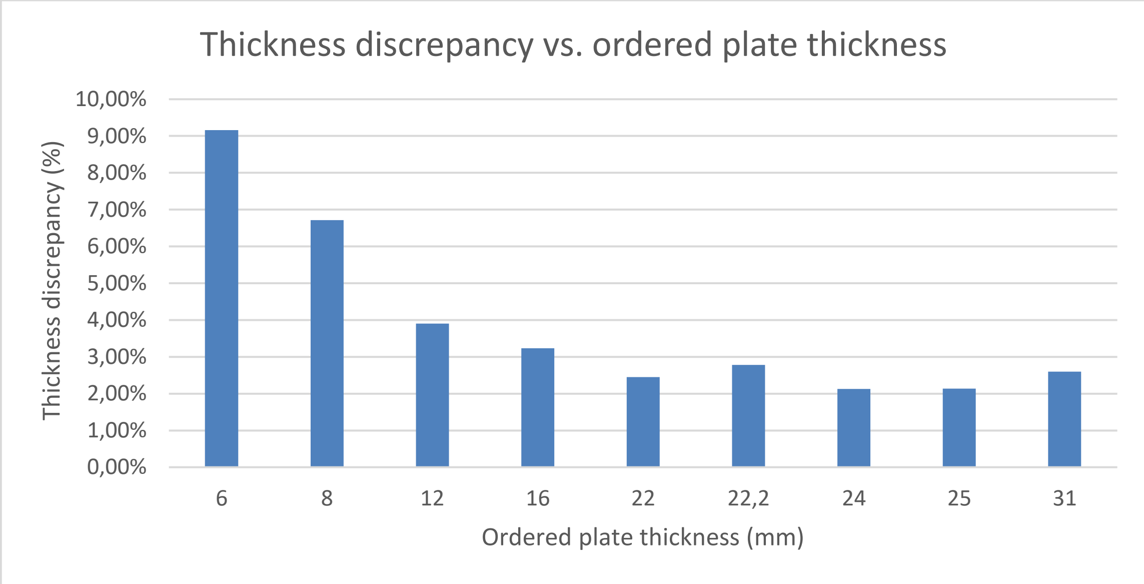

Figure 10. Percentage of deviation in thickness from ordered SS 304 plates.

Table 3. Plate thickness discrepancy analysis of SS 304 plates

Ordered plate thickness (mm)	Average received plate thickness (mm)	Average discrepancy ordered/received	Standard deviation of received plates (mm)
6,00	6,55	9,16%	0,05
8,00	8,54	6,71%	0,01
12,00	12,47	3,91%	0,01
16,00	16,52	3,23%	0,02
22,00	22,53	2,41%	0,02
22,20	22,82	2,78%	0,02
24,00	24,49	2,05%	0,04
25,00	25,54	2,14%	0,01
31,00	31,81	2,60%	0,04

The stainless-steel plates follow a similar pattern as the low-carbon nickel alloy steel. Large deviation is observed in the thinner plates, with a declining trendline towards the thicker plates, which exhibit a lower deviation. The deviation ranges from 9,16% to 2,14%. It can be noted that both the 6 mm and 8 mm plates have e remarkably high deviation of 9,16% respectively 6,71% which is significant. Similar to the X7NI9 plates, the standard deviation is low ranging from 0,01 to 0,05.

5.2.2 Accuracy of current weight estimates

A data analysis was conducted to see how accurate our current weight estimate is. Currently, the weight estimation is determined mostly from CAD drawings. On top of the weight estimation received from the CAD program, a margin percentage is multiplied by roughly 5% to accommodate manufacturing tolerances and missing items such as cabling, electrical equipment, and other potential additions during the manufacturing process.

This data analysis examines whether we predominantly bear positive weight upwards or negative weight downwards. The data was extracted from final delivery reports, detailing both the design weight and the measured weight. Utilizing this dataset, diagrams were created to represent our standing in terms of our current weight estimation accuracy.

In Figure 11 and Figure 12, the result from the current weight evaluation is presented. The y-axle represents the deviation from the design weight in percentage, and on the x-axle, the tanks examined are listed, unfortunately, the real names of the tank project name are not showcased due to being confidential information. The raw data was sourced from roughly 30 LNG tanks that have been built. Unfortunately, the result is only showcased for the double-shelled tanks. This limitation arises from the low number of data available for the single-shelled tanks and due to the tanks only being weighted without the tank foundation before delivery, thereby compromising the reliability of the data. The complete datasheet can be found in Appendix 3.

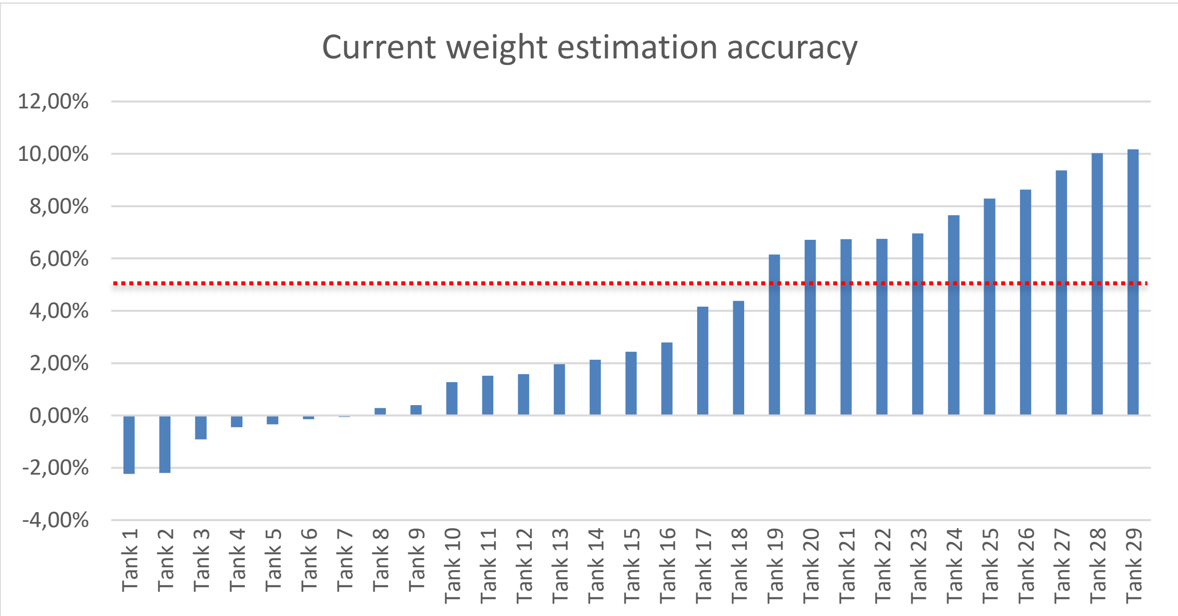

Figure 11. Deviation between design and measured weight on double-shelled tanks

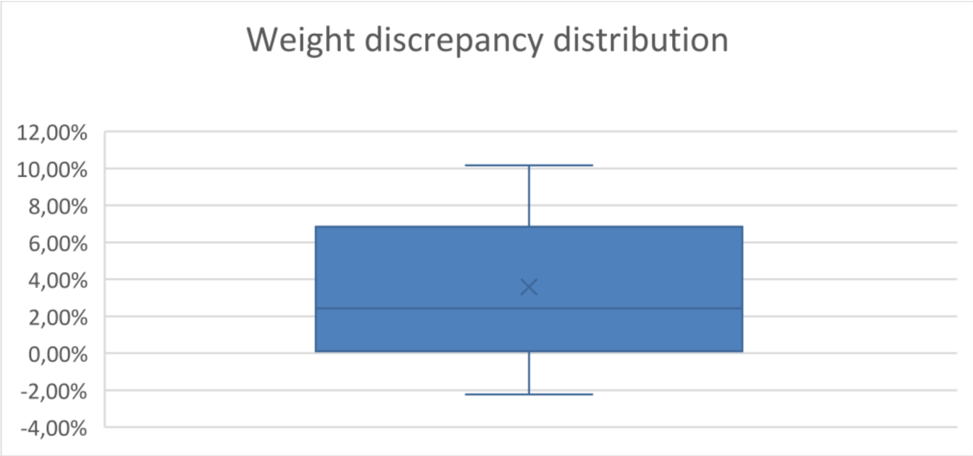

Figure 12. Weight discrepancy distribution with current estimation method.

Figure 11 and 12 present that our current weight estimates are too low, with the majority of the LNG tanks having a positive weight deviation. While most of the tanks are within the specified tolerance of ±5% as marked with a dotted red line, there is still a meaningful amount that exceeds these specifications. From this data, the following can be concluded:

- 22 out of the 29 tanks (approximately 76%) have a positive deviation, with 11 exceeding the specified tolerance of +5%.
- 7 out of 29 tanks (approximately 24%) have a negative deviation, with no tanks exceeding the specified tolerance of -5%.
- In total 11 tanks are not within the specified tolerance, which accounts for approximately 38 % of all tanks.
- Average weight discrepancy is 3,6% and the median value is 2,4% (see Figure 12).
- 50% of the tanks have a weight discrepancy between 0,1 – 6,8% (see Figure 12).

5.2.3 Manufacturing consistency analysis

The following data analysis was conducted to determine how consistent the tank manufacturing is. To examine this, two identical tanks built by the same manufacturer were compared against each other. By doing this, factors that otherwise affect the weight estimate are eliminated, focusing instead solely on manufacturing consistency. The complete data sheet is presented in Appendix 4

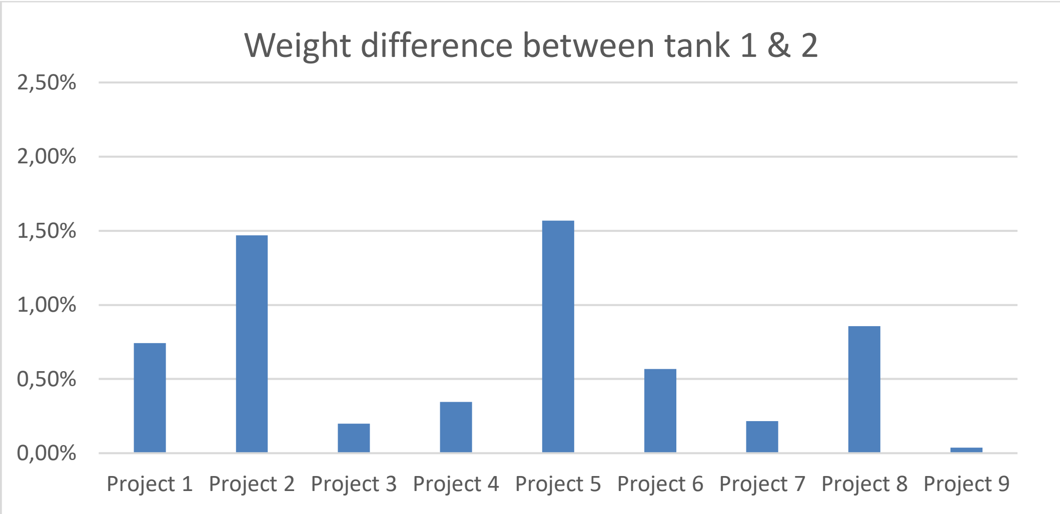

Figure 13. Weight difference between two identical tanks.

It can be noted that the weight difference between two identical tanks is moderately low. The weight difference between two identical tanks ranges from approximately 0 – 1,5%, with the majority being under 0,6%. Notably, Project 2 and Project 5, have a higher deviation of roughly 1,5% between their two tanks.

5.3 New weight estimating approach

After enough information had been gathered about the weight estimation factors and the results from the data analysis were evaluated, the planning of improving the weight estimation method started. The purpose of improving the current method is to achieve a more precise weight estimation, ensuring that the product's weight stays within the range of ±5% of the design weight. The new method should preferably be simple, and easy to use, to not overcomplicate the current way of working. It was concluded that the most viable option was to adjust the percentage that is multiplied on top of the weight estimation received from the CAD-modelling program as described in Chapter 5.2.2. The reason why this option was used is discussed in Chapter 6.

Two different kinds of approaches have been made. In Figure 14, the average weight deviation (3,6%) taken from the result of Chapter 5.2.2, has been multiplied to the current theoretical weight. While in Figure 15, the median weight deviation percentage (2,4%) has been used. These two figures give an idea of what the deviation would be with the new adjusted margin used to estimate the construction weight. The dotted red line in the figures represents the ±5% weight tolerance.

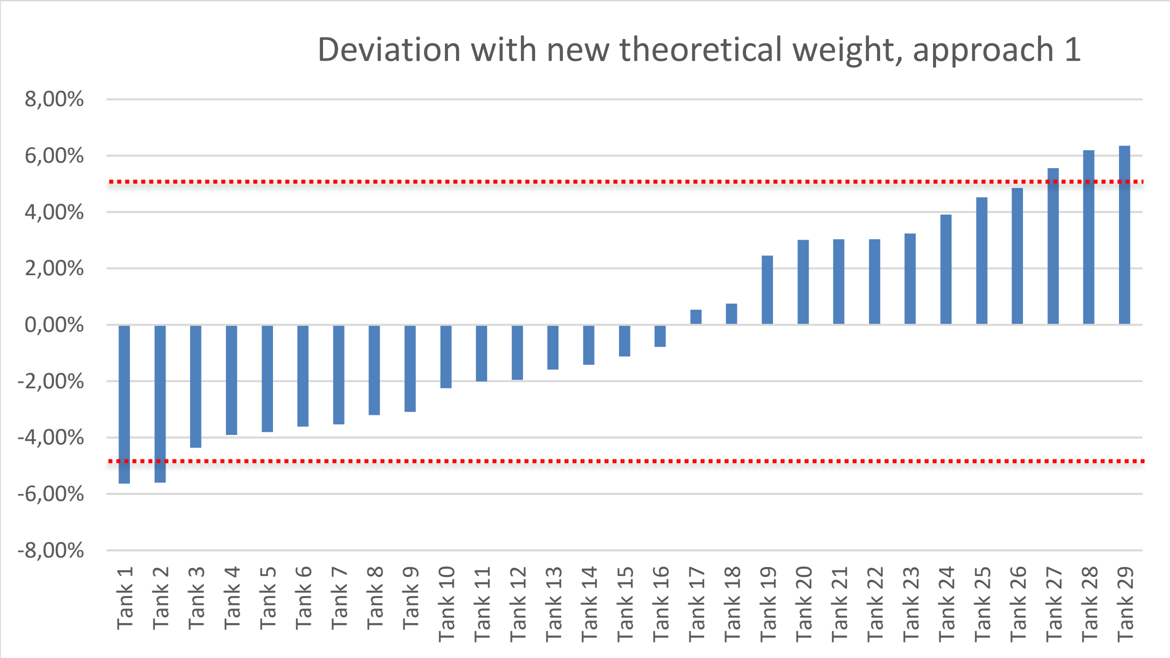

Figure 14. Deviation with new theoretical weight, with average percentage approach used.

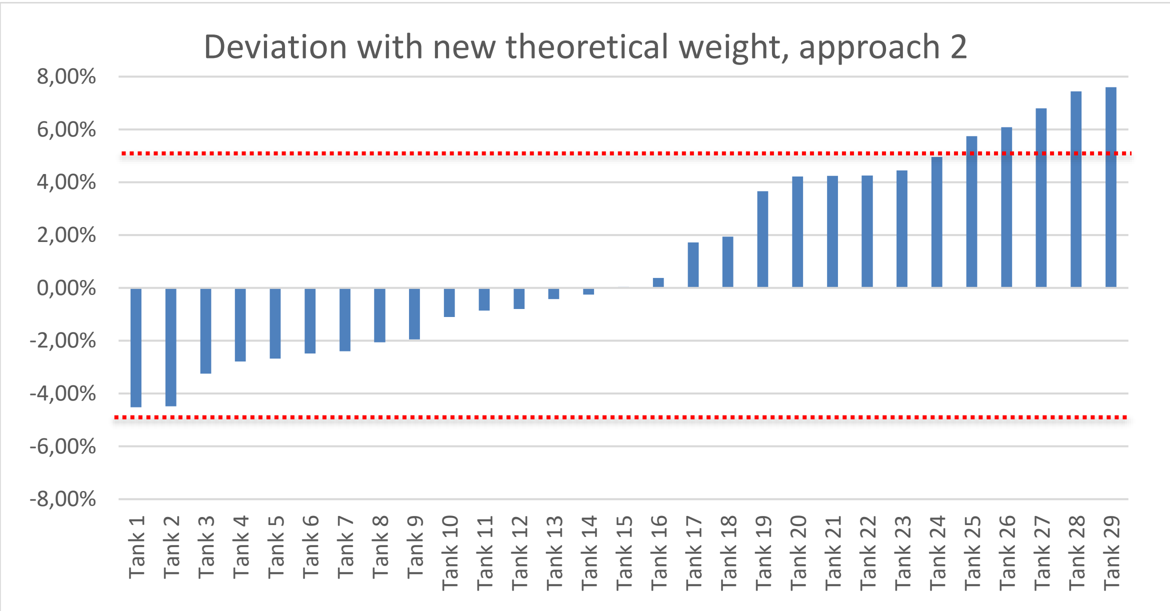

Figure 15. Deviation with new theoretical weight, with median percentage approach used.

6 Discussion

The previous chapter presented the empirical findings of the research. In this chapter, a critical discussion of the findings will be presented. Additionally, the new approach of estimating the weight will be evaluated and discussed.

The analysis of the plate thickness discrepancies revealed a consistent trend of receiving thicker plates than what had been ordered. The stainless-steel plate seems to have a moderately higher deviation than the nickel-based steel plates, especially in the thinner plates ranging from 8-12 mm. This discrepancy greatly impacts the weight estimation and is one of the greatest reasons why the current weight estimates are flawed. Another observation that was made is that the standard deviation of the delivered plates is remarkably low, proving that the plate manufacturing is highly consistent. This analysis gives a good idea of what the typical thickness deviation can be, but there is no guarantee that in the future the deviation will follow the exact same pattern. Maintenance conducted on the steel mill machines, along with regular wear and tear, especially on machines such as the metal rolling mill, could directly affect the future plate thickness deviation. Arguably, it would have been good to also include data from old projects to get an idea of how this deviation can change over time.

Although the deviation between the ordered and received plate thickness is within the standard specification showcased in Table 1, it can still be concluded that the deviation is high and leads to a lot of extra unnecessary weight. Considering reducing the weight of the system it would be beneficial to source plates with less weight deviation, however this can come at the expense of higher material prices.

The evaluation of the current weight estimation accuracy reveals that the deviations from the theoretical weight lean heavily towards the positive side. More than 75% of the tanks weigh more than the theoretical weight, with some having immense deviations over +8%, while the tank on the negative side has a maximum deviation of only -2%. The reason why some projects have such large deviations is something that could be more thoroughly inspected. My reflections are that in these extreme cases, there have been some errors in the documentation or missing features and components in the CAD model. My reasoning is that according to Figure 13, the tank manufacturing seems to be quite consistent, also deviation in the delivered plates as seen in Table 2, and Table 3 follows a consistent pattern with a low standard deviation, which suggests that these mentioned factors alone could not have led to these extreme cases. Another possible reason for the high deviation observed in some projects could be that thin plates are used in the outer and inner shell which stands for most of the weight of the construction. The thin plates that have high positive deviation as seen in Table 3 would result in a heavier construction which is not factored into consideration.

From the analysis of the weight deviation between two identical tanks, as presented in Figure 13, it can be concluded that the tank’s manufacturing process is relatively consistent. The max deviation from the examined tanks is roughly 1,5% but most of the tanks in beneath 0,6%. Therefore, it can be concluded that inconsistency in the manufacturing process does not stand as a large contributor to the weight estimation issue, thus not accounting for the substantial deviations observed in some tanks.

The new approach of estimating the weight as presented in Figure 14 and Figure 15, is a simple but effective way of enhancing the current way of working. The reasoning behind this approach was to not overcomplicate the new weight estimation process. Even if complex Excel calculations were to be made that would consider the delivered plate thickness deviation, it is not certain that it would achieve a much better estimate than the new weight estimation method as presented in Chapter 5.3. Additionally, that approach of estimating the weight would have been highly time-consuming and difficult to perform. This is because most of the tanks are constructed according to the customer's demand, meaning that most of the tanks have different designs, ranging from volume capacity, length, width, and orientation placement, which leads to changes in the internal construction of the tanks. This would have led to tens of different Excel calculation sheets, each tailored to a specific tank design, requiring continuous updating when a new type of design is introduced. Additionally, a lot of manual work would be needed for that specific approach, as for measuring and listing all the measured plates, and cross-checking what the thickness should be for each component in the drawings.

With the new weight estimating approaches, the new success rate of fulfilling the weight deviation tolerance of ±5%, is 83%, in comparison to the old approach of 62%, which is a significant improvement. Additionally, the deviation is not nearly as high as the old approach. As per which approach is more suitable, is discussable. As seen in Figure 14, with the average percentage approach used, the weight deviation is more concentrated on the negative side, but high deviation peaks on the positive side are better elapsed. With the median percentage approach, as presented in Figure 15, it can be noted that the deviation is distributed more evenly, but high deviation peaks exceed the specified ±5% tolerance with a larger margin.

Arguably the average percentage method would be a better choice. With this method, the high deviation peaks are better considered than with the median percentage approach. Even if there are cases where the deviation exceeds the weight tolerance of ±5%, it would not greatly surpass it. The old method had a max deviation of 10,18% versus the new method of 6,35%. The negative aspect of this method is that the deviation is more negatively concentrated, resulting in most of the projects weighing less than the estimated weight, but arguably this is preferable to a more positively concentrated deviation, as customers typically do not raise concerns when LNG tanks weigh less than specified.

Implanting the new enhanced weight estimation method is effortless, it is just about changing the final margin that is multiplied by the weight received from the CAD program. Instead of employing a 5% margin, we would use an 8.7% margin instead.

6.1 Proposal for further research

In the future, it would be beneficial to conduct a thorough study into why some projects have a high deviation, especially those that exceed 8% deviation as seen in Figure 11. Factors that could be analyzed post-delivery are for example, if there have been any design changes that have not been updated to the new drawings and if there are features or components missing in the drawings. Additionally, it could be examined if there is a connection between shell thickness and the degree of deviation, since thinner plates have more positive deviation from the design thickness, as observed in Table 3.

From the reached mentioned above, the new estimation method as presented in Figure 14 could be further developed. Even though the new estimating approach will decrease the number of projects that exceed the weight tolerance and decrease the total deviation between theoretical and actual weight, it would still be good to narrow down the estimation error so that the majority of the tanks lie between ±2,5%. This could for example be to identify patterns in the LNGpac constructions, group them accordingly, and assign a own margin percentage that would be multiplied on the 3D drawing. This could be that tanks that have thin shells would have a larger percentage multiplied because of larger plate thickness deviation, and tanks with thicker plates could have a smaller percentage multiplied.

From the result of this thesis plus the further research topics as described above it would be beneficial to create a new Wärtsilä internal document where it would be described how the estimate should be performed. This document would stand as a standard on how the weight should be estimated, and how the equipment would be divided into categories to make all estimations like each other. This would be beneficial to create because there are no real guidelines on how the estimation should proceed, which may result in confusion when each person approaches the task in their own manner.

7 Conclusion

Throughout this thesis, I have succeeded in analyzing which factors influence the weight estimations and assessed our current estimation accuracy. Based on these analyses a new optimized weight estimation method was created, aimed to achieve a more accurate result. The goals that were initially set for this thesis are mostly achieved. One of the goals of this thesis was to try to make all projects weigh within ±5, unfortunately, this has not been achieved. To make the new method perfect, future research is needed which was discussed in Chapter 6.1.

The objective of this thesis was more challenging than I initially anticipated. There are numerous factors that influence the final weight of the construction, and pinpointing where this extra weight comes from, and which factors have influenced the end result at that particular moment have been particularly demanding. This is because no individual parts of the construction have been measured, only the tank and TCS as a whole. This made it hard to determine how the weight is distributed, and where, and by how much the real-world weight deviates from the design weight in that specific part of the construction.

What went well during the work was the result chapter, especially the data analyses, which gave a clear picture of where flaws are in the current estimation method. For these analyses, conducting prior laboratory research at school has been beneficial, which has given me knowledge in data management, and how to present the handled data in a suitable way. Another thing that went well was the result discussion, with critical thinking, reflecting on implications, and drawing conclusions are key for this process and was a step I fairly enjoyed doing.

7.1 Closing remarks

I want to thank Wärtsilä FGSS for giving me the opportunity to write this thesis. During this research, I have learned a lot, which has given me knowledge that will be beneficial in the future. Colleagues have been motivating, and supporting, making the work feel meaningful. I would also like to give a big thank you to Torbjörn Lall and Björn Sandgärds, who have been supporting me during the progression of the work.

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Appendix 1. X7NI9 thickness measurements

8 mm plates																
Material	Thickness	Width	Length	Quantity	Plate No.	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Average	Deviation
X7Ni9	8	2500	8250	1	3C22M50200	8,34	8,44	8,55	8,42	8,53	8,35	8,37	8,42	8,32	8,42	5,19%
X7Ni9	8	2500	8250	1	3C17783300	8,37	8,41	8,33	8,38	8,42	8,48	8,33	8,53	8,45	8,41	5,14%
X7Ni9	8	2280	8250	1	3C16109100	8,32	8,47	8,42	8,51	8,45	8,33	8,39	8,42	8,35	8,41	5,08%
X7Ni9	8	2280	8250	1	3C16109200	8,45	8,32	8,53	8,33	8,41	8,38	8,42	8,31	8,47	8,40	5,03%
X7Ni9	8	2400	8600	1	3C12346300	8,36	8,44	8,35	8,47	8,39	8,52	8,33	8,38	8,36	8,40	5,00%
X7Ni9	8	2400	8600	1	3C12346500	8,54	8,32	8,37	8,42	8,36	8,42	8,37	8,32	8,55	8,41	5,10%
X7Ni9	8	2400	8600	1	3C12347400	8,32	8,43	8,35	8,39	8,52	8,34	8,44	8,35	8,43	8,40	4,96%
X7Ni9	8	2400	8600	1	3C12347500	8,42	8,35	8,32	8,43	8,53	8,34	8,39	8,54	8,33	8,41	5,07%
X7Ni9	8	2400	8300	1	3C12346100	8,38	8,41	8,35	8,52	8,31	8,37	8,52	8,33	8,39	8,40	4,97%
X7Ni9	8	2400	8300	1	3C17784300	8,37	8,53	8,32	8,44	8,36	8,39	8,45	8,52	8,42	8,42	5,28%
X7Ni9	8	2400	8700	1	3C12334400	8,45	8,36	8,38	8,42	8,54	8,45	8,33	8,41	8,38	8,41	5,17%
X7Ni9	8	2400	10000	1	3C12334300	8,32	8,53	8,32	8,44	8,36	8,39	8,45	8,52	8,42	8,42	5,21%
X7Ni9	8	2400	10550	1	3C12334200	8,38	8,44	8,51	8,42	8,45	8,37	8,32	8,43	8,53	8,43	5,35%
X7Ni9	8	2100	10400	1	3C16112200	8,55	8,56	8,37	8,34	8,42	8,53	8,46	8,45	8,33	8,45	5,57%
X7Ni9	8	2100	10500	1	3C16112300	8,32	8,42	8,56	8,37	8,48	8,33	8,38	8,52	8,45	8,43	5,32%

12.8 mm plates														
Material	Thickness	Width	Length	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Average	Deviation
X7Ni9	12,8	2650	9000	13,24	13,41	13,22	13,31	13,19	13,26	13,19	13,25	13,32	13,27	3,64%
X7Ni9	12,8	2650	9000	13,34	13,16	13,25	13,33	13,23	13,22	13,33	13,21	13,18	13,25	3,52%
X7Ni9	12,8	2650	9000	13,14	13,26	13,27	13,25	13,27	13,18	13,42	13,25	13,28	13,26	3,58%
X7Ni9	12,8	2650	9000	13,24	13,23	13,21	13,18	13,21	13,33	13,22	13,23	13,23	13,23	3,37%
X7Ni9	12,8	2650	9000	13,31	13,27	13,19	13,23	13,33	13,32	13,26	13,25	13,17	13,26	3,59%
X7Ni9	12,8	2650	9000	13,41	13,33	13,24	13,27	13,31	13,27	13,21	13,27	13,25	13,28	3,78%
X7Ni9	12,8	2650	9000	13,22	13,25	13,28	13,25	13,42	13,33	13,25	13,32	13,29	13,29	3,83%
X7Ni9	12,8	2650	9000	13,33	13,29	13,22	13,21	13,17	13,24	13,33	13,24	13,21	13,25	3,51%
X7Ni9	12,8	2650	9230	13,41	13,33	13,27	13,19	13,15	13,21	13,24	13,27	13,31	13,26	3,63%
X7Ni9	12,8	2650	9230	13,21	13,17	13,33	13,24	13,12	13,42	13,55	13,21	13,27	13,28	3,75%
X7Ni9	12,8	2650	9230	13,27	13,23	13,19	13,23	13,33	13,36	13,29	13,19	13,21	13,26	3,56%
X7Ni9	12,8	2650	9230	13,14	13,27	13,33	13,27	13,42	13,23	13,15	13,35	13,42	13,29	3,80%
X7Ni9	12,8	2650	9230	13,34	13,22	13,13	13,24	13,14	13,35	13,27	13,21	13,53	13,27	3,67%
X7Ni9	12,8	2650	9230	13,24	13,25	13,31	13,22	13,44	13,28	13,15	13,45	13,31	13,29	3,86%
X7Ni9	12,8	2650	9230	13,44	13,35	13,27	13,17	13,32	13,22	13,52	13,22	13,19	13,30	3,91%
X7Ni9	12,8	2650	9230	13,15	13,21	13,22	13,37	13,25	13,24	13,42	13,26	13,32	13,27	3,68%
X7Ni9	12,8	2610	9000	13,32	13,28	13,19	13,24	13,21	13,32	13,28	13,22	13,41	13,27	3,71%
X7Ni9	12,8	2610	9000	13,44	13,22	13,23	13,27	13,25	13,23	13,25	13,33	13,21	13,27	3,67%
X7Ni9	12,8	2610	9000	13,33	13,25	13,26	13,21	13,22	13,29	13,33	13,44	13,35	13,30	3,89%
X7Ni9	12,8	2610	9000	13,45	13,27	13,21	13,34	13,18	13,22	13,18	13,22	13,25	13,26	3,58%
X7Ni9	12,8	2650	9230	13,17	13,33	13,19	13,22	13,32	13,44	13,51	13,31	13,18	13,30	3,88%
X7Ni9	12,8	2650	9230	13,25	13,18	13,27	13,35	13,15	13,21	13,19	13,37	13,26	13,25	3,50%
X7Ni9	12,8	2650	9230	13,33	13,26	13,24	13,24	13,44	13,52	13,38	13,24	13,43	13,34	4,24%
X7Ni9	12,8	2650	9230	13,44	13,21	13,33	13,15	13,25	13,32	13,23	13,19	13,27	13,27	3,64%
X7Ni9	12,8	2880	9000	13,18	13,27	13,21	13,36	13,27	13,17	13,34	13,53	13,23	13,28	3,78%
X7Ni9	12,8	2880	9000	13,26	13,19	13,34	13,27	13,42	13,35	13,21	13,27	13,38	13,30	3,90%
X7Ni9	12,8	2880	9000	13,17	13,12	13,19	13,43	13,27	13,22	13,34	13,19	13,24	13,24	3,45%
X7Ni9	12,8	2880	9000	13,35	13,29	13,33	13,23	13,43	13,25	13,18	13,25	13,33	13,29	3,85%
X7Ni9	12,8	2880	9000	13,21	13,17	13,19	13,34	13,19	13,34	13,35	13,16	13,19	13,24	3,42%
X7Ni9	12,8	2880	9000	13,53	13,24	13,33	13,26	13,27	13,25	13,36	13,35	13,27	13,32	4,05%
X7Ni9	12,8	2880	9000	13,23	13,35	13,27	13,21	13,19	13,27	13,44	13,18	13,35	13,28	3,72%
X7Ni9	12,8	2880	9000	13,44	13,21	13,35	13,28	13,21	13,34	13,29	13,23	13,27	13,29	3,84%
X7Ni9	12,8	2880	9000	13,22	13,34	13,47	13,33	13,29	13,19	13,32	13,19	13,42	13,31	3,97%
X7Ni9	12,8	2880	9000	13,32	13,27	13,33	13,21	13,19	13,26	13,34	13,27	13,22	13,27	3,65%
X7Ni9	12,8	2880	9000	13,52	13,44	13,27	13,33	13,21	13,35	13,25	13,36	13,47	13,36	4,34%
X7Ni9	12,8	2880	9000	13,32	13,24	13,21	13,19	13,15	13,26	13,19	13,15	13,22	13,21	3,24%
X7Ni9	12,8	2880	9000	13,22	13,28	13,25	13,15	13,23	13,22	13,33	13,24	13,19	13,23	3,39%
X7Ni9	12,8	2880	9000	13,35	13,22	13,19	13,27	13,29	13,18	13,24	13,19	13,23	13,24	3,44%
X7Ni9	12,8	2880	9000	13,22	13,29	13,41	13,22	13,18	13,33	13,45	13,26	13,18	13,28	3,77%
X7Ni9	12,8	2880	9230	13,47	13,31	13,26	13,27	13,33	13,19	13,17	13,21	13,28	13,28	3,72%
X7Ni9	12,8	2880	9230	13,27	13,19	13,22	13,42	13,22	13,33	13,27	13,26	13,21	13,27	3,64%
X7Ni9	12,8	2880	9230	13,15	13,23	13,33	13,25	13,19	13,21	13,23	13,31	13,19	13,23	3,38%
X7Ni9	12,8	2880	9230	13,45	13,29	13,44	13,38	13,26	13,34	13,44	13,35	13,23	13,35	4,32%
X7Ni9	12,8	2880	9230	13,25	13,33	13,24	13,18	13,21	13,17	13,24	13,22	13,15	13,22	3,29%
X7Ni9	12,8	2880	9230	13,35	13,21	13,18	13,37	13,42	13,35	13,28	13,38	13,22	13,31	3,96%
X7Ni9	12,8	2880	9230	13,21	13,17	13,44	13,25	13,18	13,26	13,22	13,17	13,36	13,25	3,52%
X7Ni9	12,8	2880	9230	13,43	13,22	13,18	13,21	13,41	13,47	13,28	13,31	13,16	13,30	3,88%
X7Ni9	12,8	2880	9230	13,23	13,28	13,33	13,27	13,19	13,27	13,21	13,18	13,21	13,24	3,45%
X7Ni9	12,8	2880	9230	13,34	13,16	13,25	13,33	13,23	13,22	13,33	13,21	13,18	13,25	3,52%
X7Ni9	12,8	3370	9230	13,17	13,32	13,19	13,13	13,27	13,22	13,37	13,19	13,24	13,23	3,39%
X7Ni9	12,8	2700	7200	13,24	13,35	13,18	13,31	13,29	13,21	13,19	13,25	13,18	13,24	3,47%
X7Ni9	12,8	2700	7200	13,33	13,22	13,15	13,21	13,21	13,37	13,28	13,31	13,16	13,25	3,51%
X7Ni9	12,8	2700	7200	13,25	13,38	13,44	13,18	13,21	13,17	13,29	13,22	13,15	13,25	3,55%
X7Ni9	12,8	2700	7200	13,35	13,22	13,24	13,38	13,26	13,34	13,44	13,35	13,23	13,31	4,00%
X7Ni9	12,8	3100	12000	13,22	13,31	13,37	13,23	13,29	13,19	13,32	13,14	13,35	13,27	3,66%
X7Ni9	12,8	3100	12000	13,33	13,27	13,21	13,25	13,18	13,22	13,15	13,22	13,25	13,23	3,37%
X7Ni9	12,8	3100	12000	13,25	13,21	13,33	13,21	13,42	13,35	13,28	13,38	13,22	13,29	3,86%
X7Ni9	12,8	3100	12000	13,45	13,24	13,19	13,34	13,21	13,32	13,28	13,22	13,41	13,30	3,87%
X7Ni9	12,8	3100	12000	13,47	13,25	13,39	13,25	13,33	13,27	13,21	13,18	13,28	13,29	3,85%
X7Ni9	12,8	3100	12000	13,15	13,23	13,13	13,25	13,19	13,21	13,23	13,31	13,19	13,21	3,20%
X7Ni9	12,8	3100	12000	13,27	13,24	13,19	13,16	13,23	13,22	13,22	13,15	13,23	13,21	3,22%
X7Ni9	12,8	3100	9900	13,24	13,36	13,21	13,15	13,21	13,33	13,29	13,23	13,41	13,27	3,67%
X7Ni9	12,8	3100	9900	13,31	13,27	13,19	13,44	13,47	13,22	13,26	13,25	13,33	13,30	3,94%
X7Ni9	12,8	3000	9750	13,35	13,22	13,45	13,27	13,51	13,18	13,24	13,19	13,23	13,29	3,85%
X7Ni9	12,8	3000	9750	13,22	13,25	13,19	13,23	13,33	13,32	13,45	13,25	13,38	13,29	3,84%
X7Ni9	12,8	3000	9750	13,44	13,22	13,17	13,38	13,19	13,24	13,44	13,19	13,23	13,28	3,73%
X7Ni9	12,8	3000	10000	13,32	13,27	13,33	13,21	13,53	13,26	13,34	13,27	13,22	13,31	3,95%
X7Ni9	12,8	3000	10000	13,27	13,22	13,18	13,27	13,33	13,42	13,28	13,31	13,42	13,30	3,91%
X7Ni9	12,8	3000	10000	13,24	13,35	13,45	13,31	13,29	13,21	13,19	13,25	13,18	13,27	3,71%
X7Ni9	12,8	3000	11500	13,33	13,27	13,19	13,23	13,33	13,43	13,26	13,25	13,33	13,29	3,84%
X7Ni9	12,8	3000	11500	13,47	13,16	13,25	13,33	13,23	13,22	13,13	13,21	13,34	13,26	3,59%
X7Ni9	12,8	3000	11500	13,24	13,23	13,21	13,18	13,28	13,33	13,22	13,23	13,27	13,24	3,46%

16 mm plates														
Material	Thickness	Width	Length	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Average	Deviation
X7Ni9	16	3150	10250	16,57	16,66	16,73	16,62	16,52	16,75	16,58	16,65	16,61	16,63	3,95%
X7Ni9	16	3150	10250	16,67	16,73	16,81	16,54	16,62	16,68	16,77	16,53	16,73	16,68	4,22%
X7Ni9	16	3350	10200	16,81	16,77	16,61	16,67	16,52	16,53	16,72	16,63	16,54	16,64	4,03%
X7Ni9	16	3000	11500	16,77	16,57	16,82	16,72	16,58	16,57	16,63	16,87	16,61	16,68	4,26%
X7Ni9	16	3000	11500	16,73	16,52	16,63	16,59	16,75	16,62	16,78	16,82	16,57	16,67	4,17%
X7Ni9	16	3000	11500	16,75	16,84	16,69	16,72	16,63	16,58	16,61	16,75	16,68	16,69	4,34%
X7Ni9	16	3000	11500	16,82	16,68	16,73	16,65	16,68	16,82	16,73	16,64	16,55	16,70	4,38%
X7Ni9	16	3000	11500	16,66	16,62	16,71	16,83	16,75	16,63	16,59	16,73	16,68	16,69	4,31%
X7Ni9	16	3000	11500	16,72	16,83	16,74	16,62	16,58	16,75	16,62	16,83	16,77	16,72	4,49%
X7Ni9	16	1700	8800	16,64	16,75	16,81	16,64	16,52	16,64	16,57	16,67	16,62	16,65	4,07%

17 mm plates														
Material	Thickness	Width	Length	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Average	Deviation
X7Ni9	17	2650	12100	17,47	17,68	17,55	17,42	17,58	17,53	17,66	17,62	17,59	17,57	3,33%
X7Ni9	17	2650	12100	17,52	17,63	17,59	17,62	17,55	17,47	17,61	17,53	17,53	17,56	3,30%
X7Ni9	17	2650	12100	17,57	17,46	17,52	17,77	17,65	17,52	17,54	17,82	17,63	17,61	3,58%
X7Ni9	17	2650	12100	17,52	17,48	17,67	17,71	17,82	17,58	17,57	17,62	17,72	17,63	3,72%
X7Ni9	17	2650	12100	17,45	17,42	17,53	17,66	17,52	17,47	17,52	17,48	17,62	17,52	3,05%
X7Ni9	17	2650	12100	17,55	17,63	17,77	17,82	17,48	17,53	17,57	17,62	17,53	17,61	3,59%
X7Ni9	17	2650	12100	17,51	17,48	17,72	17,56	17,45	17,62	17,54	17,72	17,55	17,57	3,37%
X7Ni9	17	2650	12100	17,43	17,54	17,64	17,52	17,53	17,66	17,57	17,65	17,47	17,56	3,27%
X7Ni9	17	2650	8100	17,36	17,52	17,45	17,39	17,62	17,51	17,45	17,43	17,67	17,49	2,88%
X7Ni9	17	2650	8100	17,52	17,33	17,42	17,64	17,48	17,44	17,52	17,34	17,45	17,46	2,71%
X7Ni9	17	1900	8100	17,45	17,61	17,56	17,63	17,73	17,48	17,57	17,45	17,56	17,56	3,29%
X7Ni9	17	1900	8100	17,71	17,64	17,74	17,54	17,52	17,41	17,62	17,51	17,43	17,57	3,35%
X7Ni9	17	2400	11900	17,57	17,42	17,52	17,77	17,49	17,55	17,52	17,47	17,51	17,54	3,15%
X7Ni9	17	2400	11900	17,44	17,48	17,57	17,63	17,55	17,43	17,49	17,63	17,53	17,53	3,10%
X7Ni9	17	2400	11900	17,36	17,52	17,49	17,55	17,43	17,71	17,57	17,44	17,51	17,51	2,99%
X7Ni9	17	2400	11900	17,53	17,68	17,44	17,36	17,67	17,41	17,52	17,49	17,66	17,53	3,11%
X7Ni9	17	2200	10300	17,43	17,56	17,67	17,43	17,51	17,64	17,48	17,54	17,42	17,52	3,06%
X7Ni9	17	2200	10300	17,67	17,48	17,43	17,55	17,62	17,74	17,52	17,64	17,49	17,57	3,36%
X7Ni9	17	2200	10300	17,75	17,83	17,55	17,65	17,76	17,88	17,57	17,52	17,65	17,68	4,03%
X7Ni9	17	2200	10300	17,53	17,45	17,64	17,49	17,55	17,42	17,52	17,63	17,71	17,55	3,23%
X7Ni9	17	2200	10300	17,47	17,53	17,62	17,53	17,48	17,71	17,45	17,52	17,63	17,55	3,23%
X7Ni9	17	2200	10300	17,62	17,58	17,46	17,64	17,52	17,47	17,64	17,53	17,45	17,55	3,21%
X7Ni9	17	2200	10300	17,44	17,52	17,49	17,62	17,43	17,57	17,52	17,64	17,49	17,52	3,08%
X7Ni9	17	2200	10300	17,51	17,63	17,42	17,53	17,48	17,64	17,45	17,54	17,62	17,54	3,15%

20 mm plates														
Material	Thickness	Width	Length	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Average	Deviation
X7Ni9	20	2570	12650	20,47	20,55	20,68	20,53	20,57	20,43	20,44	20,66	20,51	20,54	2,69%
X7Ni9	20	2750	12800	20,64	20,71	20,55	20,58	20,63	20,57	20,49	20,51	20,43	20,57	2,84%
X7Ni9	20	2750	12800	20,52	20,83	20,66	20,53	20,75	20,64	20,62	20,56	20,51	20,62	3,12%
X7Ni9	20	2750	12820	20,61	20,65	20,46	20,72	20,53	20,59	20,52	20,48	20,67	20,58	2,91%
X7Ni9	20	2650	12870	20,77	20,81	20,54	20,47	20,45	20,65	20,58	20,52	20,63	20,60	3,01%
X7Ni9	20	2350	12400	20,47	20,62	20,58	20,53	20,42	20,51	20,52	20,66	20,54	20,54	2,69%
X7Ni9	20	3100	11400	20,66	20,57	20,48	20,44	20,63	20,59	20,57	20,73	20,62	20,59	2,94%
X7Ni9	20	3000	9800	20,43	20,52	20,65	20,47	20,58	20,62	20,49	20,61	20,57	20,55	2,74%
X7Ni9	20	3000	9800	20,53	20,49	20,62	20,52	20,44	20,73	20,42	20,43	20,52	20,52	2,61%
X7Ni9	20	3000	9800	20,47	20,42	20,53	20,58	20,62	20,78	20,57	20,48	20,59	20,56	2,80%
X7Ni9	20	3100	12800	20,63	20,75	20,48	20,66	20,53	20,62	20,45	20,63	20,56	20,59	2,95%
X7Ni9	20	3100	11500	20,54	20,47	20,71	20,49	20,65	20,52	20,43	20,56	20,67	20,56	2,80%

30 mm plates														
Material	Thickness	Width	Length	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Average	Deviation
X7Ni9	30	1760	9020	30,65	30,57	30,77	30,62	30,59	30,64	30,83	30,63	30,53	30,65	2,16%
X7Ni9	30	1760	9020	30,77	30,81	30,62	30,58	30,72	30,58	30,63	30,75	30,64	30,68	2,26%
X7Ni9	30	1760	9020	30,62	30,73	30,69	30,77	30,54	30,62	30,61	30,53	30,69	30,64	2,15%
X7Ni9	30	1760	9020	30,68	30,64	30,55	30,72	30,73	30,75	30,68	30,66	30,64	30,67	2,24%
X7Ni9	30	1760	9250	30,55	30,72	30,62	30,54	30,68	30,74	30,65	30,53	30,57	30,62	2,07%
X7Ni9	30	1760	9250	30,47	30,62	30,55	30,59	30,48	30,66	30,62	30,59	30,46	30,56	1,87%
X7Ni9	30	1760	9250	30,52	30,67	30,49	30,72	30,45	30,61	30,58	30,52	30,64	30,58	1,93%
X7Ni9	30	1760	9250	30,82	30,63	30,74	30,78	30,57	30,65	30,63	30,59	30,71	30,68	2,27%

Appendix 2. SS 304 thickness measurements

6 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Deviation
SS 304	6	6,57	6,43	6,62	6,45	6,47	6,55	6,61	6,43	6,52	8,60%
SS 304	6	6,49	6,57	6,47	6,49	6,55	6,49	6,62	6,64	6,54	9,00%
SS 304	6	6,51	6,43	6,57	6,61	6,49	6,51	6,63	6,44	6,52	8,73%
SS 304	6	6,51	6,43	6,57	6,61	6,49	6,51	6,63	6,44	6,52	8,73%
SS 304	6	6,51	6,45	6,67	6,47	6,63	6,51	6,47	6,42	6,52	8,60%
SS 304	6	6,59	6,63	6,77	6,65	6,59	6,62	6,57	6,61	6,63	10,48%
SS 304	6	6,55	6,67	6,81	6,55	6,61	6,67	6,55	6,72	6,64	10,69%
SS 304	6	6,47	6,52	6,51	6,44	6,67	6,45	6,46	6,55	6,51	8,48%

8 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Deviation
SS 304	8	8,47	8,51	8,49	8,55	8,62	8,62	8,57	8,45	8,54	6,69%
SS 304	8	8,5	8,48	8,54	8,5	8,48	8,49	8,61	8,59	8,52	6,55%
SS 304	8	8,53	8,45	8,59	8,42	8,4	8,6	8,65	8,73	8,55	6,83%
SS 304	8	8,54	8,53	8,56	8,53	8,61	8,53	8,69	8,45	8,56	6,94%
SS 304	8	8,59	8,39	8,69	8,54	8,44	8,45	8,67	8,5	8,53	6,67%
SS 304	8	8,62	8,36	8,5	8,3	8,51	8,61	8,77	8,55	8,53	6,59%

12 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Deviation
SS 304	12	12,57	12,39	12,47	12,45	12,46	12,47	12,51	12,43	12,47	3,91%
SS 304	12	12,52	12,56	12,52	12,45	12,43	12,6	12,45	12,39	12,49	4,08%
SS 304	12	12,6	12,55	12,57	12,45	12,4	12,41	12,39	12,35	12,47	3,88%
SS 304	12	12,44	12,55	12,45	12,45	12,41	12,4	12,46	12,45	12,45	3,76%
SS 304	12	12,49	12,45	12,46	12,45	12,41	12,57	12,46	12,46	12,47	3,91%

16 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Deviation
SS 304	16	16,47	16,73	16,35	16,49	16,4	16,47	16,55	16,52	16,50	3,11%
SS 304	16	16,43	16,52	16,62	16,41	16,55	16,41	16,63	16,55	16,52	3,22%
SS 304	16	16,47	16,63	16,51	16,49	16,55	16,43	16,57	16,63	16,54	3,34%
SS 304	16	16,61	16,49	16,47	16,63	16,41	16,57	16,49	16,47	16,52	3,23%
SS 304	16	16,47	16,63	16,54	16,61	16,51	16,43	16,87	16,44	16,56	3,52%
SS 304	16	16,57	16,43	16,47	16,51	16,62	16,53	16,61	16,44	16,52	3,27%
SS 304	16	16,41	16,62	16,57	16,63	16,51	16,49	16,44	16,53	16,53	3,28%
SS 304	16	16,51	16,63	16,71	16,44	16,47	16,52	16,43	16,51	16,53	3,30%
SS 304	16	16,43	16,63	16,57	16,63	16,44	16,45	16,47	16,53	16,52	3,24%
SS 304	16	16,43	16,51	16,67	16,63	16,47	16,51	16,49	16,53	16,53	3,31%
SS 304	16	16,43	16,51	16,67	16,63	16,44	16,45	16,51	16,43	16,51	3,18%
SS 304	16	16,57	16,45	16,86	16,44	16,53	16,55	16,44	16,46	16,54	3,36%
SS 304	16	16,43	16,51	16,43	16,61	16,57	16,44	16,53	16,32	16,48	3,00%
SS 304	16	16,47	16,43	16,44	16,62	16,51	16,43	16,45	16,44	16,47	2,96%
SS 304	16	16,51	16,44	16,53	16,71	16,47	16,51	16,42	16,47	16,51	3,17%
SS 304	16	16,51	16,63	16,44	16,62	16,51	16,47	16,52	16,43	16,52	3,23%

18 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Deviation
SS 304	18	18,46	18,52	18,33	18,57	18,55	18,47	18,31	18,62	18,48	2,66%
SS 304	18	18,57	18,63	18,39	18,63	18,45	18,43	18,51	18,42	18,50	2,80%
SS 304	18	18,35	18,49	18,53	18,57	18,46	18,39	18,44	18,52	18,47	2,60%
SS 304	18	18,57	18,43	18,59	18,47	18,55	18,43	18,53	18,45	18,50	2,79%

22 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Delta
SS 304	22	22,59	22,54	22,57	22,61	22,47	22,61	22,43	22,51	22,54	2,46%
SS 304	22	22,49	22,51	22,61	22,59	22,47	22,51	22,43	22,56	22,52	2,37%
SS 304	22	22,51	22,47	22,55	22,46	22,62	22,57	22,71	22,52	22,55	2,51%
SS 304	22	22,57	22,65	22,51	22,62	22,47	22,51	22,46	22,61	22,55	2,50%
SS 304	22	22,57	22,63	22,47	22,56	22,43	22,55	22,45	22,57	22,53	2,40%

22,2 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Delta
SS 304	22,2	22,85	22,79	22,75	22,83	22,9	22,87	22,77	22,83	22,82	2,81%
SS 304	22,2	22,93	22,87	22,79	22,81	22,83	22,92	22,82	22,84	22,85	2,93%
SS 304	22,2	22,87	22,73	22,69	22,87	22,74	22,65	22,77	22,92	22,78	2,61%
SS 304	22,2	22,95	22,81	22,76	22,85	22,79	22,76	22,91	22,81	22,83	2,84%
SS 304	22,2	22,81	22,73	22,91	22,87	22,85	22,83	22,79	22,81	22,83	2,82%
SS 304	22,2	22,87	22,75	22,83	22,76	22,91	22,81	22,77	22,79	22,81	2,75%
SS 304	22,2	22,79	22,77	22,85	22,81	22,92	22,77	22,76	22,85	22,82	2,77%
SS 304	22,2	22,77	22,88	22,79	22,81	22,73	22,83	22,72	22,91	22,81	2,73%
SS 304	22,2	22,87	22,76	22,92	22,85	22,91	22,81	22,77	22,67	22,82	2,79%

24 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Delta
SS 304	24	24,47	24,51	24,63	24,65	24,55	24,41	24,47	24,56	24,53	2,21%
SS 304	24	24,47	24,51	24,62	24,51	24,57	24,55	24,56	24,42	24,53	2,19%
SS 304	24	24,41	24,63	24,54	24,44	24,67	24,57	24,48	24,45	24,52	2,18%
SS 304	24	24,39	24,41	24,51	24,51	24,44	24,47	24,51	24,47	24,46	1,93%

25 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Delta
SS 304	25	25,47	25,51	25,63	25,54	25,62	25,49	25,47	25,49	25,53	2,11%
SS 304	25	25,57	25,43	25,46	25,61	25,53	25,57	25,44	25,63	25,53	2,12%
SS 304	25	25,61	25,57	25,43	25,69	25,63	25,57	25,45	25,47	25,55	2,21%
SS 304	25	25,62	25,67	25,53	25,49	25,41	25,51	25,59	25,42	25,53	2,12%

31 mm plates											
Material	Thickness	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Average	Delta
SS 304	31	31,87	31,92	31,77	31,81	31,75	31,74	31,63	31,77	31,78	2,52%
SS 304	31	31,92	31,82	31,88	31,79	31,83	31,67	31,75	31,77	31,80	2,59%
SS 304	31	31,87	31,75	31,93	31,79	31,85	31,77	31,85	31,92	31,84	2,71%
SS 304	31	31,88	31,95	31,79	31,87	31,75	31,87	31,93	31,85	31,86	2,78%
SS 304	31	31,77	31,85	31,75	31,89	31,92	31,81	31,77	31,8	31,82	2,65%
SS 304	31	31,63	31,77	31,69	31,81	31,77	31,67	31,75	31,61	31,71	2,30%
SS 304	31	31,81	31,77	31,91	31,79	31,85	31,91	31,72	31,65	31,80	2,58%
SS 304	31	31,89	31,79	31,81	31,92	31,77	31,85	31,72	31,83	31,82	2,65%

Appendix 3. Weight deviation of delivered double shelled tanks.

Tank	Design weight (kg)	Actual weight (kg)	Deviation (%)	Tank type	Delivery Year
Tank 1	136650	133600	-2,23 %	Double shell	2019
Tank 2	136650	133650	-2,20 %	Double shell	2019
Tank 3	190450	188700	-0,92 %	Double shell	2018
Tank 4	22300	22200	-0,45 %	Double shell	2018
Tank 5	50371	50200	-0,34 %	Double shell	2020
Tank 6	50371	50300	-0,14 %	Double shell	2020
Tank 7	94200	94150	-0,05 %	Double shell	2018
Tank 8	31550	31640	0,29 %	Double shell	2020
Tank 9	80530	80850	0,40 %	Double shell	2017
Tank 10	102000	103300	1,27 %	Double shell	2016
Tank 11	80530	81750	1,51 %	Double shell	2017
Tank 12	22200	22550	1,58 %	Double shell	2019
Tank 13	102000	104000	1,96 %	Double shell	2016
Tank 14	97910	100000	2,13 %	Double shell	2024
Tank 15	226095	231600	2,43 %	Double shell	2024
Tank 16	226095	232400	2,79 %	Double shell	2024
Tank 17	44500	46350	4,16 %	Double shell	2019
Tank 18	44500	46450	4,38 %	Double shell	2019
Tank 19	149038	158200	6,15 %	Double shell	2021
Tank 20	121160	129300	6,72 %	Double shell	2021
Tank 21	87500	93400	6,74 %	Double shell	2022
Tank 22	149038	159100	6,75 %	Double shell	2021
Tank 23	149038	159400	6,95 %	Double shell	2020
Tank 24	87500	94200	7,66 %	Double shell	2022
Tank 25	121160	131200	8,29 %	Double shell	2021
Tank 26	149038	161900	8,63 %	Double shell	2020
Tank 27	103360	113040	9,37 %	Double shell	2020
Tank 28	44500	48960	10,02 %	Double shell	2023
Tank 29	103360	113880	10,18 %	Double shell	2020

Appendix 4. Weight difference between two identical tanks

Project	Design weight (kg)	Tank 1 weight (kg)	Delta (%	Tank 2 weigh	Delta (%)	Weight difference tank 1 & 2	Tank type	Delivery Year
Project 1	103360	113880	9,37%	113040	10,18%	0,74%	Double shell	2020
Project 2	121160	131200	8,29%	129300	6,72%	1,47%	Double shell	2021
Project 3	50371	50300	0,34%	50200	0,14%	0,20%	Double shell	2020
Project 4	226095	232400	2,79%	231600	2,43%	0,35%	Double shell	2024
Project 5	149038	161900	6,95%	159400	8,63%	1,57%	Double shell	2020
Project 6	149038	159100	6,75%	158200	6,15%	0,57%	Double shell	2021
Project 7	44500	46450	4,38%	46350	4,16%	0,22%	Double shell	2019
Project 8	87500	94200	7,66%	93400	6,74%	0,86%	Double shell	2022
Project 9	136650	133650	2,23%	133600	2,20%	0,04%	Double shell	2019