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Improving reliability of propulsion system hydraulic connections

Thesis submitted in partial fulfilment of the requirements for the Degree Master of Science in Technology.

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Abstract of master's thesis

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Abstract

The purpose of this research was to examine how leakages in hydraulic connections can be reduced at the design phase. The research question was, how can leak-free hydraulic connections for the propulsion system be ensured in the design phase. The thesis was conducted for an international company that specializes in propulsion systems. The need for the research arose as a result of the case company's increased hydraulic fitting leakage observations.

This thesis was carried out as qualitative research which includes literature research and empirical study. First, all the relevant literature and previous research were studied; the design requirements of hydraulic connections, properties of different fittings models, causes of leakages and requirements of the six classification societies. The empirical research was conducted by the cross-functionals interviews, internal documents and data from the case company. The current state in the propulsion system was mapped and visualized using a Pareto chart. The Pugh method was used to map the most reliable fitting models for the propulsion system. Finally, Failure Mode and Effect Analysis was utilized to detect the root causes of the worst leaking designs in the propulsion systems.

Findings of the study indicated that the company has particularly reliable fitting models. However, the current state mapping and root cause analysis revealed that the leakages were mainly reflected in the installation procedure and the lack of guidance. The study revealed that leakages occur very systematically in four design models. The company's four design models cause 80% of leakages out of all mapped leaking designs. Design changes that can be utilized to reduce or prevent the number of leakages are straightforward, and with a little consideration, the number of fittings could be reduced. Reducing the fittings would affect the number of possible leakages and reduce possible installation errors. However, providing a completely leak-free system in the design phase is unlikely.

As a result of this study, guidelines were created for the designers of the company. The guidelines provide modelled methods for the design of hydraulic connections, recommended fitting types and requirements that should be considered already in the design phase. The guidelines aimed to harmonize the operating methods of design, service and production departments of the company. The study indicated which designs models cause leakages and identified the root causes of leakages. Recommendations for the company are proposed to improve and to develop inadequate work instructions and installation procedures, making it possible for the case company to prevent and mitigate leakages.

Keywords hydraulic, fitting, connection, propulsion system, leakage, Failure Mode and Effect Analysis, Pugh matrix

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Tiivistelmä

Tässä diplomityössä tutkitaan kansainvälisesti toimivan ruoripotkurilaitteita tarjoavan yrityksen hydrauliikkaliitosten luotettavuuden parantamisen mahdollisuuksia. Tutkimuksen tavoitteena oli hydrauliikkaliitosten vuotojen vähentämisen selvittäminen ja vastata tutkimuskysymykseen siitä, miten luoda vuotamaton järjestelmä suunnitteluvaiheessa. Tarve tutkimukselle syntyi tapausyrityksen lisääntyneistä hydrauliikkanestevuotohavainnoista.

Hydrauliikkaliitosten suunnittelua, liittimien ominaisuuksia, mahdollisia vuodon syitä, sekä kuuden luokituslaitoksen asettamia vaatimuksia tarkasteltiin ensin kirjallisuuden ja aiempien tutkimuksien avulla. Empiirisen tutkimuksen tiedonkeruumenetelminä sovellettiin monialaisia haastatteluita, yrityksen dokumentaatiota ja dataa. Nykytila selvitettiin ja esitettiin Pareto kaaviolla. Haastatteluiden ja kirjallisuuden avulla määritettiin luotettavan liittimen ominaisuudet sekä yrityksen vaatimukset liittimille, jotta Pugh matriisia soveltaen oli mahdollista löytää sopivat liitimet järjestelmään. Lopulta yrityksen vuotavimman liitosmallin juurisyitä analysoitiin käyttäen vika- ja vaikutusanalyysia.

Tapaustutkimuksessa havaittiin, että yrityksellä on käytössään erityisen luotettavat liittimet. Nykytilan kartoitus ja juurisyyanalyysi kuitenkin paljastivat, että vuodot johtuivat pääosin virheellisistä asennustoimenpiteistä sekä puutteellisesta tuotannon ja suunnittelun ohjeistuksesta. Tutkimus paljasti, että vuotoja esiintyy hyvin järjestelmällisesti neljässä eri liitosmallissa. Kaikista kartoitetuista vuodoista 80% johtui näistä malleista. Tutkimuksessa selvisi, että vuotojen määrää olisi mahdollista vähentää tai ehkäistä suoraviivaisilla suunnittelumuutoksilla liittimien määrää vähentämällä. Liittimien vähentäminen vaikuttaa mahdollisten vuotojen määrään ja samalla vähentää mahdollisia asennusvirheitä. Kuitenkaan täysin vuodotonta järjestelmää ei pystytä luomaan suunnitteluvaiheessa.

Tutkimuksessa tehtyjen havaintojen perusteella yrityksen suunnittelijoille luotiin ohjeistus. Se tarjoaa hydrauliikkaliitosten suunnitteluun mallinnettuja menetelmiä, suositeltuja liitinmalleja ja vaatimuksia, joita tulee huomioida jo suunnitteluvaiheessa. Ohjeistuksen tarkoituksena on yhdenmukaistaa yrityksen suunnittelu-, huolto- ja tuotanto-osastojen toimintatavat, jotta vuotoja olisi mahdollista eliminoida tai vähentää jo suunnitteluvaiheessa ennen kuin lopullinen tuote saavuttaa asiakkaan. Työn avulla tunnistettiin nykyisten liitosten todennäköisimmät vuotojen aiheuttajat. Yritykselle suositellaan puutteellisten työohjeistuksien ja asennustoimenpiteiden parantamista ja kehittämistä. Niiden avulla olisi mahdollista estää ja vähentää hydrauliikkaliitosten vuotoja tulevaisuudessa.

Avainsanat hydrauliikka, propulsiojärjestelmä, liitin, vuoto, design, vika- ja vaikutusanalyysi, Pugh

Preface

I want to thank the case company for this exciting and challenging opportunity to examine how to improve the reliability of propulsion system hydraulic connections. Many thanks especially to my thesis supervisor Professor Matti Pietola, advisors Antti Kopsa and Ari Turunen, who supported me during the thesis. I also want to thank Juuso Laherma for finding the topic, and Juha Viitakangas who encouraged me throughout the study. Many thanks to the colleagues of the case company for the interviews and support. I thank all the professional interviewees from outside the case company who offered their help with this study. I also thank my family and friends who have supported me throughout this project. Finally, I thank all my friends at University as well as at University of Applied Sciences, that have created remarkable memories throughout my studies.

Lastly, I quote Arttu Wiskari and ask, "Tässäkö tää oli?" No, this was just one completed milestone, and the journey continues towards new challenges.

Helsinki 28.08.2020

Erik Ojapalo

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Abbreviations

BSPP	British Standard Pipe Parallel
BSPT	British Standard Pipe Tapered
DIN	German Institute for Standardization
DKO	O-Ring seal cone
DN	Diameter Nominal
FFWR	Flats from wrench resistance
FMEA	Failure Mode and Effect Analysis
IACS	International Association of Classification Societies
ID	Inner diameter
ISO	International Organization for Standardization
JIC	Joint Industrial Council
NDT	Non-destructive testing
NPT	National Pipe Thread
NPTF	National Pipe Thread Fuel
OD	Outside diameter
ORFS	O-ring Face Seal
PDM	Product Data Management
PM	Pugh Matrix
PSK	PSK Standards Association
SAE	Society of Automotive Standardization
SFS	Finnish Standards Association
TFFT	Turns from finger tight
UNF	Unified National Thread

1 Introduction

The first chapter of this master's thesis presents the background and research problem of the phenomenon under study. The section defines the research question, objectives, methods, and scope of the study.

1.1 Background

Hydraulic systems consist of several connections, which increases the number of potential leakage points in the system. Hydraulic systems cause almost 400 million litres of oil leakages from equipment each year (Gates 2009, p.4). According to Lahtinen (2004, p.2), as many as 45% of leakages occur as a result of tubes, hoses, and fittings. Several hydraulic component vendors advertise leak-free fittings, but the hydraulic system connections have nevertheless been found to leak.

Several connections are leaking in the case study company, which specializes in propulsion systems. Such leakage can lead to reduced customer satisfaction, increased numbers of service visits, and the development of problems with root causes related to other components. Various modelling and selection programs exist for the dimensioning and fabrication of the hydraulic tubing itself, but no program has yet been created to select hydraulic connections. As the importance of leak-free hydraulic connections in the industry has increased, requirements and components have evolved. Choosing the right connection type is highly necessary, and the importance of choice is reflected throughout the lifetime of the hydraulic system. Currently, the long-term importance of the design phase is underestimated or not understood.

1.2 Research problem

Previous research has found that hydraulic systems cause leakages. However, only a few studies available for public access have focused purely on the connections within the systems. The main research question relates to the problem faced by the case company. The assumption of the study is that the current fittings are unsuitable for the propulsion system and cause leakages. The company has found that hydraulic connections are leaking in the propulsion system, but the root cause of the problem has not been identified. The research question is as follows:

- *How can leak-free hydraulic connections for the propulsion system be ensured in the design phase?*

1.3 Objectives

The research question created a baseline for the objectives of this thesis. The study has four objectives, whose achievement can answer the research question (Figure 1). The first objective is to map the current state of leaking hydraulic connections in the propulsion system. The second is to identify the root causes of connection leakages. The third objective is to determine suitable and reliable connection types for the propulsion system environment. The final objective is to create guidelines for designers based on the findings of the study, which will constitute the study's recommendations. The purpose of the guidelines is to provide general design prescriptions for connections and fitting components so that the required quality level of the final product can be assured. The guidelines are intended to harmonize the operating principles of the design and installation procedures. In order to achieve these goals, the following requirements must also be considered: What is the environment inside the propulsion system, and the environment in which the installations are performed, and how do these key criteria affect the fitting selection?

1.4 Methods

Research methods are a combination of empiric and literature research and interviews of different hydraulic field professionals. The literature review examines factors to be considered in the design phase, the various types of fittings and couplings, potential causes of leakages, and the demands of six classification societies. The literature review is intended to provide a reliable basis for connections so that fittings can be considered throughout the thesis.

The current leakages in the propulsion system are mapped and illustrated with a Pareto 80/20 graph. Qualitative semi-structured interviews are used to gather cross-functional information about the current state of the case company, what kinds of connections are used in different hydraulic applications, and what information has been gained from the previous user experience. The questions seek to find the root causes of connection leakages and determine what corrective action would be taken. After the information in the theory and interviews is presented, the Pugh method is used to map the most reliable fitting types for a propulsion system. Finally, Failure Mode and Effect Analysis (FMEA) is utilized to detect the root causes of the worst leaking design models in the propulsion systems. FMEA is used to examine whether leak-free connections can be ensured in the design phase. Finally, the Siemens NX modelling program is used to formulate design recommendations for FMEA and the guidelines.

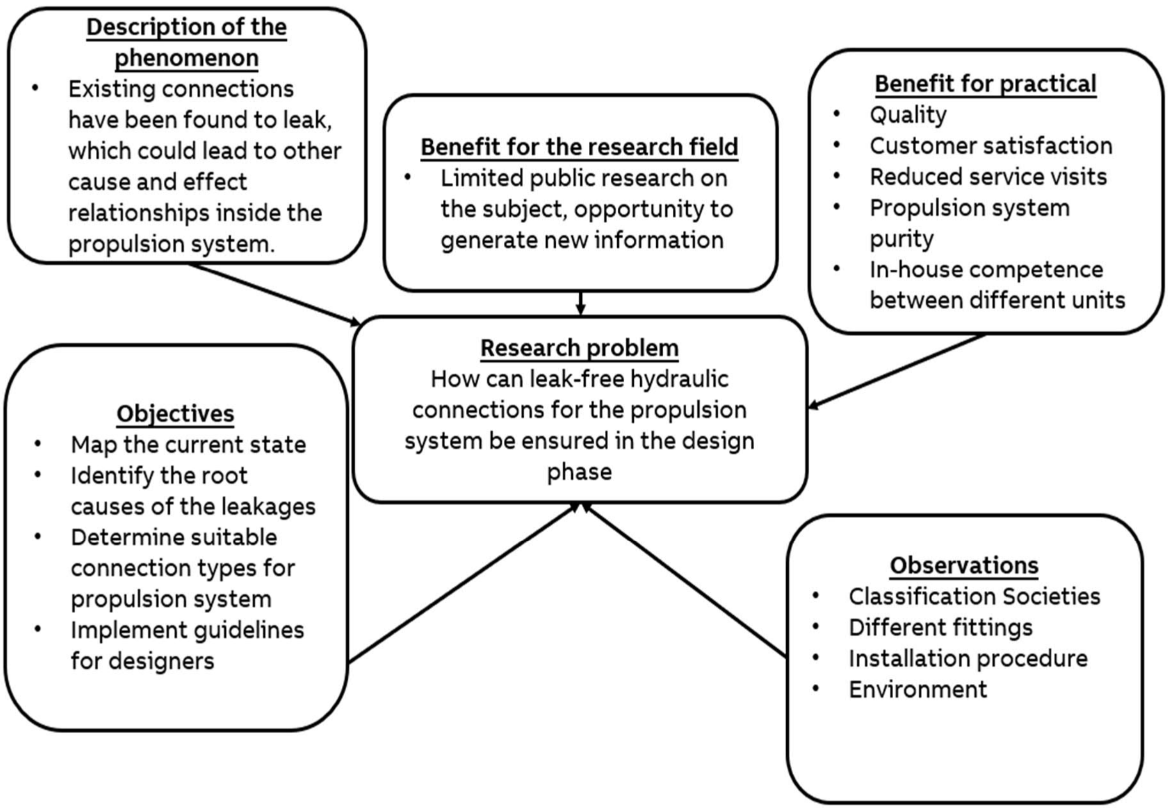


Figure 1. Main characteristics of the study.

1.5 Scope

This study focuses on finding reliable hydraulic system connections for the propulsion systems in the case company. The research is limited to comparing the most common types of connections in the twenty-first century and does not aim to invent a new type of fitting.

The selection process is influenced by the environmental performance of the propulsion system. The thesis focuses on finding low-pressure hydraulics while excluding the high-pressure system. This exclusion was made because fittings in the propulsion systems of low-pressure hydraulics have been found to leak. The thesis examines what connections are currently used in the propulsion system and what are the most typical leakage points. Six typical classification societies of the case company are included in the study. Due to the limited time allowed for the research conducted in this thesis, the dimensioning of the hydraulic lines and fittings was excluded, and it was possible to focus precisely on the causes of leakages in the connections of the propulsion systems.

2 Theory

At the beginning of this study, knowledge was developed by exploring previous research and literature. The aim of the literature review is to clarify the framework of leak-free hydraulic connections. This chapter provides a comprehensive explanation of several hydraulic fittings and the factors that directly and indirectly affect reliability. The presentation of the various connections provides the starting point for the thesis, so that, as the study progresses, the fittings can be scored according to a list of requirements. In addition, the guides of several hydraulic component manufacturers and previous studies were used.

At the end of the literature review, the rules set by the six classification societies are introduced. These rules are important when choosing a connection, for if the classification society does not approve the connection, it will not be allowed for use in propulsion.

2.1 Design of hydraulic connections

As discussed in the introduction, many component manufacturers offer leak-free connections. Horgan (1998) stated in his article that the development of fitting and sealing techniques enabled a leak-free hydraulic system to be produced. The most prominent example of this development is the automotive industry. In the 1960s, car hydraulic connections failed under varying conditions, but the new cars of today remain leak-free for a long time (Lahtinen 2004, p.4-5). The fighter industry has also reported outstanding results from leak-free systems. Aaltonen had stated that he did not detect any oil leakages in a fighter except for when it was parked for a long time (Jokela. 2017, p.13).

Despite such developments, leaking hydraulic connections have been detected in applications such as earth- moving equipment and propulsion systems in the case company. Imel (2008, p. 5-6) found in his study that hydraulic connections are leaking in Skid-Steer loaders. It has also been observed that low-pressure hydraulic systems are more likely to leak than high-pressure systems (Lahtinen 2004, p.2). Most leaking connections are not critically functional components or systems, so they are maintained to a much lesser degree. Each connection has the potential to leak and should be analysed individually. There is no accurate information and data on the number of leakages, and estimates vary depending on the source. However, it can be stated that the main cause of the external hydraulic leakages is the tube connections (Fitch 1992, p.71;80).

Hydraulic connections have two essential functions: guaranteeing a leak-free connection and providing a sufficiently secure connection between the tubes or components under varying conditions (Hunt & Vaughan. 1996, p.275). Fitch (1992, p.68) stated that external leakages are due to four reasons: poor maintenance, inadequate installation procedures, demanding conditions, and incorrect design and fitting selection.

System design is the first important step in preventing leakage, and 20% of leakages occur due to weakness in the system design phase (Parker 2004, p.4-5). Hydraulic system design should aim to produce a reliable and leak-free system (Bailey, 2017). The PSK Standards Association (PSK) 6706 standard (2006, p.6) mentions that one element of achieving a leak-free system is a correct and professional design, which includes choosing the right hydraulic connections and sealing methods. Virta also specifies that adequate installation of the hydraulic connections and the selection of the right components for the environment are the first steps towards leak-free hydraulics. Installation errors are directly reflected in the system's reliability, and even small changes in the fitting can affect differences in the tightening procedure. A connection is as reliable as its weakest link, which can be an inadequately assembled fitting. Rabie (2009, p.65) mentioned that choosing the correct hydraulic connections is essential to ensure proper and safe operation. The pressure classes of the fittings should never be mixed, as there is a possibility that the low-pressure fitting connected to the high-pressure fitting may cause damage to the fitting or hose (FReSH 2012, Virta 2010, p.62&71).

A modern hydraulic design contains as few different parts as possible in order to reduce the number of potential leakage points. Proper piping design, such as bending the tubes to a shape that eliminates the need for additional connections, can also reduce the number of fittings that are required. Hunt and Vaughan (1996, p.275) mentioned that the safest way to avoid leakages is to avoid hydraulic connections entirely, but due to different applications and requirements, this is challenging to implement in practice.

It may not be possible to build the entire line without connections in all applications, and the serviceability of the hydraulic system should also be considered at the design stage (Hunt & Vaughan 1996, p.275). According to the standard PSK 6701 (2006, p.61), connections must be constructed such that they can be tightened without the removal of other tubes. In a poorly designed system, maintenance is not possible when a fault occurs (Lahtinen 2004, p.5). When designing a leak-free hydraulic connection, several factors, shown in the list below, must be considered (Parker 2004, p.6-28):

- the hydraulic application and fluid
- type of tube or hose
- the system working pressure
- accessibility
- fitting or coupling price
- permanent or breakable connection
- requirements of standards and classification societies rules
- the environmental conditions in which the system is located.

2.2 Connections

The International Organization for Standardization (ISO) 8434-1 2018, p.9) standard specifies that hydraulic machinery/equipment “may be connected through their ports by connections (connectors) and conductors (tubes and hoses)”. Typically, the connections of mobile hydraulic systems are flanged, threaded, or quick-release couplings (Kauranne et al. 2013, p.418). However, the terminology used for the connections may vary throughout the literature and across manuals. The terms “connector”, “coupling”, and “fitting” can refer to the same thing, depending on the source. In this thesis, the term “fitting” used for all connection types except for quick-release fittings, for which the term “coupling” is used. Fittings are further divided according to their intended use. Tube and hose connections are referred to as “tube-ends” and “hose-ends”. The term “stud-end fitting” is used for the port end of components such as motors or actuators, as illustrated in Figure 2. (Parker 2004, p.8)

Hydraulic connections vary depending on the application and the environment of use. Fittings are available from various manufacturers, and although the fittings themselves may look the same, their threads may differ. Several types of threads are used, with the most common worldwide being British Standard Pipe Parallel (BSPP), British Standard Pipe Tapered (BSPT), Metric (M), National Pipe Thread Fuel (NPTF), and Unified National Thread (UNF). The most commonly used thread types in Europe are the ISO standard metric thread, and the BSPP thread also referred to as the G-thread (Kauranne et al. 2013, p.418). The ISO aims to internationalize different fitting types in response to the wide variety of fittings. For instance, ISO 6149 is recommended for the port connection design, and ISO 8434 is recommended for the tube-end of a new system (Watson 2010, p.105).

2.3 Tube-end connections

Tubes used in hydraulics are mainly standardized thin-walled welded or seamless precision steel tubes. Hydraulic tubes defined by the outside diameter (OD) and wall thickness, which also determines the size of the fitting. Typically, tubes are used when there are no moving or rotating joints or parts in the application. (Parr 2006, p.184, Watson 2010, p.89.)

Watson (2010, p.89) has mentioned that when vibrations of applications and the bending of the tube are minimal, then tubes are a more affordable and robust option than hoses. Tubes transmit more vibration than hoses, which can increase the leakage sensitivity of the connection. Tubing is also stiffer than hoses, and tubes are more accurate in dimensioning than hoses. Virta (2010, p.92-93) suggested that even a small dimensional error in an incorrectly routed tube will most likely lead to a leak. As the temperature fluctuates, thermal expansion may cause length changes to metal tubing, which can loosen the fitting. Dimensional changes can be compensated for at the design phase by adding U-shaped or S bends to the tube.

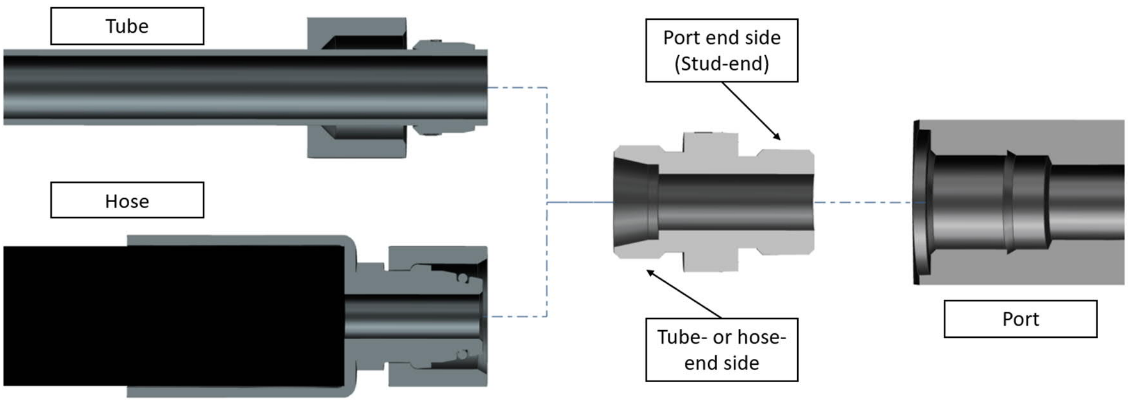


Figure 2. Definition of connection types (adapted from Parker 2004, p.8).

The tube-end connection is located between the fitting and hydraulic lines, as illustrated in Figure 2. Tube-end fittings are made for tube sizes 6–42 mm. In addition, each tube-end fitting has its own needs for tube-end preparation, which sets skill requirements for fabrication. Seven subgroups of tube-end fittings are included in the thesis: 24° cone, flared, O-ring face seal, weld fittings, flanges, compression, and press fittings. (Drexel et al. 2003, p.277, Parker 2005, p.57)

2.3.1 24° Cone (ISO 8434-1/DIN 2353)

In Europe, the most common tube-end connection is considered to be the Metric 24° cone fitting (McDonough, 2017). This threaded connection is also called a flareless, cutting ring, or bite fitting connections. Many variations of 24° cone fittings exist, and the first generation introduced in the early 1930s was based solely on single cutting ring metal-to-metal sealing.

The current connections are based on a double-cutting ring. The bite fitting has three parts, and the tightening procedure often involves two steps. In the first step, the pre-assembly phase, the cutting ring is pre-tightened to the tube using a male-fitting body and a nut. The cutting ring wedges against the 24° internal cone of the male body, and the cutting ring forms a securing shoulder on the tube surface. In the second step, the actual assembly phase, the connection is tightened to the tube by flats from the wrench resistance (FFWR) method, which involves the connection being tightened first to finger tension, then with a wrench to the point of considerable resistance and finally to the degree indicated by the manufacturer (King 2017). Finally, the fitting is formed by metal-to-metal sealing by clamping the cutting ring to the tube. (Hunt & Vaughan 1996, p.277, Parker 2005, p.19, Virta 2010, p.17-19)

A bite connection does not require major tube-end modifications. The tube-end must be rounded and burred according to the manufacturer's instructions, and the cutting-ring material must be harder than the tube in order to provide a leak-free connection. (Drexler et al. 2003, p.277, Virta. 2010, p.19)

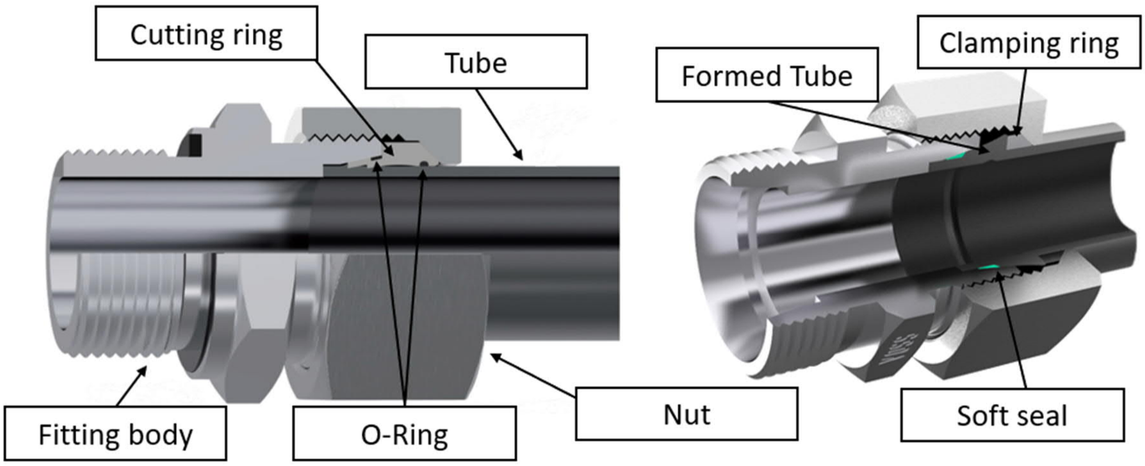


Figure 3. Bite fitting with elastomer seal on the left and formed tube-end fitting on the right (adapted from Voss 2018, p.28;432).

The second-generation bite connection largely supplanted the first generation. The sealing method was based on a combination of the cutting ring and the elastomer sealing ring, as illustrated in Figure 3. These connection methods provide a more secure connection and facilitate the tightening procedure of the fitting, preventing over-tightening. With multiple clamping points, the connection has a separate gripping and sealing function, and the edge in the cutting ring prevents over-tightening. An elastomeric seal adapts better to temperature changes and dampens vibrations than the bite with the metal-to-metal seal. (Hunt & Vaughan 1996, p.276-279, Virta 2010, p.19-21)

The twenty-first-century tube connection is considered to be the formed tube-end, which also uses a fitting body according to ISO 8434-1 (Lahtinen 2004, p. 5). The connection does not have a cutting ring. Instead, a suitable shoulder is cold formed by a separate machine into the tube and the sealing ring is placed in front of the shoulder, against which nut with integrated clamping ring and fitting body is tightened, as illustrated in Figure 3. Therefore, the same pre-assembly phase as in bite is no longer required. When no bite onto the tube surface is required, the tightening torques are lower than in the bite fitting. The fitting structure also prevents over-tightening, because when the nut is tightened, the end of the tube presses against the shoulder of the fitting body, preventing over-tightening. Virta (2010, p.21) has mentioned that the formed tube withstands vibrating conditions better than bite fitting. However, objective tests are minimally available to the public. (Parker 2005, p.31-33, Voss 2018, p.33-36)

In the 2010s, the latest version of the 24° cone fitting was introduced. The EO-3 connection consists of only two parts: the fitting body and the nut. The fitting end has a 24° inner cone with an elastomer seal, to which the formed tube-end is secured with an octagonal nut. In addition, the tightening procedure differs from traditional 24° cone fittings. The EO-3 fitting has an indicator ring, which immediately indicates whether the connection is correctly tightened. Therefore, the EO-3 connection also differs in that the fitting body does not fit the fitting bodies presented earlier. At the moment, questions raised about the newness of the connection are reflected in the fact that there is no user experience or studies available for the fitting. (Fluid Finland 2017, Parker 2014, p.2-5)

A bite fitting can be installed in field conditions without a separate machine. However, the installation procedure has been found to be challenging. A study by Närhi (2014) found that the experience of the connection assembler greatly influences the fitting's reliability. Problems with an overtightened fitting occur if the connection must be opened and retightened. Once the connection has been overtightened, leakage may occur after retightening, since the tightening capacity of the fittings has already been used. The problem with under-tightened fittings includes the fact that the connections may not leak under test pressure but will leak over time. In addition, Cundiff (2002, p.358) noticed that a bite connection will leak if the fitting is not appropriately tightened. Both under-tightened and over-tightened connections showed leakages, and vibration and temperature fluctuations loosened the connection; in bite fittings, this is prevented by soft sealing.

Cundiff (2002, p.360) mentioned that bite fitting requires retightening because the metal-to-metal connection is sensitive to loosening and can cause leakage. However, the ability to tighten the connection is limited by the brittleness of the tube material. The connection can tighten several times, but the more often the connection is tightened, the deeper the cutting ring penetrates the tube surface, which may eventually result in the tube breaking. Therefore, a bite connection is not suitable for a thin-walled tube without the installation of an additional support sleeve inside the tube. Hydraulic components manufacturers provide tables showing suitable tube wall thicknesses for connections. (Drexler et al. 2003, p.277, Virta 2010, p.19)

Different standards also define Metric flareless 24° cone connections. ISO 8434-1 simplifies the selection process by classifying fittings by pressure class and application. The connections are divided into three categories: extra light-duty (LL), light-duty (L), and heavy-duty (S). The size of fittings is determined by both the pressure class and the outside diameter of the tube (ISO 8434-1 2018, p.14). Despite standardization, Hunt and Vaughan (1996, p.276) has pointed out that fittings of different vendors should not be mixed.

2.3.2 Flare (ISO 8434-5/-SAE J514)

The most commonly used fitting type in the United States is the UNF threaded 37° flare, known as the JIC fitting (Cundiff 2002, p.380). A traditional flare-type fitting requires a thin-walled steel tube, to which a 37° flare is cold formed by a separate machine. The fitting body is tightened by a nut, whereby the sleeve presses the conical surface of the fitting onto the flared end of the tube, creating a metal-to-metal seal, as illustrated in Figure 4 (Fonselius et al. 2008, p.126). Flare fittings also exist without a support sleeve. However, they are recommended only for stable and low-pressure systems, as the sleeve prevents vibration and twisting friction (Watson 2010, p.101).

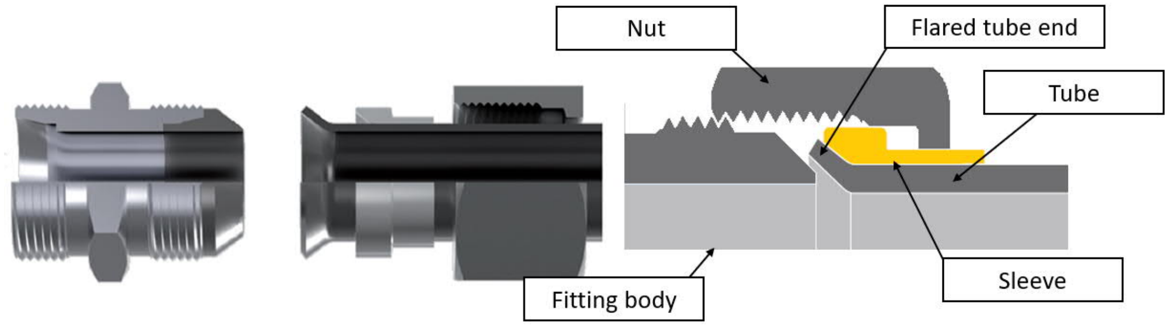


Figure 4. 37° Flare connection with O-ring (adapted from Voss 2018, p.471).

According to Eaton's guide (2009, p.33), the force required to tighten the 37° flare fitting is less than that for bite fittings due to the smaller seal surface area. That facilitates the installation of the fitting and provides useful maintenance features. However, statements about the usability of the fitting are contradictory. Fonselius et al. (2008, p.126) noted that the connections can open and close several times, while Parker's guide (2004, p.16) indicated that due to the lower clamping force requirement, the connection could be over-tightened, causing the fitting cone to collapse. Moreover, this can cause leakages or reduced flow.

The reliability of flare connections has been studied previously. Imel (2008, p.25-53) found several flare connections leaking, especially at 37° flare hose-end fittings. The dimensions of the fittings were measured and found to be within the standard tolerances. After the addition of the sealant, leakage increased, and tightening also increased the number of leakages. Eventually, the investigation revealed poor flare formation as the root cause of the hydraulic leak. The eccentric sealing was due to the hose material being too stiff and the fitting not sealing correctly. This study also supports Hehn's (1994, p.392) contention that the reliability of the 37° connection is largely based on the quality of the tubing flare.

Fluid Power Research Center (FPRC) (cited in Fitch 1992, p.73) researchers investigated the leak tightness of flare, flange, and bite fittings by experimental pressure impulse and rotation tests. 37° flare fittings resisted the stress the worst of all connection types, as illustrated in Table 1. Unlike the bite fitting standard 8434-1, the ISO 8434-2 standard for the flare 37° connection does not require the fittings to be leak-proof from vacuum to operating pressure. However, according to ISO 8434-2, the flare fitting provides full-flow metal-to-metal sealing at operating pressures (BS ISO 8434-2 2007, p.1).

Table 1. Pressure and flexure test.

Connection	Average stress	Stress Cycles	Cycles to Failure	Time to Failure (min)
*Flare 37°	39236	1078	20	0.62
*Flange	58000	137462	2425	106
*Bite/flareless	60000	713664	11758	413

*Results from FPRC test (cited in Fitch 1992, p.73).

2.3.3 ORFS (ISO 8434-2)

The O-Ring face seal (ORFS) fitting differs from the connections mentioned above in that its sealing is based on the soft-sealing method. The UNF-threaded ORFS fitting consists of four parts (Figure 5). The male fitting body has a groove on its end face for the O-ring. The O-ring is resting in the groove, and sealing occurs when the male fitting body is tightened with a female nut and sleeve to the flanged-end face of the tube. One of the functional properties of the ORFS fitting is that even if the fitting is overtightened, the O-ring or threads are not damaged. When the fitting is tightened, the planar surfaces of the connection form a metal-to-metal contact, positioning an O-ring in its groove. The ORFS fitting also called zero-clearance fittings because it can install radially. In this case, the fitting can be installed or removed between the tubing by loosening only the nut. (Virta 2010, p.25, Watson 2010, p.103)

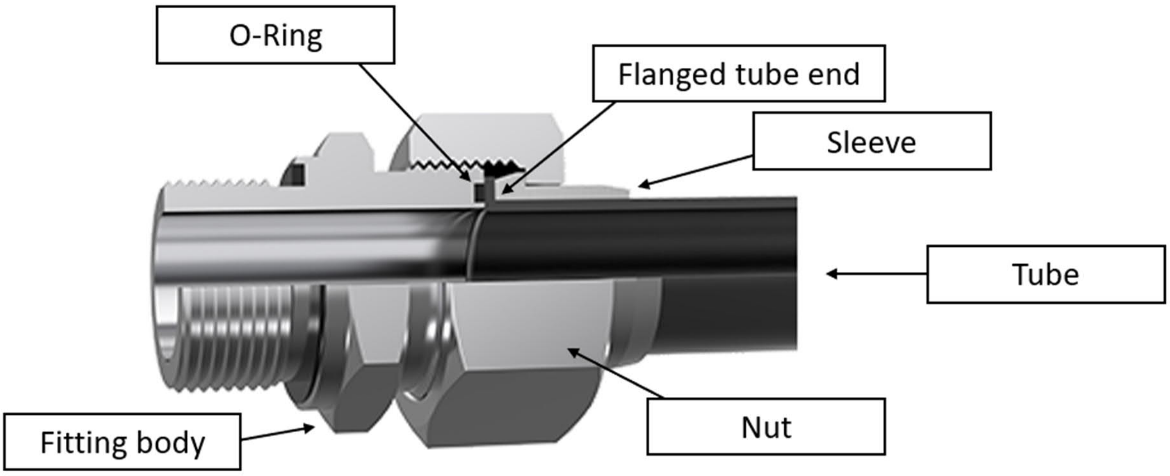
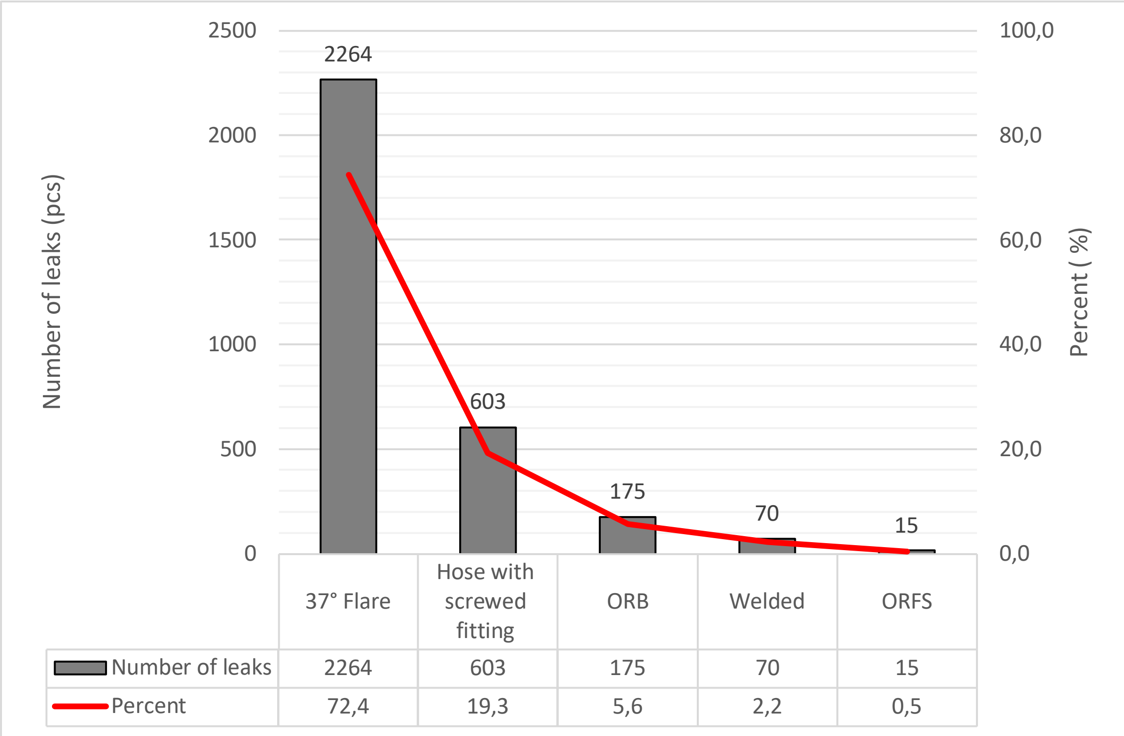


Figure 5. O-ring face seal fitting (adapted from Voss 2015, p.2).

The flanged tube-end can be manufactured in two ways, by brazing or by cold forming a flat flange at the end of the tube. Of these two preparation methods, cold forming by machine is faster and less laborious than brazing, making cold work more effective. Cold forming imposes the same requirements on tubes as on flare connections. (Parker 2005, p.40-42)

Studies comparing different types of fittings have been very limited. However, several hydraulic component manuals and articles have recommended O-ring sealing on the fitting. Reaves (2003) mentioned an ORFS seal as the most reliable sealing method, and Watson (2010, p.102) also suggested that this is one of the best leak-free connections. A study by Imel (2008, p.24) showed that of the five different connection types in the skid-Steer loader, the one that experienced the least leakage was ORFS. Of the 3,127 leaking hydraulic connections, only 15 leakages came from the ORFS fitting, as shown in Figure 6.



	37° Flare	Hose with screwed fitting	ORB	Welded	ORFS
Number of leaks	2264	603	175	70	15
Percent	72,4	19,3	5,6	2,2	0,5

Figure 6. Investigation of leakages from different connection types (adapted from Imel 2008, p.24).

ORFS connections have higher ambient temperature and fluid limits than metal-to-metal connections. Parker's catalogue of hydraulic connections (2004, p.21) states that the ORFS fitting is suitable for low-pressure systems, but Hertz (1979, p.2) has stated the opposite. The O-ring material selected for the fitting must suit the conditions for use. The pressure of the system affects the sealing properties of the O-ring. The ORFS connection was initially designed for high operating pressures. When the system pressure is above 10 bar, the O-ring is squeezed and provides sealing. Nevertheless, under lower pressure, the seal does not necessarily squeeze as planned, which may cause leakage (Hertz. 1979, p. 2). However, this study has been challenged, as the ORFS fitting's latest standard requires that the fitting be tested from a vacuum pressure of 0.065 bar to the stated working pressure of the fitting (ISO 8434-3 2005, p.1).

Although the ORFS is said to be a reliable fitting, the manufacturer has also listed several different causes of leakage in the ORFS, including an incorrect installation procedure (Parker 2004, p.19):

- O-ring missing
- inadequate tube flaring
- inadequate tightening
- tube is sawn inclined
- excessive vibration due to inadequate routing and supporting of the tube.

2.3.4 Welded connections

Tube connections welded directly to each called permanent connection. Permanent connections are said to be particularly suitable for applications that do not require disassembly (Drexel et al. 2003, p.276). Fitch (1992, p.81) mentioned that welded connections should be used whenever possible, as they enable the number of leakage points to be reduced. Majumdar (2002, p.446), by contrast, stated the opposite, noting instead that it is generally wise to avoid welded connections if possible. However, if welded connections are used, a butt weld should be performed, as this reduces internal scaling in tubes.

The connections to be welded can be made in two different ways, either by welding the tubes directly to each other or welding a suitable nipple or flange at the end of the tube. Weld-on nipples utilize tube-end fittings. Weldable nipples and flanges can detach from each other, but when using weldable nipples, it should remember that the mating connection should rotate to allow ease installation. For instance, the fitting to be connected should include a swivel nut that rotates 360°. In a welded connection, the tube need not be seamless, as in the fittings discussed earlier. Lahtinen stated that using welded steel tubes and weldable fittings is associated with lower costs compared to using seamless stainless steel tubes and bite fittings. (Kauranne et al. 2003, p.420-421, Lahtinen 2004, p.6, Watson 2010, p.100)

2.3.5 Swage fittings

Swage fitting, also called a mechanical-grip fitting or a compression, resembles a bite fitting. These fittings also come from several manufacturers and differ in design, and the connections are also based on metal-to-metal sealing; however, with swage fittings, the fitting ferrules clamp into the tube without the tube's cut feature, as illustrated in Figure 7. The swage consists of a fitting body, the nut, and either a single or double ferrule. The principle of a double ferrule differs in that the front ferrule acts as a sealing part, pressing both the tube and the fitting body, while the rear ferrule acts as a thrust bearing. This prevents the tube and ferrule from rotating when the connection tightens and dampens vibrations from the sealing surfaces. Swage fittings have also been tested against vibrations under earthquake-like conditions. When the swage is not subjected to resonance in the tubing, the fitting remains leak-proof up to a 10 on the Richter scale. With resonance, the fitting remained leak-proof up to an 8. (Drexel et al. 2003, p.279, Nesbitt 2007, p.250, Swagelok 2019, p.78)

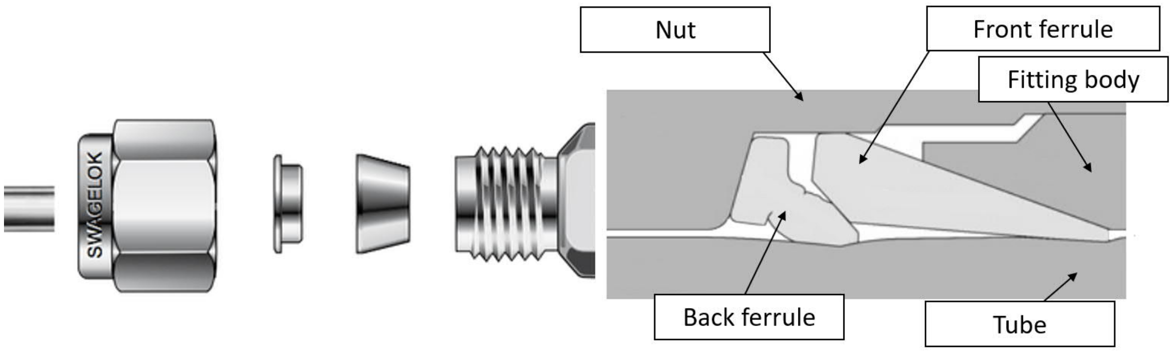


Figure 7. Swage fitting (adapted from Swagelok 2003, p.4).

The fitting does not require tube-end modification, which speeds up and simplifies the installation procedure. A swage is also suitable for both a metric and an inch tube. The correct tightness of the connection can also be inspected utilizing a gauge placed between the nut and the body (Parker 2009, p.2). Hehn (1992. p.392) pointed out that this fitting can be successfully installed by a semiskilled technician. The fitting body is non-standardized, but the port end side uses standardized threads. The connection is said to be suitable for thin-walled to heavy-walled tubes, in which complete leak-tightness is required, but this raises the question of why the swage has not become the most widely used tube fitting. (Kauranne et al. 2008, p.419, Nesbitt 2007, p.248-249)

2.3.6 Press

In the twenty-first century, non-standardized permanent fittings have become more common, utilized especially in paper machines. A press fitting is classified as a permanent type, as the fitting cannot be disassembled after installation like threaded fittings. Press fittings are based on either an O-ring (Figure 8) or a metal-to-metal sealing method, depending on the manufacturer. A press fitting lacks the weaknesses of welded connections, such as non-destructive testing (NDT) inspections. When the fitting is installed, only the tube is cut to the correct length, and burrs are removed. Finally, the fitting is pressed into the tube with a manual hydraulic press, after which the finished connection is inspected visually or by an inspection gauge, depending on the manufacturer. In addition, the fitting is suitable for both a seamless and a welded tube. (Haelok 2020, Jokela 2019, p.102-103, Tube-Mac 2020)

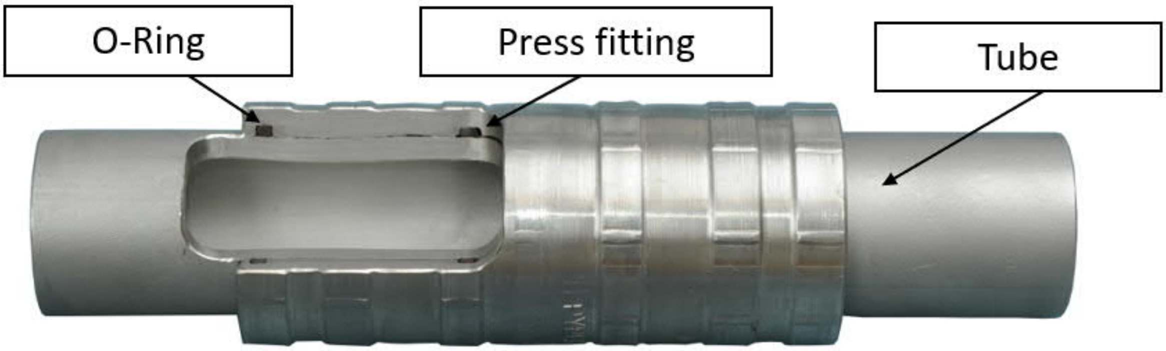


Figure 8. Press fitting (adapted from Tube-Mac 2020, p.8)

The press fitting installation procedure is the least prone to installation errors, as the installation involves the least number of work steps. The manufacturers state that the fitting is suitable for vibrating and hot environments from a vacuum to conditions of high pressure (Haelok 2020). However, no comprehensive public studies have been conducted on the press fittings. However, Wei et al. (2016, p.12) found in their research that press fittings tend to leak under internal pressure. The reason was found to be the surface scratches in the tube, providing microleakage paths. Nevertheless, Kairama stated that the press fitting is faster and more cost-effective than welding or flange fitting and that it is certainly the most leak-proof fitting (Jokela 2019, p.102-103).

2.4 Port End

According to the definition in ISO 6149-1 (2019), "ports are an integral part of fluid power components, i.e., pumps, motors, valves and cylinders". The port end, referred as the thread end, is a connection between component and fitting (Figure 2). Port-end fittings also have a tube- or hose-end side, which is called a tube grip. Two main fitting models exist for port-end connections: threaded or non-threaded fittings. Threaded connections can be further divided into parallel and tapered fittings in mobile and industrial applications. Parallel fittings form a seal using a flat surface, while tapered connections form a thread seal. Non-threaded connections, meanwhile, are flanges which also form a seal using a flat surface. Selecting a port fitting is more difficult than selecting a tube- or hose-end fitting, since the component connection port determines which fitting type to use. (Drexel et al. 2003, p.280, Virta 2010, p. 51)

2.4.1 Parallel fittings

The functional differences between the parallel port-end fittings are mainly focused on the shape of the seal and thread. It should be noted that the tightening torque of each model vary (Parker 2005, p.146). The threaded port-end fittings are divided into an alphabetical order that clarifies the sealing form of the fitting. In the Form A stud-end, sealing is done by a flat sealing washer. The Form B stud-end does not have a separate seal, and the fitting instead has a machined seal edge, and when tightened, it forms a metal-to-metal face seal. Re-use of the fitting is not possible, as the sealing method damages the sealing surface ((ISO 9974-3 2000, p.7). The Form E fitting is sealed with an elastic profile seal, also called an ED seal, and the rectangular sealing ring sits in the machined groove of the fitting (Drexel et al. 2003, p.280). The Form F stud-end is sealed with an O-ring. The stud-end does not have a separate O-ring groove, but the O-ring seals the port-side chamfer, thus preventing liquid from escaping. In Form G, the O-ring with a retaining ring seals against the connection port side of the planar surface. When tightening the fitting, the detachable metal retaining ring supports the outer circumference of the O-ring. (Parker 2004, p.33-44, Virta, 2010, p.52-53)

Table 2 and Figure 9 illustrate the most common female ports and their corresponding stud-ends with their standards. The sectional view illustrates the difference between sealing methods. The male stud-ends of Forms A, B, E, and G fit the Form X female port. In addition, it is worth noting that when using a Form G stud-end, the port-end spot face is wider than other forms. Standard ISO 1179-1 (2013) and ISO 9974-1 (1996) specifies manufacturing drawings for port connections. The Form W female port is different from the others, so the Form F stud-end is suitable only to the W-type port. Identification methods have been made for a Form W port to reduce the possibility of installing the wrong stud-end in the port. Form W may have an optional identification ridge shown in Figure 9 or the stamped letter M next to the port. There are other Metric and BSPP threaded stud-ends than the form type, such as those with a bonded seal or USIT seal that fit into the female X port. In these, the sealing takes place on the same principle as in the Form A type, but the sealing ring consists of a metal ring with a rubber ring moulded on the inside. (Fonselius et al. 2008, p.129, Parker 2005, p.59-61, Virta 2010, p.52-53)

Table 2. Stud-end and port form.

Stud-end	Form A	Form B	Form C	Form E	Form F	Form G
Sealing	Washer	Sealing edge	Thread	Elastic profile ring	O-ring	O-ring with retaining ring
Metric	DIN 3852-1	ISO 9974-3	DIN 3852-1	ISO 9974-2	ISO 6149-2/3	-
BSPP	DIN 3852-2	ISO 1179-4	-	ISO 1179-2	-	ISO 1179-3
BSPT	-	-	DIN 3852-2	-	-	-
UNF	-	-	DIN 3852-2	-	ISO 11926-2/3	-
Port	**Form X**	**Form X**	**Form Z**	**Form X**	**Form W**	**Form X**
Metric	ISO 9974-1	ISO 9974-1	DIN 3852-1	ISO 9974-1	ISO 6149-1	ISO 9974-1
BSPP	ISO 1179-1	ISO 1179-1	-	ISO 1179-1	-	ISO 1179-1
BSPT	-	-	DIN 3852-2	-	-	-
UNF	-	-	-	-	ISO 11926-1	-

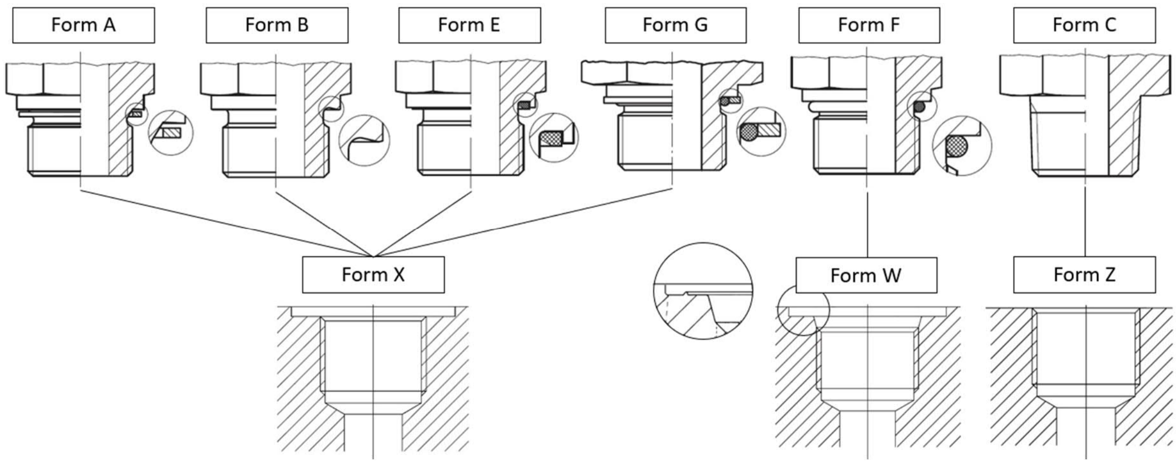


Figure 9. Stud-end and port connections.

The Society of Automotive Standardization (SAE) has commissioned objective burst and cyclic endurance (ISO 19879:2010), testing for the Form F, ISO 6149 fittings. The tests were performed for a heavy-duty application, in which case the pressures were high. During the tests, none of the fittings in a size class from M12 to M42 leaked (Miller & Patel 1992, p.548). The standard ISO therefore states that fittings of type ISO 1179, ISO 9974, and ISO 11926 should not be used for new design in hydraulic fluid power applications (ISO 9974-3 2000, p.7). In addition, Watson and several component manufacturers, such as Parker, identify the Form F fitting as the most reliable, recommending the fitting for new applications (Watson 2010, p.102, Parker, 2004, p.33).

2.4.2 Tapered fittings

A tapered fitting is sealed on a metal-to-metal basis, but often a sealant is added or required (Cundiff 2002, p.379). A tapered male fitting can be installed in tight spaces and is available in a wide range. The fitting is available in four different thread types: NPT, NPTF, Form C fittings with M, and BSPT. Form C stud-ends attach to a parallel shaped female port, while the rest of the tapered fittings attach to a tapered female port. The difference between tapered fittings is the angle of the thread, the shape, and the pitch. (Drexel et al. 2003, p.281, Parker 2004, p.24-30, Parker 2005, p.61)

The conical structure of the thread is deformed as it tightens, and the connection may later become loose, causing leakages (Casey 2005, p.2). Cundiff (2002, p.357) has previously shown how conical threads condense when tightened. Figure 10 clearly shows a spiral clearance in the NPT thread when the fitting is tightened without sealant. NPTF, meanwhile, generates full contact when properly tightened without sealant. A threaded fitting should provide 100% metal-to-metal sealing to avoid creating a path for leakage. In addition, Drexel et al. (2003, p.280) mentioned that high bursting forces may be generated by tightening the connection between fitting and component. In addition, Watson (2010, p.100) noticed that an adequately installed fitting can provide an effective and secure seal, but installation is challenging because the tapered connection is not torque-controllable.

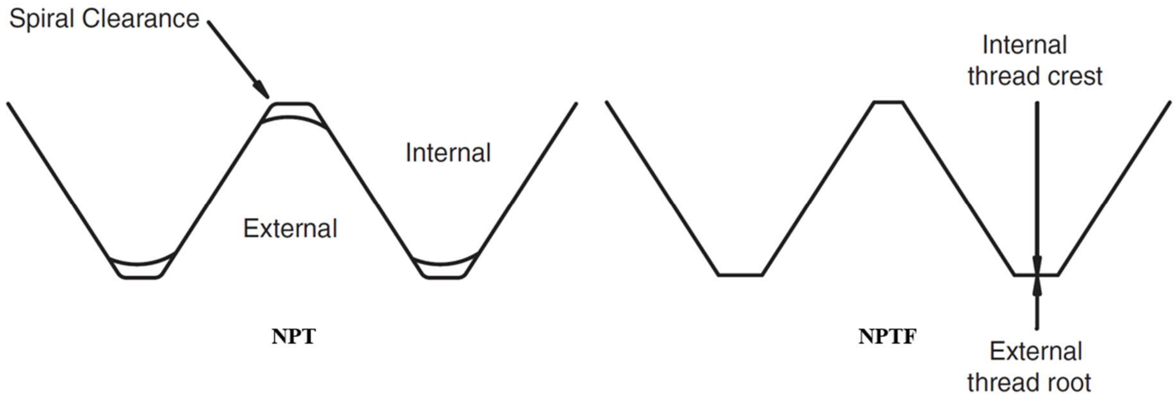


Figure 10. NPT and NPTF clearance difference (adapted from Cundiff 2002, p.357).

A tapered fitting is one of the oldest, and the development of newer connections has reduced its use in Europe, since the fitting has been found to cause leakage (Parker 2004, p.28). Many component manufacturers recommended abandoning the use of tapered connections and replacing them with other fittings. However, Ford's experimental tests of more than two years tested tapered NPTF fittings with a pre-applied thread sealant, a dry instant sealant that has elastic and non-curing properties. In pressure tests, tapered connections were not found to leak during any of the conditions tested. Note, however, that the hydraulic fluid was not tested. (Barsness & Barbeau 1984)

2.4.3 Flange

Several types of flange fittings are available, and the most common types of flanges are SAE J518 and ISO 6162-1/2. Flange fitting differs from previous connections because it can be used in a tube, in a hose, or directly as a port connection. The flange can be attached to the tube by welding, forming tube-end, or using retaining clip flanges, whereby a groove for retaining the ring is machined into the tube. For hoses using split flanges or flange adapters. Mounting to the tube or hose can also be achieved with a threaded port of flange, as illustrated in Figure 11. (Fonselius et al. p.127, Virta 2010, p.79)

Flange fittings are designed initially for large-diameter high-pressure piping. Nowadays, use has been expanded from industrial systems with a tube size over 38 mm or larger to mobile hydraulics starting from 16 mm tube size. The use of flange connections has expanded to demanding applications, as flange connections are not sensitive to shocks, high-pressures, and vibrations, especially at larger sizes. However, Lahtinen mentioned in his article that the flanges of large-diameter low-pressure lines have still been found to leak. However, according to the Parker guide (2004, p.29), many leakage problems caused by tapered thread design can be avoided using a flange connection. In some cases, the flange fitting is the only option, as the port connection component may have a hole spacing for a four-bolt flange connection. (Drexel et al. 2003, p.282, Kauranne et al. 2013, p.419, Lahtinen 2004, p.3-6)

The flange connection is physically more massive than the other connection types and requires a larger installation space. However, the design of the flange connection allows for a smaller clamping space because there are four clamping bolts. The design allows a lower tightening torque for the bolts and facilitates installation in confined spaces. The flange design requires the bolts to tightened evenly, and Hunt & Vaughan (1996, p.286) and Watson (2010, p.102) mentioned the most common cause of leakage to be due to improper tightening. (Parker 2005, p.566)

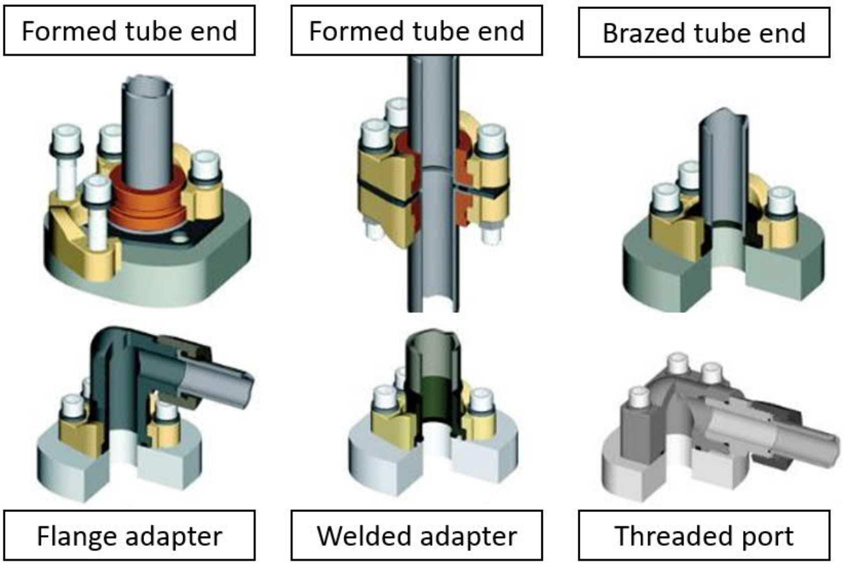


Figure 11.Different types of flange fitting (adapted from Allwes & Salvato 2012).

2.5 Hose-end connections

Hoses are flexible piping systems. Normally, hoses are used especially in areas in which there are rotating or moving parts, such as cylinders or in locations in which installation on rigid tubing is difficult. Hoses dampen vibrations more effectively than tubes and are not as sensitive to thermal expansions as tubes. Hoses expand as the pressure increases and thus act as dampers for vibrations and pressure shocks. The hose's length can increase by 2% as the temperature rises, and the length decreases by 4% when the hose is pressurized. Therefore, hoses should be dimensioned to be longer than tubes to allow the hose to shrink and expand so that the connection is subjected to no stress. The inside diameter (ID) of the hose determines the size of the fitting used. In addition, the hose's choice is influenced by operating conditions, fluids, and pressure, and SAE J517 provides a more detailed specification of hose properties. (Watson 2010, p.87-88, Zhang 2018, p.93-103)

Hose routing design differs from tube routing procedure. According to Felperin (2015, p.49), the most common causes of hose leakages are improper installation and abrasions. An excessively tight bending radius and twisting must be avoided when installing hoses, as the hose shell or crimp connection can suffer (Fitch 1992, p. 88). For the hose connections, a minimum straight section length is also required and must be at least 1.5 times the OD of the hose, measured from the crimp connection of the hose. Length is illustrated by the letter D in Figure 12. In addition, the minimum bending radius of the hoses must be checked separately from the hose manufacturer. (Parker 2007, p.21, Virta 2010, p.98)

Hose-end fittings are alike to tube fittings, but the main difference is that the hose-ends can be attached to the hose by two methods, either field attachable or a crimp connection. Reusability is considered to be an advantage of field attachable fittings, although its use has decreased due to the higher safety standards and cost. In addition, machines for crimp connections have become more common. Thus, field attachable fittings are not considered further. The crimp is a permanent connection which is attached using a special crimping machine. Oinonen (2002, p.2) stated that the most critical leakage point of all hose connections is the part between the hose and the fitting. However, he added that when a crimp connection is assembled professionally, it can be made leak-free and secure. (Fitch 1992, p.86, Fonselius et al. 2008, p.125-128)

Table 3. Hose fitting standards and corresponding tube-end standard.

Fitting name	Hose-end standard	Tube-end standard
O-ring face seal (ORFS)	12151-1	ISO 8434-3
24° cone/24° cone with O-ring (DKO)	12151-2	ISO 8434-1
Flange end	12151-3	ISO 6162-1 & ISO 6162-2
Metric stud end (Form F)	12151-4	ISO 6149*
37° flared	12151-5	ISO 8434-2
60° cone	12151-6	ISO 8434-6

*Stud-end standard

ISO 12151-1-6 presents the most typical hose-end connections based on the fittings previously described. It is possible to equip the hose-end connections with fittings that fit directly into the tube-end connections. Hose fittings suitable for tube-ends are shown in Table 3. The table shows that it is also possible to equip the hose with a stud-end fitting. An advantage of using hoses includes the fact that the hose-end crimp can be elbow-shaped, either 45° or 90°, to facilitate hose routing planning. Figure 12 shows the typical elbow-shaped fitting structure of a hose-end connection. However, Virta has said that design should avoid having elbow-shaped fittings at both ends of the hose, as such a structure makes it difficult to determine the position of the hose-ends and increases the risk of confusion. (Kauranne et al. 2013, p.422, Virta 2010, p.91)

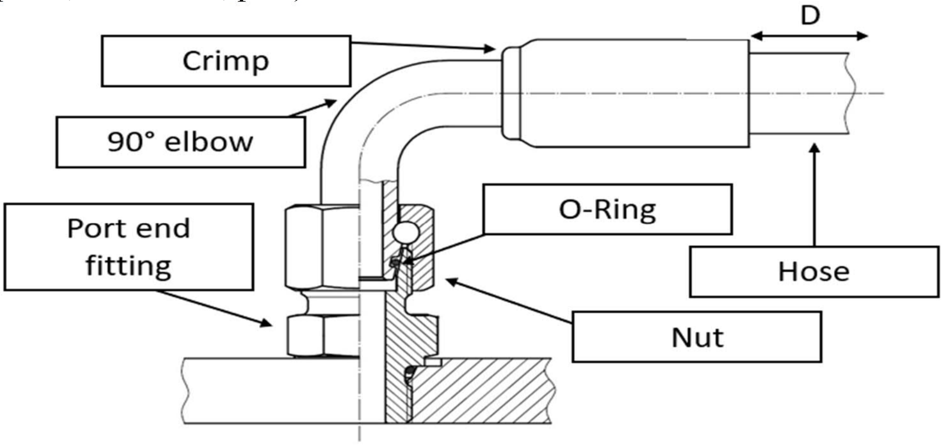


Figure 12. Hose-end with 24° cone with O-ring (DKO) (adapted from ISO 12151-2, p. 2).

2.5.1 Couplings

It is also possible to equip hoses with a quick-release coupling, whereas there is no corresponding quick-release connection for tube connections. Quick-release couplings are particularly popular in mobile equipment, such as forestry and earthmoving machines, because couplings are easy and quick to connect and disconnect repeatedly without tools (Kauranne et al. 2013, p.424).

The coupling has two basic connection structures: either a male plug or a female socket, locked together by a locking mechanism and sealed with a soft seal, as illustrated in Figure 13. As with other fittings, several types of coupling exist, and couplings are equipped with different locking methods, such as twist, pin, ball, or roller locking mechanisms that prevent unintentional release (Fonselius et al. 2008, p.128). The quick-release coupling could have a check valve that prevents oil from spilling from the system or air entering the system when the coupling is disconnected (Rohit & Satheesh 2014, p.43).

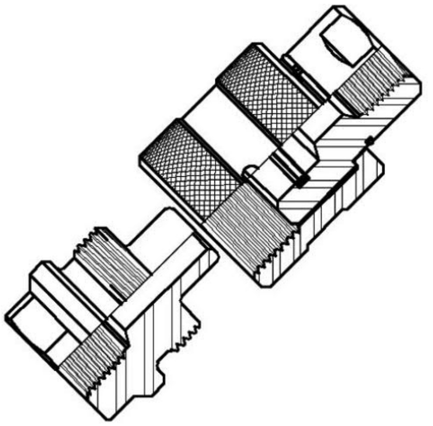


Figure 13. Quick-release coupling (adapted from Liquid Laser Jetting systems n.d.).

2.6 Adapters

As discussed in the port section, port connections are either flange or threaded connections. In order to install a suitable hydraulic line in the port, a suitable adapter is installed between them, facilitating installation. The connections between the lines can be implemented in several ways. If the line size changes or it is necessary to connect several lines to the same line, the adapters shown in Figure 14 are utilized. As the size of the line changes, reducing fittings or reducing elbows are used. A t-adapter or cross adapter is used to connect multiple lines. When sharp turns are required to set the line, elbow adapters can be used. The adapters are also based on the fitting standards described earlier. (Kauranne et al. 2013, p.423, Zhang 2019, p.103)

One of the features of modern hydraulic system design is that the hydraulic line contains as few different components as possible. Multiple fittings in series can be avoided by utilizing different forms of adapters and adjustable stud-end fittings. Adjustable stud-end fittings allow the freedom to set the fitting to the desired angle with just one connection. In addition, adjustable stud-end fittings make it possible to avoid stresses in tubing or hoses that could arise from tube being in the wrong position. (Virta 2010, p.53)

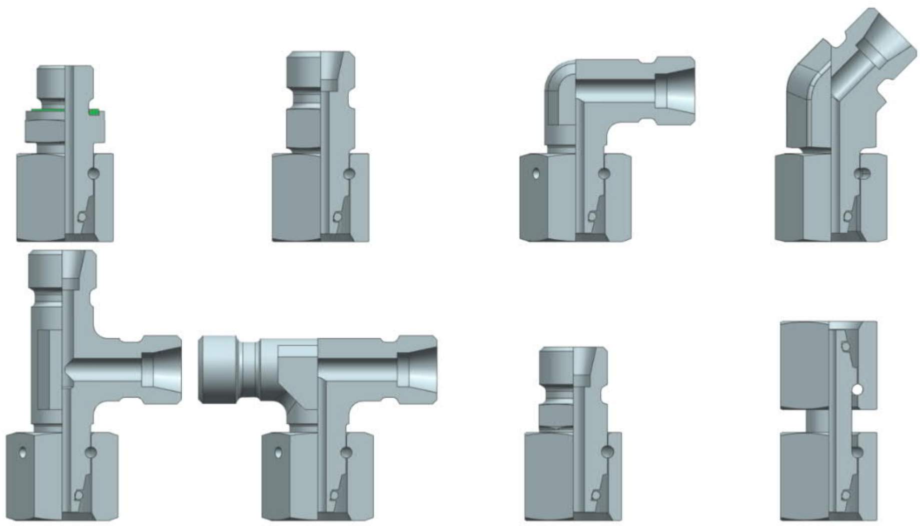


Figure 14. Section view of various swivel adapters.

2.7 Sealings

According to Airila et al. (2010, p.636), the purpose of the seals is to mitigate and prevent leakages in the connection, thereby reducing the need for maintenance and extending the life of the equipment. The sealing of hydraulic connections is generally guaranteed by two different methods or a combination of these. The first method is metal sealing for a more versatile fluid and temperature range. There is no risk of chemicals or high temperatures damaging the seal. The second method is soft sealing, which has become more common due to more demanding technical requirements (Parker 2004, p.35). In addition, Cambell (2010, p.480) reported that elastomers also prevent metal-to-metal contact and absorb motion.

Two different soft sealing materials are primarily used in standard fitting: acrylo-nitrile-butanide (NBR) and fluorocarbon (FKM). NBR is a rubber compound approved for fuel, oil, solvent, and grease. As requirements grow, more than 300 material grades have been developed from NBR. Milner (1987) commented that NBR remains the best elastomer available in terms of cost and performance for oil and fuel resistance and is still the standard option for this type of application. The main applications of NBR are power steering pumps, gearbox seals, and fuel hoses. FKM was originally developed for aerospace applications, in which high-temperature resistance is required for the seal. FKM use has increased, especially in applications in which maintenance is expensive and high reliability of the seal is required, with the automotive industry being one example. (Parker 2005, p.54, Sweet 1979, p.85)

As the use of the fittings with elastomeric sealings has increased, more cases of leakage have also been revealed. Not all seal materials can withstand the same environments. Seals may become brittle, and inappropriate material will undergo excessive thermal expansion, causing leakage. The hydraulic fluid used also limits the choice of connections. Undesirable material changes can occur in seals if the material is not resistant to chemicals. The most common causes of failure to seal are mechanical or physical impacts, temperature fluctuations, fluid, and manufacturing and installation. In addition, Walz (2016, p.224) mentioned that rubbers become unusable over time due to varying conditions. (Parker 2004, p.28, Gates 2009, p. 45, Lahtinen 2004, p.7-8 Virta 2010, p.16)

Various adhesives and sealants can be used in the fittings to prevent the loosening of connections and to seal the threads. However, the choice of sealant must be determined by whether the connection must be serviceable, as not all sealants can be opened with hand tools or without heating after they have cured. Furthermore, some sealants also act as lubricants, so their use affects the tightening torques of the fitting. Finally, the chemical resistance of the hydraulic must be considered when selecting sealants. (Parker 2004, p.46-47, Virta 2010, p.54-55)

2.8 Connection material

The material of the fittings has also influence on the selection and assembly process. In demanding environments, such as seawater or high humidity, incorrectly selected materials can corrode (Aromaa 2013. p.29). Different materials and coating materials can affect the tightening force required for the connection. (Virta 2010, p.71) Also, standards specify the material to be used for fitting. The more demanding the environmental conditions, the more resistant the material must be (Parker 2004, p. 9).

There are often only two types of materials used in hydraulic fittings, stainless steel and carbon steel. Carbon steel fittings are made from bar stock or forging and are available in various coatings, such as "Parkerized," which is manganese-based phosphatizing. The method improves the corrosion resistance of the steel and increases the wear resistance. Carbon steel is the most widely used material and has a market share of approximately 85%. The most typical applications of the material are transportation, mining and metal processing equipment. Austenitic stainless steel (306 or 316) is suitable for corrosive environments, and the most typical applications are laboratory equipment, vessel fittings and chemical and petrochemical equipment. Tubes and fitting materials should not be mixed to avoid galvanic corrosion between two different materials. (Chem n.d., Parker 2020, p.21-22, Majumdar 2002, p.449)

2.9 Supports

Virta (2010, p.92) stated that when aiming for leak-free hydraulic connections, support for tubing is one of the most important aspects of reliability that must be considered in the design. The correct type of fitting may leak due to various factors if these are not considered at the design phase. The hydraulic tubes and fittings may be subjected to vibrations and temperature variations depending on the application and environment. Chapple (2015, p.71) mentioned that in mobile hydraulics, the fluid temperature could be as high as 80 °C due to higher operating temperatures, variations which cause thermal expansion in the tubing. (Drexel et al. 2003, p. 285)

Rabie (Rabie 2009, p.6) mentioned that heavy fittings and valves should be attached to avoid tubing fatigue. Attaching the hydraulic components solely to the tubing also causes stress on the connections and pipelines. The purpose of the supports is to prevent harmful vibrations by transferring the forces exerted on the pipelines to suitable structural members. Antaki (2003, p.187) stated that experience has shown that vibration should be minimized or eliminated at the design stage by following good building practices. He justified this by the complexity and questionability of quantitative analyses.

Supports or clamps can be divided into two groups, depending on the literature: those that longitudinal movement and fixed supports. Supports that take into account thermal expansion allow longitudinal movement of the pipeline. Fixed supports, meanwhile, are classified as anchor points, cable and tube transits, and flange mounting (Fonselius et al. 2008, p.129). The support that prevents vibration and insulate structure-borne sound include a flexible element such as rubber between the tube and the support (Drexel et al. 2003, p.286).

The support distance for the tubing will vary according to the outside diameter of the tube, and the standard EN ISO 4413 (2010) presents the recommended support spacing distances (Figure 15, Table 4). Table 4 also shows that the supports should not be too close to the connections. Additionally, clamp vendors reported their spacing distance recommendations for the clamps to marine applications. Vendors have also considered tube wall thickness, unlike the ISO standard (GS hydro, 2014, p.186). A suitable material for the clamps must be appropriate to the operating conditions, and DIN 3015-1-3 provides standard series-fastening clamps (Parker 2005, p.810-815).

The clamp design phase, outlined below, should be taken into consideration:

- Changes in the dimensions of the tubes in the axial direction due to thermal expansions should be considered.
- The tube supports must be laced as close as possible to the bends.
- Vibration from other components and structures must be prevented.
- For the tube to hose connections, the support should be as close as possible to the tube-end (PSK 6706 2006, p.63).

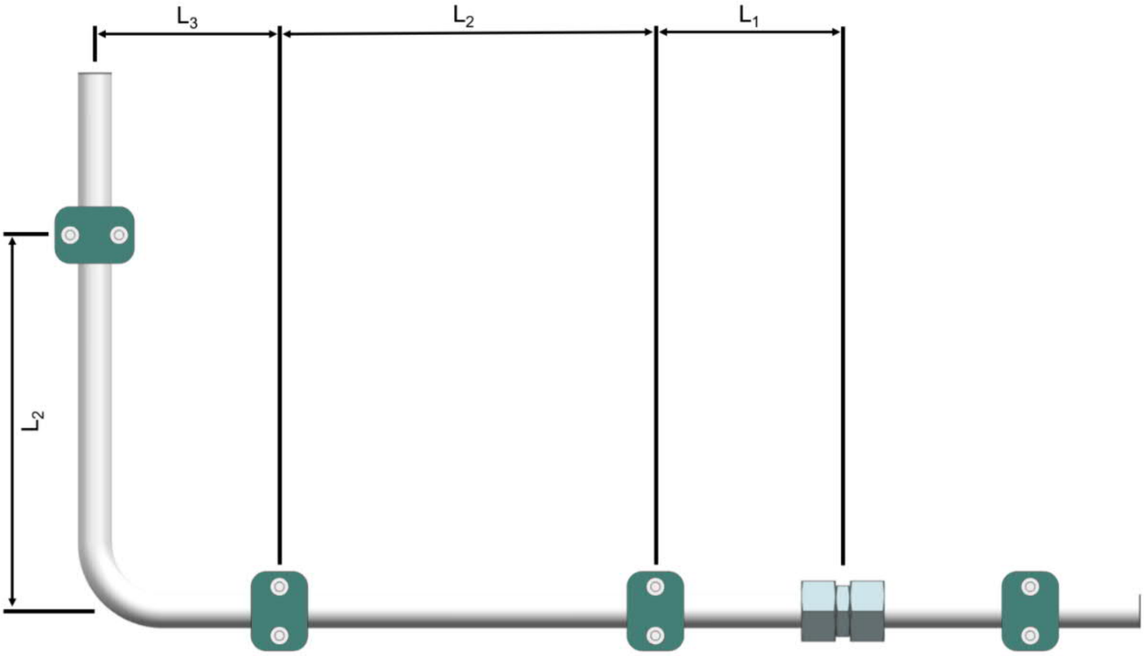


Figure 15.Spacing distance for fastening clamps (adapted from ISO 4413 2010, p.20).

Table 4.Recommended spacing for the fastening clamp.

Tube outside diameter (mm)	L_1 (mm)	L_2 (mm)	L_3 (mm)
*up to 10	50	600	100
*over 10 up to 25	100	900	200
*over 25 up to 50	150	1200	300
*over 50	200	1500	400

**Values from* SS-EN ISO 4413

2.10 Classification societies

Classification societies are organizations that develop and apply technical standards related to the design and construction of the vessel and offshore structures. The societies publish these standards as rules. Once a vessel has been built and designed according to the rules, it can apply for a classification certificate from a society, which aims to verify the vessel's structural strength and the reliability of essential components such as auxiliary equipment, the steering system, and the propulsion system. (IACS n.d., p.5, IACS 2018, p.3-5)

Fifty organizations around the world define their operations as providing some features of marine classification services. However, in 2020, there were 12 approved members of the International Association of Classification Societies (IACS) The study explicitly examines the rules of six different members of the IACS. The requirements of the societies mentioned above will be clarified, as the case company's propulsion systems have been installed on vessels approved by the following classification societies (IACS 2018, p.3-18):

- American Bureau of Shipping (AB)
- Bureau Veritas (BV)
- DNV GL (VL)
- Lloyd's Register (LR)
- RINA Services (RI)
- Russian Maritime of Register of Shipping (RS)

Societies divide tubing systems into three classes according to design pressure and design temperature, as illustrated in Table 5. Design temperature refers to the maximum temperature of the fluid and design pressure to the maximum pressure within the system. The requirements are the strictest in Class 1 and the loosest in Class 3. Classes define strongly what tube, hose, and fitting materials and models shall be used. The requirements of different classification societies can vary widely. The requirements also vary depending on the fluid used. If the hydraulic fluid is non-flammable, the requirements are not as stringent as for flammable oils. Oils that are not officially classified as non-flammable are considered to be flammable liquids. (AB 2019, p.429, VL 2019, p.82)

Table 5. Classes of tubing systems (Values adapted from all classification societies).

System	Class 1		Class 2		Class 3	
	p (bar)	t (°C)	p (bar)	t (°C)	p(bar)	t (°C)
Lubrication oil and flammable hydraulic oil	> 16	or >150*	≤ 16	and ≤ 150*	≤ 7	and ≤ 60
Non-flammable hydraulic oil	> 40	or > 300	≤ 40	and ≤ 300	≤ 16	and ≤ 200

* RS value for temperature 300 °C

The certification requirements for the fittings are similar in all categories. All fittings must have a manufacturer's identification, and the fittings used must have a manufacturer's certification stating that the fitting complies with the standard. In addition, Class-1 and -2 fittings must have class approval in accordance by the classification societies (AB 2019, p.431). If the fitting is class-approved, that means that it has passed all the test procedures set by the classification society, including the following:

- vacuum (not required for fittings with metal-to-metal seal)
- vibration
- burst pressure
- tightening
- pull-out
- fire endurance
- pressure pulsation
- repeated assembly (not required for press fitting) (BV 2020, p.353).

The hoses must comply with international or national standards and be approved by the classification society. Hose-end fittings must be type-approved. Crimp fittings should be used for hoses. Screw connections are only permitted for systems in which the working pressure is a maximum of 5 bar. The use of hoses is intended for systems that may be subject to high levels of vibration or have a pressure pulse in the system. In addition, the hose-ends must be supported when necessary (BV 2020, p.209, RI 2020, p.182).

The tubes must be in accordance with international or national standards or codes. Societies define the minimum wall thicknesses for the different tube materials as well as the minimum bending radius, which must be at least three times the OD. In special applications, such as due to geometric shapes, even smaller bends may be accepted. Societies also require that heavy components such as valves in the tubing be supported and that the tubing not be subjected to abnormal stresses. In addition, supports must not be used to align tubes. (RI 2020, p.182, IACS 2019, p.15)

The classification societies instruct that the number of fittings in inflammable oil systems be kept to a minimum to allow disassembly and installation. The fittings must also be assembled according to the manufacturer's instructions. (RI 2020, p.167, RS 2020, p.26)

Welded connections should be welded by a qualified welder using type-approved welding consumables and methods. Welds should be visually inspected, in addition to which societies define different NDT procedures for different classes of tubing. (VL 2019, p.102)

Table 6 shows examples of the different hydraulic fitting types and classification societies. The number in the table indicates the class for which the fitting is approved (AB 2019, p.471).

Table 6. Tube fittings approved by classification societies for different classes.

Fitting type	AB	BV	LR	VL	RI	RS
Bite	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$
Flare	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$
Press	3	3	3	3	3	3
Swage	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3
Welded/brazed	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$
ORFS	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$	$1^*,2^*,3$

* allowed if OD $\leq$ 60,3

3 Research methods

This section presents the research materials and methods used in the thesis as illustrated in Figure 16. The research method is a qualitative case study, whose the starting point is to look at an individual case as diversely as possible. This study aims to form a clear understanding of the characteristics of the phenomenon under study. The material collected for the case study consists of internal documentation, known hydraulic component vendors, and interviews.

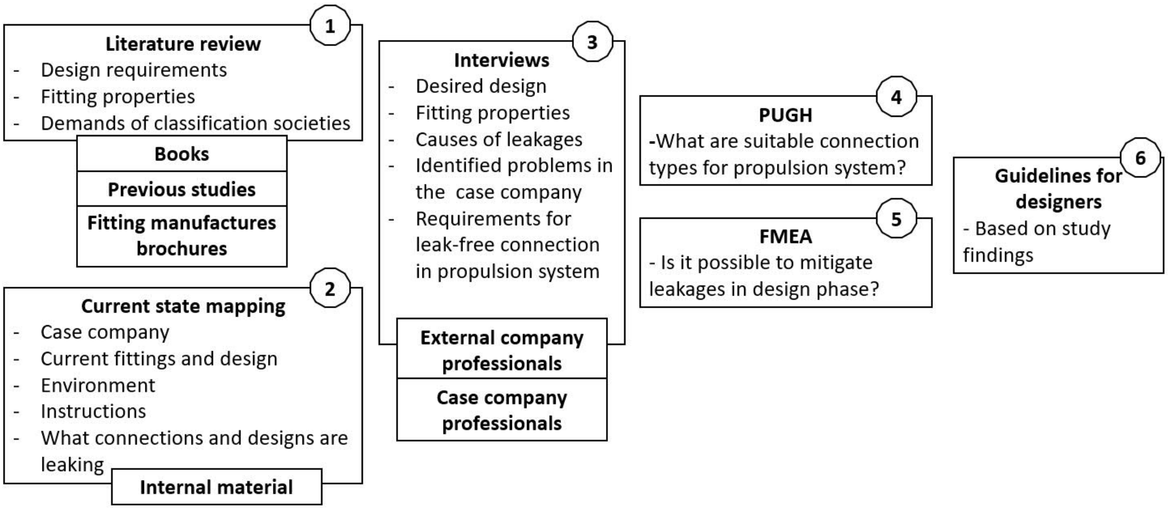


Figure 16. Structure of the research methods.

3.1 Interviews

The information for the case study is collected through semi-structured qualitative interviews. Predetermined questions guide the interviews, but the structure of the interviews is free, which encourages open discussion.

The company’s internal interviews aim to identify the shortcomings of the current design. The interviews aim to determine what features research and development, service, product support, and production departments require from the design so that previously unfavourable installations are not implemented in the future, and what features are desired from the fitting. In addition, six hydraulics professionals from external companies were selected for interview. Interviewees were asked questions about the case company's current designs and the problems that they encountered. The questions were used to find the exact root causes of the current leakages. The interviews determine the case company's needs of the for the required design and fittings. The interviews also served as a brainstorm for the creation of the FMEA, helping identify potential design pathways and causes of failure and determine whether external professionals have found a solution to leakages with a specific fitting model or design.

3.2 The Pugh matrix

Fittings are scored and evaluated using the concept screening method developed by Stuart Pugh in the late 1980s. Concept screening often called the Pugh matrix (PM) was originally developed to delineate and develop concepts based on needs or requirements. However, the use of the method can expand to enable different products to be compared, as it is possible to limit the number of products to be evaluated. The matrix provides a simple approach when multiple alternatives exist. If the concept screening method does not provide a clear resolution between different products, the concept scoring method can be applied. (Burge 2009, p.1-2, Ulrich & Eppinger 2015, p.152-162)

Defining requirements is a vital part of the selection process as it involves the evaluation and scoring of the concepts or products to be selected for further review. The term requirements may vary within companies. Some talk about engineering characteristics and some about product requirements or just specifications or technical specifications. Without accurate knowledge of the requirements and needs, it is not easy to move forward systematically with the required goal in mind. The aim of using the PM is to select the fitting that best meets the selected requirements. (Ulrich & Eppinger 2015, p.92-93)

A combination of concept screening and concept scoring methods is used to compare the fittings. The methods include six steps:

- The first step is to define the fitting requirements of the case company.
- The second step is to determine currently used fitting, which becomes the benchmark against which all other examined fittings are compared.
- The third step is to rate and rank different fittings using better than (+), same as (0), and worse than (-) specifications for different properties.
- The fourth step is to re-evaluate the fittings with the most points by allocating 100 percentage points among the requirements.
- The fifth step is to rate and rank the fittings that scored the most points, using a scale from 1 to 5.
- The sixth step is to select the most suitable fitting.

3.3 FMEA

The research method used to evaluate current designs in the study is a reliability improvement method developed in the 1950s in the aerospace industry, namely, Failure Mode and Effects Analysis (FMEA). The use of FMEA has expanded from the aerospace industry to the automotive industry, and today, FMEA is required by various quality management system standards. Initially, FMEA was developed for equipment and material failures, but it can be applied to various technology categories, such as electrical, mechanical, and hydraulic. Generally, four forms are used in the FMEA, as illustrated in Figure 17. (Gullo & Dixon 2017, p.153, Stamatis 2003, p.41&224)

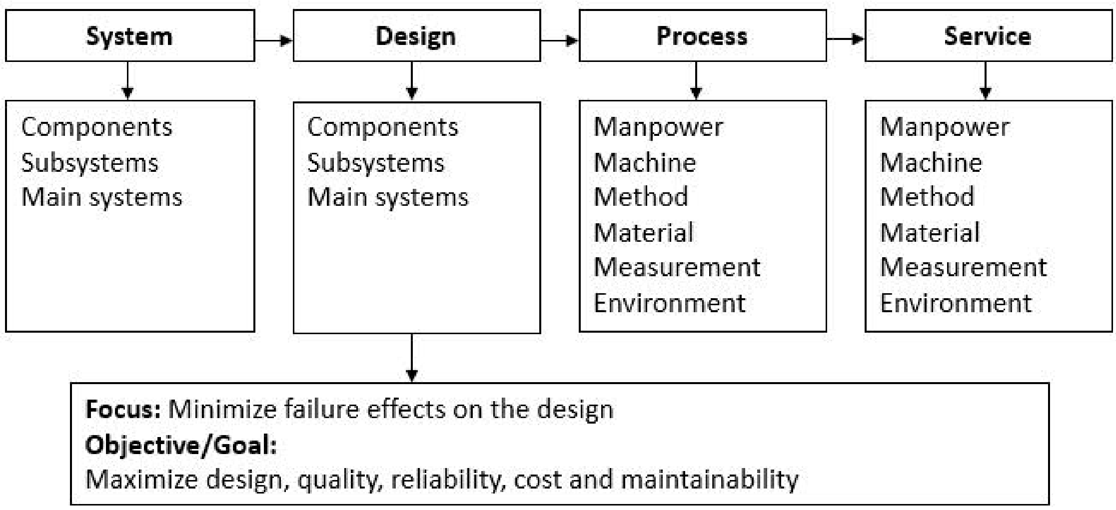


Figure 17. Forms of FMEA (adapted from Stamatis 2003, p.41).

The study applies design FMEA as the research tool to eliminate the potential cause of failure and prevent errors from reaching the customer at the design phase. Therefore, the aim is to achieve the highest quality, durability, and reliability. Stamatis mentioned that when improvements to the current system, design, process, or products are considered, FMEA should be applied. The FMEA helps plan the path to continuous improvement, and its use can begin at any stage of the process. As FMEA is known as a tool for continuous improvement, it should be updated as often as necessary. (Stamatis 2003, p.22-24, Heikkinen 2020)

FMEA is based on qualitative guidelines and should not be performed by a single researcher. Stamatis stated that if FMEA is performed alone, the problem is that the results are not discussed later. Depending on the analysis, a suitable team for the project should be assigned to the FMEA. Problems can be unique, and solutions should be considered multidisciplined and cross-functional. (Stamatis 2003, p.24)

FMEA does not have a standardised format; instead, each company has its format that reflects the needs of the organisations. In this study, FMEA consists of nine phases, as illustrated in Figure 18:

1. The first step is to determine the component, subsystem, or main system to be analysed using FMEA.
2. The second step is to identify a potential failure mode that may occur. The failure mode indicates how fault occurs. The failure mode that is specified may also occur in the higher-level subsystem or the main system.
3. The third step is to determine the potential failure causes, that is, the root cause of the failure chain. The root causes indicate design weakness that can lead to the failure mode.
4. The fourth step is to determine the potential failure effects, which means the immediate effect of the failure mode.
5. The fifth step is to identify the current detection method, that is, to answer the question of how to determine that a failure has occurred. The detection method prevents failure from occurring before the product reaches the customer. The key points of current control consist of identifying or detecting the failure, eliminating causes, and reducing the impacts of failure.
6. The sixth step is to determine the Risk Priority Number (RPN) for each component separately. The RPN measures relative risk or the priority of failure. The RPN is formed by assigning a rating from 1 to 10 for severity (S), occurrence (O), and detection (D) to the failure mode of each component and multiplying the numbers together. Occurrence refers to the frequency of the failure, severity to the effect of the failure, and detection to the ability to detect the failure with current detection methods. The Severity, Occurrence, and Detection rating scales used in the thesis were modified to fit the purposes of the case company, as shown in Figures 19–21.
7. The seventh step is to consider the recommended actions, in this study, a replacement design with which the RPN can be reduced.
8. The eighth step is to model the replacement design as a recommended action/action taken.
9. The last step is to re-evaluate severity, occurrence, and detection for the new design, after which the RPN is recalculated (Dyadem 2003, p.41-45, Stamatis 2003, p.133-151).

The goal of the FMEA is to reduce critical RPN values by reducing the occurrence or severity or improving the detectability of the failure. The higher the RPN number, the more likely a fault is to occur. (Stamatis 2003, p.148)

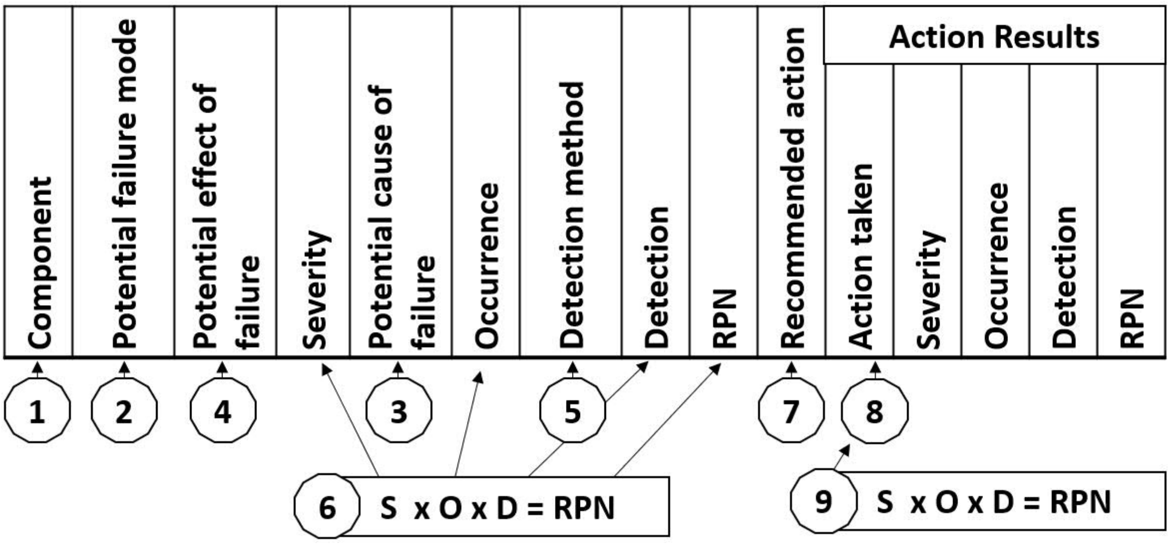


Figure 18. FMEA phases in study.

Rank	Criteria	Effect
10	Component failure resulting in hazardous effects almost certain. Non-compliance with government regulations	Maximum Severity
9	Component failure resulting in hazardous effects highly probable. Compliance with government regulations in warning.	Extreme severity
8	Component inoperable but safe. User very dissatisfied	Very high Severity
7	Component performance severely affected user very dissatisfied.	High severity
6	Component operable and safe but performance degraded. User dissatisfied	Severe
5	Reduced performance with gradual performance degradation. User dissatisfied	Moderate
4	Minor effect on component performance. User slightly dissatisfied	Minor
3	Slight effect on component performance. Non-vital faults.	Slight
2	Negligible effect on component performance. User not affected.	Very slight
1	No effect	None

Figure 19. Severity rating scale (adapted from Crowe & Feinberg 2001, p.177).

Rank	Criteria	Occurrence	Occurrence per component
10	Failure almost certain.	Extremely Likely	1 in 2
9	Very high number of failures likely.	Very High Likelihood	1 in 3
8	High number of failures likely.	High Likelihood	1 in 5
7	Moderately high number of failures likely.	Moderately High Likelihood	1 in 10
6	Medium number of failures likely.	Medium Likelihood	1 in 80
5	Occasional failures likely.	Moderately Low Likelihood	1 in 200
4	Few failures likely.	Low Likelihood	1 in 400
3	Very few failures likely.	Very Low Likelihood	1 in 1500
2	Rare number of failures likely.	Remote Likelihood	1 in 10000
1	Failure highly unlikely.	Extremely Unlikely	1 in 100000

Figure 20. Occurrence rating scale (adapted from Crowe & Feinberg 2001, p.178).

Rank	Criteria	Detection
10	Screening cannot detect a potential failure mechanism, or there is no method	Almost impossible
9	Screening probably will not detect a potential failure mechanism	Very Low
8 7	Screening not likely to detect a potential failure mechanism	Low
6 5	Screening may detect a potential failure mechanism	Moderate
4 3	Screening has a good chance of detecting a potential failure mechanism	High
2 1	Screening will almost certainly detect a potential failure mechanism	Very high

Figure 21. Detection methods rating scale (adapted from Crowe & Feinberg 2001, p.179).

4 Case study

This section clarifies the current state of the case company's procedures, instructions, and hydraulic connections to understand why it is necessary to improve the reliability of hydraulic connections in a propulsion system. The data were collected by interviewing the personnel and by examining the internal material of the case company.

4.1 Case company

The case company is specializing in manufacturing propulsion systems. The company's services include propulsion system design, sales, manufacturing, service, and dry-docking operations. By 2020, the company has installed propulsion systems in more than 200 different vessel or offshore facilities. In total, more than 500 propulsion units have delivered globally.

The hydraulic system of the propulsion unit consists mainly of low-pressure lubrication oil and seal system lines. The unit may be equipped with a brake or/and high-pressure hydraulic turning system. In lubrication and sealing systems, the pressures are in the range of 0–10 bar, and the maximum temperature of hydraulic oil is 100 °C. In the braking system, the maximum operating pressure is 157 bar. The highest pressures are in the turning system, from which 300–1100 bar was measured, and the maximum temperature of the hydraulic oil is 65 °C. The case company uses four different hydraulic oils: polyalphaolefin (PAO) synthetic, semi-synthetic, mineral, and biodegradable oils. Oils are mainly flammable.

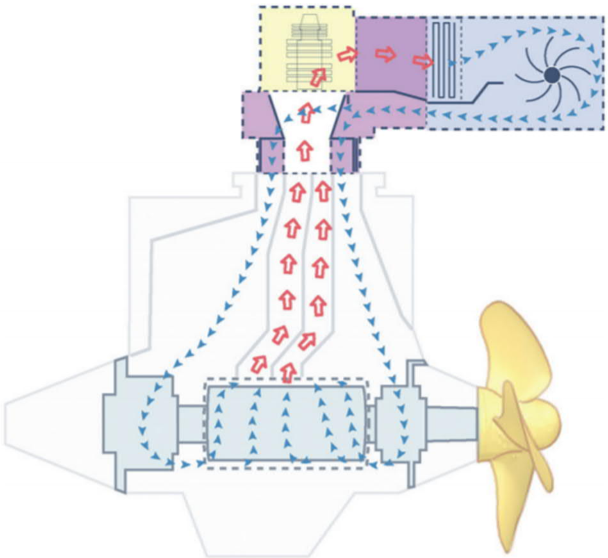


Figure 22. Propulsion system.

Propulsion system conditions vary during operation. Vessels with a propulsion system installed sail around the globe, which means that the temperature and humidity are not constant. The propulsion system consists of a cold and a hot side. The cold side refers to the side of the propulsion system into which cool air flows, and the hot side to the one into which warm air flows out of the stator, as illustrated in Figure 22. The maximum relative humidity of the system is reported as 96%. The case company has collected data on temperatures and humidity from the cold side. The measurements were performed in Florida and the Caribbean at a seawater temperature of about 25 °C. The temperatures varied from 25 °C to 42 °C and the relative humidity from 27% to 62% in the measurements. The maximum temperature of the hot side is 80 °C. In addition to this, the corrosive phenomenon may be increased by the seawater on the cold side (Ilonen).

The vibrations also vary in the propulsion system. Varying sea conditions such as waves and sea ice increase vibration in the system, so vibrations are not constant. The specific frequencies transmitted by the propeller are between 3.5 Hz and 5 Hz. Near the propulsion itself, the vibrations are highest, and the vibrations decrease the higher in the propulsion system. However, there are no measurement data of the vibrations or amplitudes of how vibrations affect the different connections.

The hydraulic lines consist of tubes and hoses. Lines are made entirely of rigid thin-walled cold-drawn AISI 316L (EN 10216-5) tubes and flexible steel-wire braided hoses. Hydraulic lines may also consist of combinations of both. Some of the shorter lines are assembled only using different types of fittings and adapters. Threaded fittings vary from metric to BSPP and NPT. Metric threads are commonly used in tube- and hose-end fittings and BSPP and NPT threads in port connections. The connections inside the propulsion system are mainly made of stainless steel. It is possible for seawater to enter specific systems, which would have a corrosive effect on steel fittings. Stainless steel is also used in the propulsion system because the material is not magnetic, thereby preventing electromagnetic radiation from affecting the electrical systems of the propulsion system.

The company mainly uses bite fittings in tubes and DKO fittings in hoses. Bite fittings are sourced from the same manufacturer, but adapters, stud-end, and hose-end fittings are sourced from different manufacturers. The stud-ends are used primarily in the company's machined products, in which case it is possible to determine which port model is selected in the design phase.

Used fitting types in the propulsion system

- Tube-end connection, Bite with elastomer seal (Metric)
- Tube-end connection, Flange (Metric)
- Tube-end connection, Weld-on straight fitting (Metric)
- Hose-end, Flange (Metric)
- Hose-end, DKOL 24° (Metric)
- Hose-end, 24° cone (Metric)
- Stud-end, Form E (BSPP)
- Stud-end, Tapered (NPT)
- Stud-end, bonded seal (BSPP)
- Hose-end, quick-release fitting

Factory installation conditions are a clean environment, while during service visits, the installation environment can be oily and poorly lit. Propulsion systems are assembled at the factory, which means that the installation phase can be completely different from service or docking installations. At the factory, the installation sequence can be completely different, leaving space around the components. The space inside the propulsion system also varies depending on the model. The installation tools are correct at the factory, but during service visits, it often noticed that there is no right kind of tool included that would fit the fitting. Service tools often consist of tube tongs and spanners and an adjustable spanner. At the factory, the installation is not as tightly tied to the schedule as at service or docking visits, in which case the schedule may be limited. When time is limited, and there are several objects to pass through, the number of errors increases during service work.

The case company's current instructions regarding tubes, hoses, and fittings primarily relate to manufacturing, purchase, and assembly instructions. The production has instructions, including the routing and supporting of the tubes, hoses, and installation bite fittings. The instructions for the bite fittings are prepared by the company and not by the fitting manufacturer. Stud-end fittings do not have tightening instructions. DKO adapters and hose-end guidelines for tightening procedures entered production in early 2020. The site assemblers have no guidance on the tightening procedures for the fittings. Deficiencies in translations were also found in the current factory guidelines. If the installer reads only the instructions in Finnish, then the thread lubrication performed in the field and factory installations may not be done, as lubrication is not mentioned in the Finnish instructions. During the interviews, it became clear that no detailed instructions have been prepared for pipeline designers in implementing hydraulic connections or what in determining the preferred fitting for hose and stud-ends. Only tube-end bite fittings have previously specified. In addition, designers do not have guidelines on the situations in which they should use which type of connection. However, the designer of the company has generally unwritten design rules.

The company only uses locking agents for stud-end fittings and valves. Previously, the company used a sealant that was impossible to open with hand tools after curing, which complicated work in the field installations. The sealant was changed to a different type, making it possible to open the connections under field conditions. Stud-end threads are instructed to be assembled with the Loctite 567 sealing compound being used with threads of 3/4" or larger, while Loctite 542 is preferred for smaller threads. Hose- and tube-end connections are instructed to be assembled with the assembly paste. In addition, connections that have been tightened and locked with a sealing compound material are marked with a red paint marker. Tightened fittings are marked with a green paint marker.

The company has manufacturing drawings, and a bill of material list for each design is integrated into Product Data Management (PDM). Designs and fittings can be found in the propulsion system model or vessel folder. The fittings also have their standard item documentation, which can be used to check the components used in the company. The purchase department has its purchase document list, which is used to purchase or identify the products. In addition, each fitting is individually named with the item name created by the company.

4.2 Current state

Leakages are detected in current connections during service visits, site survey inspections, or by the customer. The case company does not specify leaking connections in more detail in any single list. However, observations of leakages can be found in various documents. The observation of a more precise leakage point is hampered by the fact that there is no picture or information about where the fitting leaks. Examination of leaking fittings was complicated because, at some designs, there are several different fittings in a row, making it difficult to detect the exact point of leakage from the images, as shown in Figure 25. In addition, airflows within the propulsion system make it challenging to detect oil leakages, as oil can migrate elsewhere.

Twenty subassemblies were mapped from 45 different vessels to determine the type of fitting and the number of leaking fittings. Leakages were detected in the propulsion systems of 26 vessels. Leakages were eventually found in 42 propulsion units. More detailed information about the fittings was found in the manufacturing drawings and bill of material lists using product data management. The latest designs were also included in the review to obtain information in as much real-time as possible on existing fittings. Finally, the data about the leaking connections was collected in an excel file. The exact number of leaking fittings was illustrated eventually using the Pareto 80/20 method.

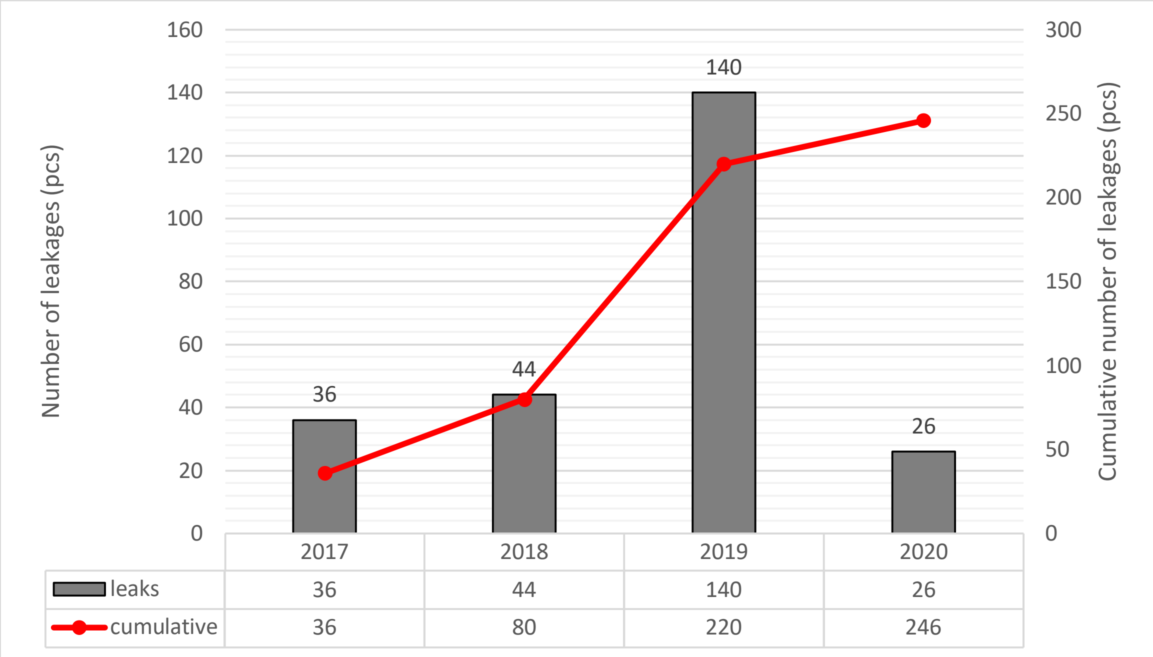


Figure 23. All leakages from 2017 to 2020.

The case company had information that fittings are leaking in the propulsion system, but no statics on this had previously been collected. The purpose of current state mapping was to determine whether the leaking fitting has a common root cause, making it possible to prevent leakages as early as the design phase. All external oil leakages were detected visually.

Figure 23 shows all internal leakages in the propulsion system from 2017 to April 2020. The red line represents the cumulative number of leakages. There are 246 leakages in total, and in 2019, the most significant number of leakages was detected. One reason for the increased number is that the reporting of leakages has improved, and these are documented in the report with photos. The earlier the data, the less accurately the leakages were documented. Older reports mentioned that the tubing was leaking, but there was no more specific clarification as to which fitting was leaking. All external leakages caused by fittings were included in the review. However, Figure 23 does not provide clear information on which fittings were leaking.

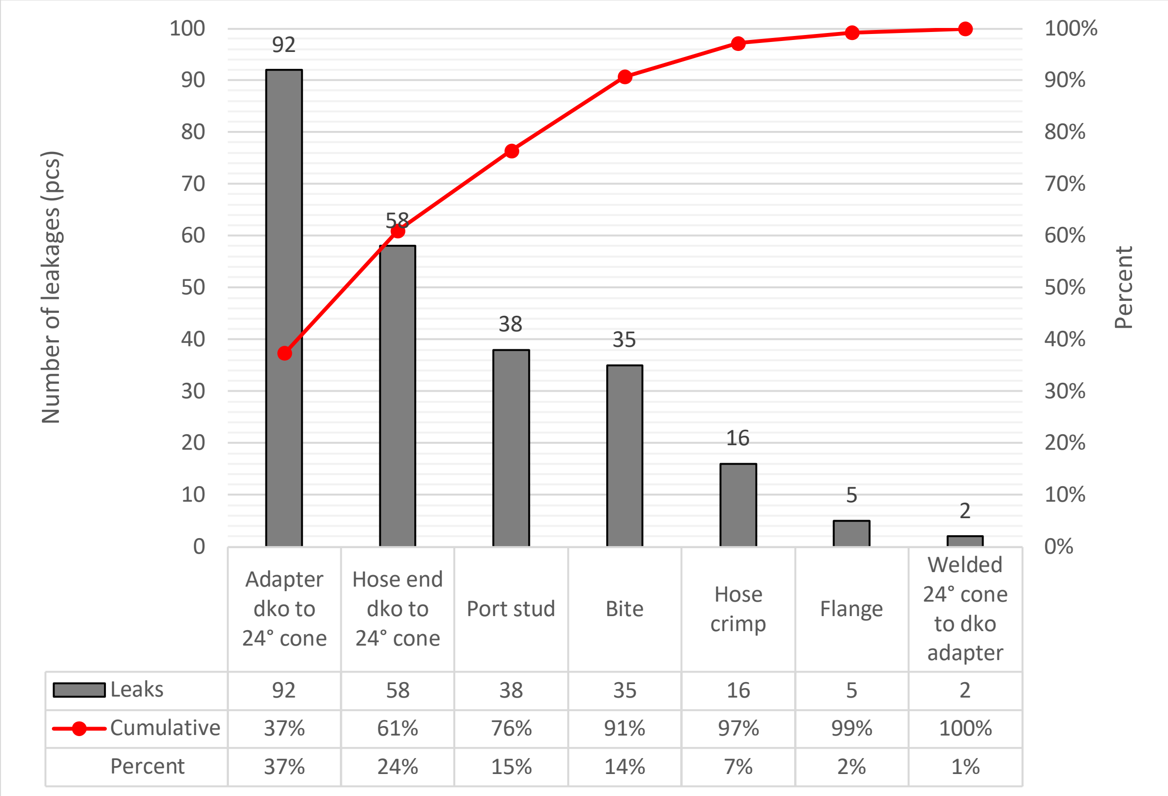


Figure 24. Pareto chart of all leaking fittings.

The leakages were further specified to determine which fittings caused the leakages. Figure 24 indicates that the most leaking fitting types are DKO and 24° cone adapter fittings, with the total number of leakages coming to 92. The same type of fitting caused leakages the second most frequently in hose-end fittings, at 58. Stud-end fittings leaked the third most in current systems, and bite fittings the fourth most. The individual specification of the fittings is the first step in identifying leaking fittings according to patterns. The root causes of leakages in these fittings are validated by examining previous studies and the current process.

Figure 25. Components from Design 2 (left) and Design 1 (right).

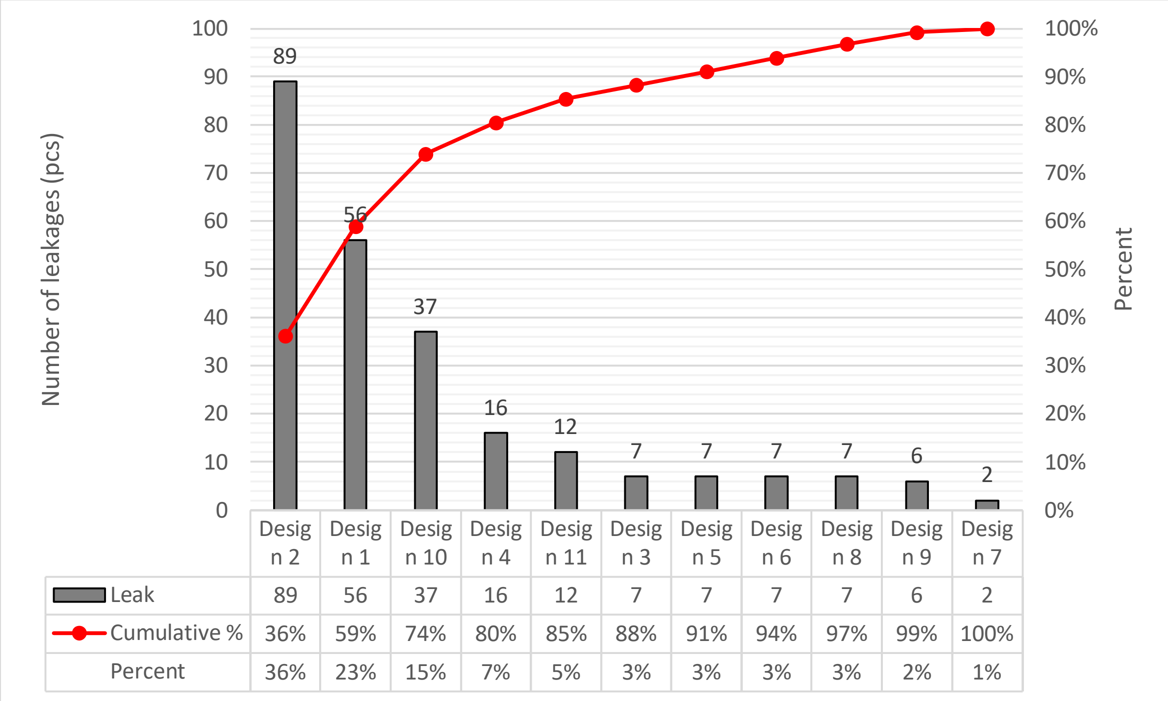


Figure 26. Leakages by design illustrated with as a Pareto chart.

The most leaking designs were mapped, as shown in Figure 26. This figure provides a much more comprehensive picture of the types of designs that leak in a propulsion system. The figure shows that four designs cause 80% of leakages. Design 2 stands out clearly in the figure, with 89 leaking connections. Design 2 involves more fittings to build a single line than other designs and consists of 15 components. In Design 1, the second most leakages were detected, at 56. Design 1 and 2 have uniform factors that can cause leakages in connections. Both use bite fittings, rigid tubes, DKO adapters, and Form E stud-end fittings. The third most leaking connections are in Design 10 , as illustrated in Figure 27. This design has since been revised, replacing the bite fittings with weld-on nipples, but connections are still leaking. The latest design does not have rigid tubes that could potentially cause stresses or stresses in the connections. In addition, the connections are located at the area where oil is migrating with cooling air, which makes it difficult to detect the exact leakage point. In Design 4, 16 leakages are observed. This design differs in its connections from those previously presented. Design 4 is implemented with NPT stud-end fittings and hoses. One observation is that the most leaking designs are located on the cold side, where ambient temperature variations are small and system pressures are 10 bar or lower.

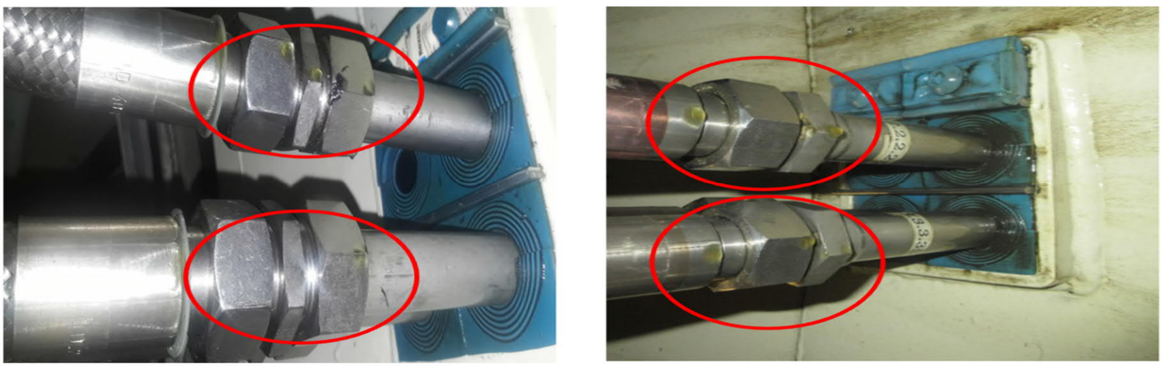


Figure 27. Leaking connections from Design 10 inside the propulsion system.

5 Results

This section presents the results of the interviews. The results of the interviews are presented in the same order as the questions were presented. Finally, the results of the interviews are discussed and compiled in a Pugh matrix and the FMEA.

5.1 Interviews

Interviewees (Table 7) were initially approached by email. Appendix 1 contains the interview template, based on which the questions were asked to the interviewees. Two people answered questions in the form of an email conversation. Ten people were interviewed by phone. The duration of the interviews varied from one to two hours. Individuals from the case company were also interviewed to refine the interviews' findings throughout the study. The interviewees were divided 50/50 between the case company and external companies. Each external interviewee was selected from various companies and expert positions to obtain a wide spectrum of different views. All the case company interviewees had been working for the company for several years, and the external professionals had more than ten years of experience in hydraulics.

Table 7. Interviews.

Interviewee	Company	Title	Date of interview
A	Case company	Product Support Specialist	14.4.2020
B	Case company	Senior Technical Specialist	15.4.2020
C	Case company	Propulsion Service R&D Manager	17.4.2020
D	Case company	Lead Engineer	22.4.2020
E	Case company	Mechanical Lead Engineer	27.5.2020
F	Case company	Production Supervisor	27.5.2020
G	External company	Development Manager	13.4.2020
H	External company	Product Manager	17.4.2020
I	External company	Chief Executive Officer	17.4.2020
J	External company	Product Sales Manager	26.5.2020
K	External company	Sales Manager	26.5.2020
L	External company	Chief Executive Officer	20.4.2020

5.1.1 Design

Interviewee A desired that the design has as few fittings as possible and different fittings to allow the connections to be brought out, as the current designs have been made quite cramped. Moreover, in some places, the fittings are in such tight spaces that it is not possible to tighten the fitting without disassembling other parts from the front. Interviewee A commented that in the design phase, the propulsion system itself was designed first, and the last step is to consider only how the hydraulic connections could fit in it.

Interviewee B noted that in field installations, he had noticed that another serviceman might assemble fittings from several different components in succession using multiple adapters to match the fittings. Interviewee A added that there are lines in which ten fittings can be aligned in series. In addition, some of the weldable fittings are assembled with separate adapters, and the weldable fitting is not made directly with the right type of fittings. This was especially emphasized in retrofit installations.

Interviewee A commented that hose supports planned in the design phase are not always implemented in field installation. For instance, the company's DIN 3015-1-3 type supports have several components, including nuts and bolts. Installation in an awkward location is often not done, as smaller components such as bolts and nuts have the potential to drop during installation. A dropped component can become lost in the propulsion system and can cause more severe damage.

Interviewee G pointed out that stacking fittings in series is a common problem in the hydraulic field, mainly due to a lack of professional skill. Design is often decentralized to numerous offices without a tube-fitting professional. This is reflected in the fact that professional installers reject designs and build up the line with fewer fittings. Interviewee G highlighted that this especially prominent in various projects. The range of fittings on the market is extensive, and with a little thought, the number of connections in the system can be reduced. Interviewee L highlighted the project departments as important for the design of the connections and that visiting in the field is essential. Interviewee A pointed out that designers could visit a field or factory, making it easier for them to outline the overall picture more clearly.

Two professionals directly answered as to the number of consecutive components. There should be two to three fittings in a row. If the number of fittings exceeds this, consideration should be given to whether the connection could be made differently by using a hydraulic manifold block or by machining that connection in one piece. Interviewee I specified that the block should be selected so that the distance between the port end is large enough for the stud-end to be replaced. Interviewee L added that, however, it might be necessary to use different adapters to give the keys space for the tool when using blocks. Interviewee H mentioned that there is no actual limitation on fittings but, in general, as few fittings as possible should be used. Interviewee H pointed out that adjustable fittings allow the number of fittings to be reduced. The rest of the interviewees recommend the literature's observations that the fewer the connections, the more reliable the line. However, Interviewee I pointed out that there are cases in which more fittings could provide better accessibility to the connection.

Due to the compact size of the propulsion system, the hydraulic lines required in the system are very short. This led to the question of whether there is a rule for when to use a hose or a tube. Interviewee J pointed out that there is no rule as to whether when a line be designed with a hose or with a tube. However, the interviewee added that if tubes with an OD of less than 24 mm are used, bends should be designed to facilitate alignment, as the bends allow the tubes to be aligned by hand. In addition, Interviewee J specified that when using hoses, adequate routing is essential to leak-free connections. In improperly routed hoses, the inner ferrule of the crimp fitting wears the inner surface of the hose, causing leakages.

5.1.2 Space and installability

Each discussion on the reliability of the fittings also led to a discussion on the installability of the fittings. Interviewee A commented that it would be simpler to change the hose connections. The entire hose with its fittings could be changed quickly in field conditions, but replacing a rigid tube is not simple. The installation of the bite fitting in the propulsion system is challenging, as space is confined, and not all the keys fit in the installation site. An individual from the case company clarified, *"I wish good luck to the person tightening bite fitting if there are no pre-assembly tools on-site at the site"*.

The challenges posed in the installation phase by rigid tubing emerged from the interviews with the production personnel. Interviewee F said that rigid, short tube fittings are particularly challenging to install in the factory because the tube remains unfavourable due to rigid material of the tube. Interviewee F added that in Designs 1 and 2, the fitting can be opened and tightened several times to make the connection tight during testing. It also emerged that often, after testing, the bite fitting may loosen and need to be retightened.

The use of tubes emerged in similar applications as in excavator booms. Easy-to-install and low-bend lines should be designed with rigid tubing connected by hoses because the hoses are easy to replace if they begin to leak. In addition, Interviewee D mentioned that machinery such as oil circulation pumps should be installed. The design should ensure that it is first possible to install the rigid tube itself, after which the machine can be installed in the tube. It should be possible for the machine can be positioned on the correct target in the machine bed. The propulsion systems are not identical in dimension, and the parts do not sit in the same way on all objects without field modification.

When asked how the installability/installation skill requirements of the fittings vary, Interviewee G commented that the most reliable fitting is when installation errors are not reflected. The fittings to which the installer’s skills or systematic errors are least reflected in tube-end connections could be formed tube-end fittings. However, Interviewees K and L commented that there are no fittings in which the installer’s experience would not be reflected in the connection’s reliability. In addition, Interviewee J commented that it is possible to make each fitting under field conditions, but almost all fittings require a separate machine, while a bite connection can be made without a machine.

The discussion also expanded to the tightening procedure of the fittings. Interviewee L suggested that over-tightening and under-tightening alone could not be prevented by the fitting, as the installer's experience is reflected in all the connections made. Each fitting has a unique tightening procedure that must be followed; for instance, fittings each have a specific tightening torque. Interviewee L pointed out the agricultural equipment factory in Finland and said the factory has torque wrenches of several different sizes and models. Each fitting is tightened to the torque recommended by the fitting manufacturer. Interviewee J pointed out that in some fittings, over-tightening is prevented, but no fitting prevents under-tightening. Interviewee L also highlighted fundamental errors, specifying that errors occur when the installer believes that he or she knows how to install connections but is incorrect. Interviewee L concluded that a skilled installer knows what he or she is doing.

Interviewees from the case company repeatedly mentioned they do not necessarily have the most qualified installers. Interviewees A and B pointed out regarding the tightening procedure in field installations that fittings are often tightened, as tight as they can be, with a very long extension arm. One interviewee from the case company commented that when he had visited the factory, he observed incorrectly installed bite fittings. He mentioned that the fittings had often been left loose from the beginning when he observed the tightening procedure.

As the fitting tightening procedures vary, the interviewees were asked whether fittings should be chosen in such a way as to favour a fitting from the same manufacturer. In this case, the interviewees stated that the choice to use fittings from the same manufacturer is also directly reflected in the installation procedure. Interviewee J mentioned that hose and tube connections from different manufacturers might have different coatings, so it is not possible to specify the correct tightening torque for those connections. Fittings from the same manufacturer should be used because this ensures that the tolerance ranges are the same and that the fittings have been tested with each other. Interviewee H replied that it is recommended for all components of the connection to be from the same manufacturer. Interviewee I agreed, stating that different manufacturers have the same type of fittings but that the same manufacturer should be favoured. Interviewee I pointed out that using the same type of connection facilitates documentation, installation, and modification. It is possible to directly install the same type of fitting as the previous fitting.

Interviewee B pointed out that the availability of the fittings is a necessary feature, as there are situations in which the wrong part has been delivered to the vessel. Alternatively, it is necessary for a specific adapter to complete the installation. When the fitting is widely available, several installation steps can be sped up. In addition, if the fitting is very common, it can be found on the customer's premises. Regarding the serviceability of the fittings, Interviewee H added that it is worth choosing the best available fitting. Interviewee J mentioned that the best available fittings are flange and bite connections. Interviewee G highlighted the elastomer seal in terms of serviceability.

5.1.3 Environment

With respect to temperature fluctuations or humidity, Interviewee H did not see problems that would cause fitting leakages. The sealing materials are located inside the fitting in machined pottery, in which moisture has not been seen to affect the seals. Interviewee H saw the ambient temperature variations of the propulsion system as minor. For temperature fluctuations, Interviewees H and G highlighted mobile applications such as forest machines, in which temperature fluctuations are large compared to the propulsion environment. Interviewee G pointed out that, in general, fittings containing an elastic seal are found to solve hydraulic leakage problems. However, as the elastic parts harden and age, leaks begin to occur. NBR rubber hardens in a few years when the oil/environment temperature is high. FKM material is more durable than NBR, and more expensive fittings come standard with this type of seal.

The propulsion system is also subjected to dynamic stresses, in which case the connection must withstand vibrations. The loosening of the fittings was a critical issue for the reliability of the fittings in providing the longest possible life cycle without leakages. There was variance in the interviewees' comments on this topic. Interviewee H mentioned that, in principle, no fitting need to be retightened, but if the vibration is strong, then locking agents should be considered in those places in which they are really necessary. Interviewee J said that when properly tightened, the fittings do not need retightening. For instance, certain manufacturers do not recommend using locking agents at all. Interviewee K pointed that metric threads do not open as easily as UNF or inches threads. Interviewee L pointed out that vibration can loosen all fittings, and this interviewee's company has prevented fittings from loosening under highly vibrating conditions with a locking agent. Interviewee G mentioned that retightening is usually not done until there is a leakage, using as an example paper machines with several fittings and no one retightening them. Interviewee I had not heard that the fittings might need retightening but saw the possibility that the serviceman may tighten the fitting, which would not be reported separately or be seen in any operation documentation. Interviewee I pointed from the DKO fittings that these types of connections are suitable for vibrating conditions, as the rubber increases the friction of the fitting, preventing it from opening. Among the interviewees, the most vibration-resistant fittings were flange, ORFS, and formed tube-end types.

Environmental conditions vary in the propulsion system, and the issue of purity was also raised. The interviewees were asked how the installation conditions affect the installation of the fitting. Interviewee L mentioned that cleanliness is essential within the system itself and that it would be possible to do a separate study on the subject. However, he referred more to the internal cleanliness of the system. In the installation phase itself, the hydraulic fluid should not act on the flat surfaces of the fittings if the threads themselves are clean.

Low-pressure connections have been found to leak in the system. The literature mentioned that leakages in low-pressure connections are reported more than in high-pressure connections. Interviewees L and I shared a common view that there should be no problems with low-pressure if the fitting is installed correctly. Interviewee G specified that low-pressure connections are often treated with less care than high-pressure connections, and due in part this, more leakages in low-pressure lines are reported than in high-pressure lines. Interviewee G also commented that the bite with the elastomer seal should guarantee leak-free operation even at low-pressures. However, Interviewee H commented that for the ORFS fitting, that is an interesting question, as sealing is also based on pressure.

5.1.4 Case company current leakages

To investigate the problems that arose in the case company, the types of fittings used in the company were introduced, and the interviewees were asked what could cause connection leakages.

Several bite with elastomer seal fittings leaked, as shown in Figure 24, and the questions also inquired as to the installation procedure for bite fittings. Interviewee F reported that the tubes are sawn and deburred, after which the bite fittings are prefabricated in the tubing with a pre-assembly machine that presses the cutting ring into the tubing. The fitting is then tightened according to the company's instructions. Interviewee B specified that there had been problems in the preparation of the tubes in the past. The sawing of the tube had previously been done with the wrong type of saw, leaving poor surface quality and causing longitudinal scratches on the cutting surface, as illustrated in Figure 28. However, this problem was solved in 2020 by acquiring the right kind of tube cutting machine for production. These defects can cause leakages, which explains the relatively high leakage rate of the bite fitting.

Interviewee H suggested looking for reasons for the installation procedure itself. A bite fitting (Voss ES-4VA) is basically based on metal-to-metal sealing, in addition to which the seals provide additional security against leakage. Interviewee H added that, however, bite fittings (ES-4VA) are also accurate in that their counterparts are made to the same standards. It has sometimes been found that bite fittings do not seal on externally threaded hose-end fittings from other manufacturers. Finally, Interviewee H highlights the importance of fitting lubrication and the use of precision steel tubing. Sometimes, in low-pressure applications, a welded or thin-walled tube has been used because it is cheaper and does not have high-pressure resistance requirements. The possibility of incorrect installation was also inquired about directly from the representative of the fitting manufacturer. The interviewee replied that if the fitting installation procedure is in accordance with the case company's instructions, then leakage is possible. The interviewee further specified that the cutting ring should also be leakage-free against the fitting. This means the cutting ring must experience a spring effect to remain leakage-free if there are any settling effects or any vibration inside the system (Degen, 2020).

Figure 28. Case company pre-assembled cutting ring versus correctly pre-assembled ring.

Several fitting manufacturers recommend support sleeves for bite fittings in thin-walled tubes, but the case company does not use support sleeves (Voss 2018, p.414, Parker 2005, p.864). The literature provides very little information about the benefits of support sleeves, so an answer to this question was sought directly from professionals. Interviewee H pointed out that in thin-walled tubes, the cutting ring is not cut into the tube, but rather, the tube collapses, and that this process does not allow the bite fitting to operate according to its operating principle. The support sleeve, as the name implies, thus supports the tube and prevents the tube collapsing. Support sleeves are little used in hydraulics, as the pressures are usually higher, which means that the walls are also thicker and that there is no need for support sleeves. Interviewee K added that the support sleeve prevents problems caused by vibrations.

Interviewees H and I mentioned that the bite connection can also be installed without special equipment. Interviewee I also mentioned that they had not detected any leakages in the bite fittings. Interviewee L noted that the installation of the bite fitting requires special skill, which is reflected especially when stainless steel is used. An improperly installed fitting will usually leak from the root of the cutting ring. The fitting installation procedure emphasizes, in particular, the importance of tube cutting and deburring.

Finally, the questions were reflected in the hose-end connections. Interviewee I had never heard of DKO leaking and could not specify a specific reason for this. Interviewee K wondered what might cause DKO fittings leakages. After pondering for a moment, he raised that in the past, leakages have been caused by inadequate lubrication in both the thread and the O-ring. If the fitting is not adequately lubricated, then the O-ring will not be positioned appropriately, which will be reflected as a leak. Inadequate thread lubrication is reflected in the fact that the force required for tightening increases with the friction generated by the thread galling. This leads to the belief that the fitting is at the correct tension when, in reality, the fitting remains loose. Interviewee F, who is involved in factory installations daily was not aware of any DKO hose-end leakages occurring in Design 10. He mentioned that the hoses of that design were installed in the field and not at the factory. Individual field installers from case company were asked about the installation procedure, and it turned out that lubricating grease for stainless steel is not used at all sites, in particular in retrofit-kit installations and pump replacements.

Thirty-eight leakages detected in the stud-end fittings, most occurring in the connections in which the stud-end was fastened to a machined planar surface. When interviewed, the company's personnel indicated that the port connections of the seal tank flanges leaked in several different propulsion units. One reason for this was that the port spot face does not provide the seal's necessary sealing area. The manufacturing drawings do not contain a chamfer width dimensions or a 45° marking, as shown in standard 1179-1 (2013). Interviewee H pointed out that machining problems with the port end chamfer have been encountered in the past, especially in domestic machining workshops. Designers forget the chamfer in the drawings, or the machining of the chamfer is made too large for some stud-ends, in which case the necessary sealing has not occurred. The production interviews also revealed that the stud-end fittings are not tightened with tightening torques. There is reluctance to apply tighten torques due to the awkward installation position, the location of the fittings, and the lack of tools.

5.2 Requirements for connections

The results of the interviews are presented and discussed in this section. The main findings of the interviews are reformulated as requirements, as illustrated in Table 8. The list of requirements was shared with ten people within the case company for evaluation. The requirements were differentiated between "nice to have" and "must have". Finally, the results from the interviews were synthesized into three Pugh matrixes. The requirements are presented on the left side in Table 10, 11 and 12. The current fittings used by the company are included in the comparison. The fittings are scored using the finding of interviews and literature. The final fitting comparisons using the concept scoring method are presented in Appendix 2.

Table 8. Key findings from the interviews formulated as requirements.

Type of requirement	Requirement
Must have	Seal reliability
Must have	Vibration resistance
Must have	Required space to install
Must have	Ease of factory assembly
Must have	Ease of site assembly
Nice to have	Ease of verifying correct tightness
Must have	Stainless Steel
Nice to have	Adjustable (only for port connection)
Must have	Removable (only for tube- and hose-end)
Must have	Versatility
Must have	Availability
Nice to have	Reusability
Must have	Approved by Classification Society
Nice to have	Price per assembly
Must have	Reliability factor from interviews
Must have	Low human error factor

The seal reliability requirement refers to sealing with the elastomeric seal. The requirement was developed based on interviews with many professionals. When the properties of a reliable fitting were discussed in the interviews, the fittings with an elastomeric seal highlighted. Each interviewee mentioned an elastomeric seal in fitting with a reliable connection. This requirement is also supported by the findings in the literature that elastomeric seals reduce the quality of surface defects and vibration compared to metal-to-metal sealing. The limitations of elastomeric seals are the temperature and the hydraulic fluid used.

The importance of vibration resistance was strongly highlighted in the interviews, in which it was emphasized that the fitting to be selected should be able to withstand vibrations as well as possible. The literature section pointed out that connection design phase should consider fittings support, but this was found to be challenging to implement in all designs. Therefore, the fittings must withstand vibration conditions. The fittings compared in the Pugh matrixes considered that each the fitting be class-approved by the fitting manufacturer. The fittings were tested using the test procedures of the classification societies, which ensures that each fitting withstands 107 cycles with a frequency of 20–50 Hz without leakage or damage (AB 2019, p.449). This frequency should be considerably higher than the vibrations measured in the propulsion system. It should also note that fittings based on the ISO standard and included in the comparison must be tested according to the ISO 19879 (2010) cyclic endurance and vibration tests. Standardized fittings are tested for at least 107 pressure-impulse cycles with an impulse frequency of 0.5–1.5 Hz without failing during the test.

The space required for installation also became a must-have requirement due to the compact size of the propulsion system. Even if the connection was found to be leak-proof under test conditions, it might not be possible to install it at the desired location. Either the connection will not fit, or it will not be possible to tighten the connection to the desired torque or tightness. The fitting must be able to be tightened in a confined space. In tube-end connections, the same requirement also considers the straight section of the tube required for the installation.

The fitting installability was noted as an important factor, and two requirements were set for installability: factory and field. Factory installations refer to the fact that the fitting can be easily installed without several preparation steps. Field installations refer to the fact that the fitting can also be installed in field conditions. The fitting scored points if the connection was easy to install and did not require extensive pre-assembly phases. The field installations were carried out under different conditions, so the evaluation also considered the tools needed for this. The easier the fittings were to install, the fewer installation errors they would display.

Ease of verifying correct tightness requirements arose from the case company interviews. If the correct tightness or installation can only be verified visually or with a separate gauge, then the connection scored points. This requirement would make it possible to prevent under- or over-tightening of the connection.

The high relative humidity of the propulsion environment and the possible seawater increased the effects of corrosion on the system. Two professionals pointed out that the use of other materials would significantly increase the risk of corrosion. Finally, the impact of possible electromagnetic radiation was highlighted by the case company, limiting the material to stainless steel, as this is the only material that is non-magnetic.

The interviewees and the findings from the literature highlighted the adjustable stud-end fittings. This need was defined as a nice to have, a requirement only for port connections. When the fitting is adjustable, it can facilitate the line’s alignment and prevent stresses from unfavourable positions.

The removable requirement refers to the necessity of being able to disassemble the connection afterwards. Some applications in the propulsion system require flushing or sampling, in which case the connection must be able to be disassembled. Permanent fittings scored lower in this case. This was a requirement only for tube- and hose-end fittings.

Versatility was defined as a must-have requirement. The fitting should have as many different adapters as possible to reduce the number of connections used. The requirement was also intended to make it possible for all connections to be standardized, which would make the fitting-tightening procedure uniform.

A high weighting factor was given for the availability of fittings. If the fitting is not widely available, then its delivery times are extended. This could be reflected in delayed production and service visits, which could lead to a decline in customer satisfaction.

The requirement for reusability refers to the serviceability of the fitting. If the fitting is reusable, for example, if it merely requires the O-ring to be replaced, the fitting scored more points, but if the sealing surfaces can be damaged by retightening, the fitting scored fewer points.

One of the essential requirements for the fitting selection is that all classification societies must approve the fittings. If the fitting has been found to be very secure but not approved for use by the societies, the fitting cannot be used in any propulsion system.

The fitting price was also a requirement of the case company. If the fitting has a very high unit price, this has a direct impact on the end product of the company.

The reliability factor from the interview requirement refers to findings raised by the professionals on the reliability of the fitting. With this requirement, it is also possible to verify whether the views of professionals are consistent with the literature.

The low-human-error factor emerged as a must requirement from the interviews. The interviewees commented that the reliability of the connection is particularly affected by its installability. The fitting types should be reliable. Reliability refers to the fact that the fitting should not start to leak. Different fittings have different properties. The connection can be very secure if it is installed completely correctly, but for some connections, the installation procedure can be demanding, which increases the possibility of human error. Reliability aims to reduce the possibility of errors that result from the installation phase. The different tightening procedures for the fittings affect the possibility of human error. Turns from finger tight (TTFT) includes two tightening steps, while FFWR includes three steps (King 2017). If tightening with a wrench is neglected when tightening the FFWR, the connection will remain loose.

5.2.1 Sealing material for fitting

Considering the propulsion system's environment, FKM would be the most suitable sealing material for the current application environment, as shown in Table 9. The table shows the average values for both rubber materials. Different manufacturers offer rubbers with various compounds, so that the properties may vary from those in the table. The FPM operating temperature scale is extensive, and the FPM would not have to be constantly at the upper operating temperature limit like NBR. The interviews highlighted the faster obsolescence of

NBR rubber, and this is also supported by the sealing material's recommendations for storage times. The manufacturer recommends a maximum storage time of six years for NBR and ten for FKM (Parker 2018, p.4). Short service life cannot be allowed if the goal is a long-lasting and reliable system. NBR and FKM are suitable for the company's oils, and both sealing materials are also resistant to seawater. In addition, FKM's seal is the safest, as this material is non-flammable, while NBR is flammable. The most unfavourable feature of FPM is its material price compared to NBR.

Table 9. Seal material comparison (values verified by CES EDUPACK program).

	FKM	NBR
Temperature range	-20°C to +210°C	-32°C to +100°C
Flammability	Non-flammable	Highly flammable
Water (salt) durability	Excellent	Excellent
Oil used by Case company	Suitable	Suitable
Price (€/kg)	21.40€	2.10€

5.2.2 Tube-end fitting comparison

Table 10. Pugh matrix from all tube-end fittings.

	Fitting type						
Requirement	**Bite elastomer seal (current)**	**Formed tube end**	**Flare 37°**	**Swage**	**Press**	**Weldable tube end**	**ORFS**
Seal reliability	0	+	-	+	+	+	+
Vibration resistance	0	+	-	+	+	+	+
Required space to install	0	-	-	0	0	0	-
Ease factory assembly	0	+	0	+	+	-	+
Ease site assembly	0	-	-	+	+	-	-
Ease verify correct tightness	0	0	0	+	+	0	0
Stainless Steel	0	0	0	0	0	0	0
Removable	0	0	0	0	-	-	0
Availability of fitting	0	0	0	-	-	0	-
Reusability of fitting	0	0	-	0	-	0	0
Versatility	0	0	0	-	-	0	0
Approved by Classification Society	0	0	0	0	-	0	0
Price	0	-	0	-	-	-	-
Reliability factor from interviews	0	+	-	+	+	0	+
Low human error factor	0	+	-	+	+	-	+
Sum +´s	0	5	0	7	7	2	5
Sum 0´s	15	7	8	5	2	8	6
Sum -´s	0	3	7	3	6	5	4
Total	0	2	-7	4	1	-3	1
Rank	4	2	6	1	3	5	3
Continue?	Yes	Yes	No	Yes	No	No	Yes

24° cone weld-on nipple (8434-1)
Weldable tube-to-tube connections are unsuitable due to the shapes of the propulsion system. Thus, only weld-on nipples are included for a Pugh comparison. Interviewee G commented that the use of a weld-on nipple with an O-ring is only emphasized in high-pressure systems, as it withstands more pressure spikes. Interviewee I mentioned that with a weld-on nipple, the manufacturing costs increase. He added that the benefit would only come in large production volumes when it is possible to utilize serial production and automation. Interviewee G commented that the lack of skilled welders causes problems in weldable fittings. The interviewee specified that the weldable connections are reliable, but the poor quality of welding is a problem when welding is not done automatically. In China, welding is cheap, and other types of fittings have been replaced by weldable connections, which is why leakages have reported more often. Tube misalignments have caused stiffnesses and stresses in the tubing, which has later resulted in leakages.

A weld-on nipple would contain the least possible leakage paths for hydraulic fluid and reduce the number of fittings. However, professional interviews highlighted the weaknesses of welded connections. Weldable connections are the most demanding in terms of workload. Classification societies require an NDT inspection of the weld, and an X-ray inspection is required at higher pressures. In addition, welded tubing must be separately approved by the classification society. Field installation was one of the weighty requirements in fitting selection. Welded connections in the field require a firework permit to weld the connection and having a certified inspector on board would increase costs and organization. One requirement was that the fitting is reusable, but this is not possible in fully welded systems. Welding can also increase contaminants within the system if tubing cleaning is deficient, increasing internal system problems. Due to these properties, weldable connections are excluded from further examination.

Flare (ISO 8434-2)
Interviewees L and I commented that the flare fittings have been popular in hose fittings, but use has decreased with the introduction of elastomeric fittings. Interviewee J highlighted the experience required by the installer for flare fitting to make the connection complete. The flare fitting cannot be considered reliable according to the Imel study and interviews. For the reliability of flare, a proper tightening procedure and tube preparation and precise alignment play an essential role and increase the possibility of installation error. In addition, the flare always has a UNF thread, which, based on the interview results, is more susceptible to loosening than the metric thread. Eaton guide mentioned that a flare requires less tightening force than a bite fitting, but its precise alignment weakens the installability. The flare would be suitable for high temperatures, as there is no elastomeric seal in the fitting. The flare was seen as unreliable if the fitting had to be opened and retightened, at which point a leak-free connection could not be guaranteed. The availability and versatility of the flare would be excellent globally, and there are several different models of suitable adapters. Field installation requires a separate machine, which further reduces flare points. None of the interviewees noted the flare when discussing a reliable connection. Due to these features, the flare was not considered further, and it scored by far the lowest compared to the current bite fitting.

Swage
One question focused directly on swage-type fittings. The literature indicated that the swage type is suitable for applications in which full leak-free performance is required. Interviewee L pointed out that although the swage-type is rarely used in Finland, the fitting may still be

found as a shelf in certain vendors. Interviewee G commented that the price limits the fitting's usability, but the swage-type is most often used with gases, in which cases absolute tightness is required. Interviewee K commented out that he would use the swage type if the price did not create constraints. Interviewee J also mentioned that he would use it worldwide, as the fitting made for both inch and mill tubes.

The swage-type fitting scored the most points in the first Pugh comparison. The swage fitting has been tested under very demanding vibration conditions, which have also included vibration values of the same value as in the propulsion system (Swagelok 2019). Two professionals noted that the swage is leakproof and said that they would personally use it if the price were lower. If swage were implemented in the system, the whole design would have to be completely changed, as the use of swage is limited by the lack of different types of hose-end and port fitting. In a tube-to-tube connection, the swage is installable without human errors, but if the swage must connect to other components, such as a Form E stud-end or a DKO hose-end, its weaknesses increase critically, increasing the number of adapters required, for instance, when connecting a tube to an actuator. However, the field installation could perform without a separate machine, and the correct tightness could be checked quickly with a separate gauge. In addition, the final score was reduced by the very high unit price of swage compared to others. Based on the interviews, the swage-type fitting can be said to be a very reliable and leak-free fitting. However, its lack of availability and versatility reduced the score. Based on the requirements, it is not the most suitable fitting for the propulsion environment.

Press

Interviewee E pointed out that the case company had previously studied the use of press fittings. The study was discontinued, and no definitive assurance was obtained as to the suitability of this fitting for the propulsion system. Press fittings performed strongly in comparison. When looking at the weighted criteria in Table 10**,** the most significant shortcomings were found to be the purchase price and the availability and versatility of the fitting. The press fitting was not extensively studied for its ability to withstand threaded fittings. Of all the options, the press fitting would be the most laborious to implement in the current design and doing so would cause the most changes to the hydraulic lines and supports, as the connections were limited with different tube-end and port connections. However, errors due to the installation would be the least of all the fitting options. The press fitting would also make it possible to reduce the theoretical leakage path, as the tube-to-tube connection has two possible leakage paths, whereas other threaded ones have four. The reliability of the press fitting is not affected even if the tube is sawn at an angle, because the tubes do not have to be aligned with each other (Ramator 2016, p.4). The fitting has no threads, so it does not require lubrication like threaded fittings. Potential leakages can be caused by insufficient fitting depression or longitudinal scratches on the tube that provide a leakage path for the fluid between fitting and tube. Press has also been tested in a vacuum and under operating pressure. This feature also increased reliability at low pressure. The company would also be tied to only one manufacturer, which could cause sourcing bottlenecks in the future. The company raised the fitting reusability as a nice-to-have requirement, which is not possible in the case of a press fitting. The press fitting would be one of the most reliable fittings with the current installer training of company. Although the classification societies state that the press-fitting is only approved in Class 3, two different fitting manufacturers have received class-approval for all tubing classes from some societies. However, the press fitting has not received approval from RI, so it could not be implemented on all propulsion systems. If the reusability and classification society requirement had been ignored in the table, the press fitting would have been the first option. Although the press scored more points on reliability than the current fitting, given the company's requirements, the press is not the most suitable fitting for a propulsion system. (Tube-Mac 2020, Haelok 2020)

ORFS (ISO 8434-2)
Interviewee H commented that if serviceability and availability are the selection criteria, then the ORFS fitting is ill-suited, as its availability is generally worse than that of bite fittings. Interviewee J mentioned that ORFS fittings are by far the most expensive. Interviewee L highlighted that the use of ORFS fittings in mobile devices is particularly emphasized because it displays the best pressure resistance of the fittings, and the interviewee noted that there is no significant difference in the sizes of threaded fittings. Interviewee G highlighted the good installability, as the parts of the fitting do not nest. However, he added that the manufacturing tube-end connection requires a separate machine. Interviewee H mentioned the opposite of the ORFS fitting. He mentioned that the only fitting that requires more space than other types is ORFS.

According to previous studies, ORFS fittings are associated with the least leakages compared to other fittings. The leakage factors have often been associated with the installation phase. For instance, preventive solutions have already developed to the problem of dropped O-rings; these include a shoulder modified in the fitting seal's groove to prevent the O-ring from falling (Parker 2005, p.37). The ORFS connection is the most maintenance-friendly of all connections. It is unnecessary to disassemble the rigid tubing to replace a defective component, as the ORFS connection can be removed between tube or hose lines. However, the professional interviews produced conflicting results about the space requirements of the ORFS fitting. The ORFS is physically slightly larger than the DIN 24° fitting. For instance, when the fitting is for a 12-mm tube, the hex size of the ORFS connection is 24 mm, while the hex of the DIN 24° fitting is 22 mm (Parker 2005, p.255;391). That also increases the size of the key required, making it challenging to install in confined spaces. By far the weakest aspects of the ORFS fitting are its field installation, availability, and price. Field installation requires a separate machine, and the lack of availability could create bottlenecks in the most critical installations. Company interviews also revealed that it would be desirable to avoid tightening torque fittings, thus weakening the choice of ORFS fittings.

24° cone (ISO 8434-1)
Comparing the various ISO 8434-1 fittings, EO-3 fell out of the comparison first, as the fitting is not available in stainless steel or approved by the classification societies. EO-3 is the only threaded fitting for which it would be possible to prevent loose tightening. As the best and only feature of all, the fitting's correct tightness can check visually. A metal-to-metal bite is already seen as a more insecure fitting than the current bite with an elastomeric seal. Changing to this model would increase the system's unreliability, as the fitting does not prevent vibrations and temperature changes as well as the model with an elastomer seal.

The current bite with elastomer seal has been found to be a secure fitting if installed correctly, as the studies in the literature section showed. The interviewees' opinions also supported this. The most challenging installability of bite fittings emerged as a major problem. The materials used in the propulsion system in particular are difficult to work with. Interviewee I mentioned that the use of stainless material increases the possibility of incorrect installation. The current bite fitting with an elastomer seal is insecure due to its many preparation steps, and the possibility of human error is highest in this fitting. Although fitting manufacturers also state in their brochures that the bite with an elastomer seal provides good resistance to external forces, the formed tube, ORFS, and flange connections provide better resistance to static and dynamic stresses. In particular, excellent properties include the short straight section of the tube required for the connection and the possibility of field installability, however, with the proviso that the site has suitable tools. (Parker 2005, p.56-58, Voss 2018, p.19)

The formed tube-end fitting emerged in the interviews as a particularly reliable fitting, especially due to its vibration resistance and low potential for human error. The formed tube-end connection is physically the same size as the current fitting, but the form type requires less tube entry than the current fitting. However, a formed tube-end requires a longer straight length for installation in the tube-forming phase than current bite fitting. For this reason, the formed end received a weaker score for the required space. The characteristics of the formed tube-end particularly enhanced by the versatility of various components. Field installability is not as good as with the current bite fitting, but it is possible to install the fitting in the field using a separate machine. A formed-end-type connection is seen as one of the most reliable tube connection methods. The form type could reduce human error during the manufacturing phase. The preparation is done entirely automatically, except for the sawing and burring of the tube, and the tightening method is TFFT or FFWR depending on the manufacturer. Furthermore, the manufacturer's brochures also indicate that the formed tube-end can be installed after one training course, but for the bite fitting, refresher training at two-year intervals is recommended (Voss 2018, p.507).

Results

The Pugh comparison did not provide a tube-end connection that met all the requirements. Therefore, the fittings were finally compared in more detail using the concept scoring method, as illustrated in Appendix 2. The company's current bite with the elastomer seal is not the most reliable of the fittings available in the market. Of the fittings included in the study, there are four more reliable models on the market that provide a more reliable connection than a bite with elastomer seal. Each fitting can be installed in the field, but only the bite and swage can be installed without a separate machine, but the rest requires a machine. When the most important requirements were emphasized, the formed tube-end would best meet the requirements of the company for a reliable connection. The weakest feature of the formed tube-end was that the connection could not be installed without a separate machine, meaning that a separate machine would have to be acquired for field installations. The formed tube-end connection is based on the same standards as the current fitting. Therefore, in urgent field repairs, it is also possible to utilize the current bite connection.

5.2.3 Hose-end fitting comparison

The hoses use the same fittings as the tubes, but the fastening method is different. Tube preparation and installation errors are not reflected in hose-end fittings in the same way. Therefore, the hose-end fittings were scored separately from the tube-end fittings.

Table 11. Pugh matrix for hose-end fittings.

	Fitting type					
Requirement	**24° DKO (current)**	**Flare 37°**	**Flange**	**ORFS**	**BSP**	**Quick-release**
Seal reliability	0	-	+	0	-	-
Vibration resistance	0	-	+	0	-	0
Requires space to install	0	0	-	-	0	+
Ease factory assembly	0	0	0	0	0	0
Ease site assembly	0	0	-	+	0	+
Ease verify correct tightness	0	0	-	0	0	+
Stainless Steel	0	0	0	0	0	0
Removable	0	0	0	0	0	+
Availability of fitting	0	0	0	-	0	-
Reusability of fitting	0	-	0	0	0	0
Versatility	0	0	-	0	-	-
Approved by Classification Society	0	0	0	0	0	-
Price	0	0	0	-	0	-
Reliability factor from interviews	0	-	+	0	-	-
Low human error factor	0	-	-	+	0	+
Sum +´s	0	0	3	2	0	5
Sum 0´s	0	10	7	10	11	4
Sum -´s	0	5	5	3	4	6
Total	0	-5	-2	-1	-4	-1
Rank	1	6	3	2	5	2
Continue?	Yes	No	No	No	No	No

60° cone (ISO 12151-6)

In interviews, the BSP threaded 60° cone hose-end fitting rarely raised when talking about a reliable connection. The BSP fitting was found to be an old connection method alongside the current ones, although its availability is excellent. Interviewee L commented that the use of the BSP fitting has decreased since more reliable DKO and ORFS fittings entered the market. Therefore, the views of the professionals were entirely in line with the suggestion of BSP fitting standard ISO 12151-6 (2009, p.7) that either a DKO or an ORFS fitting should be used in the hoses. In particular, the alignment of the BSP was seen as challenging, as with a flare fitting. Therefore, the BSP does not meet the specified requirements.

24° cone and 24° cone with O-ring, DKO (ISO 12151-2)

The DKO fitting was highlighted for its commonness in the market. The fitting is compatible with all ISO 8434-1 fittings, resulting in excellent availability and versatility. However, this also raises the possibility of human error. If the installer is not aware of the tightening procedure required for the different 24° cone connection types, the connection may be tightened incorrectly. In addition, the location of the O-ring increases human error. The O-ring is located in a cone, which complicates the lubricating of the O-ring if the adequate tools are not present. Interviewee L recommended DKO fittings, justifying the reliability of the 24° cone with the O-ring. Interviewee D agreed and pointed out that when DKO fittings are tightened correctly, the connection will remain leak-free. In addition, the ISO 8434-1 (2010) standard states that the connection is leak-free.

Quick-release coupling
Traditional quick-release couplings are large, which makes them challenging to install in confined spaces. However, in the twenty-first century, new quick-release couplings suitable for difficult-to-reach applications due to their compact design have been introduced. The Crane manufacturer's R&D manager mentioned that the new type of coupling resulted in a reduction in the number of connections, which reduced the number of leakage points (Cejn 2018, p.11). However, none of the interviewees evaluated the coupling as reliable. Two professional interviewees noted that the quick-release coupling contains several potential leakage routes. Interviewee G commented that a threaded fitting feels more reliable than a coupling if there is no need to open the connection often. In addition, the coupling would be unsuitable for a propulsion system, as there are no suitable tube-end fittings without a separate adapter. In this case, all fittings would be tied to one manufacturer. Although the coupling ranked second in the Pugh comparison, there were too many negative characteristics compared to the current fitting. Therefore, the coupling is not seen as the most reliable in the system.

Results
In the comparison of hose-end fittings, the Pugh matrix provided a clear result, so the connections were not evaluated by the concept-scoring method. The flare fitting's properties were discussed in the tube-end section, and the connection evaluated as unreliable. The main features of the ORFS fitting were also discussed in the tube-end section. According to the interviewees, the DKO, ORFS, and flange fittings were the most reliable against vibration. The selection guides from different manufacturers, such as VOSS or Parker, are consistent with this finding. The ORFS and DKO fittings received almost equal scores in the final comparison. The ORFS fitting could also be a reliable type of connection based on the results of previous studies and interviews. In addition, the ISO 8434-3 standard specifies that the ORFS provides a leak-free connection. However, when the requirements of the propulsion system are also included in the selection criteria, total scores decrease. The DKO fitting meets the set requirements of the best available hose-end connections. The final choice is reflected in the small size and availability compared to the ORFS fitting as well as the simplicity of the TFFT tightening procedure. The choice is further facilitated by the fact that the standard ISO 12151-6 (2009, p.6) recommends that DKO fittings be used, as the fitting represents state of the art.

5.2.4 Port end comparison

Leakages were also detected at the port connections, so each stud-end fitting was compared using the Pugh method.

Table 12. Pugh matrix for port fittings.

		Fitting type						
Requirement	**E (current)**	**A**	**B**	**C**	**F**	**G**	**Bonded seal**	**Flange**
Seal reliability	0	-	-	-	0	-	-	+
Vibration resistance	0	-	-	-	0	-	-	+
Required space install to port	0	0	0	+	0	0	0	-
Ease factory assembly	0	0	0	0	0	0	0	0
Ease site assembly	0	0	0	0	0	0	0	-
Ease verify correct tightness	0	0	0	-	0	0	0	0
Stainless Steel	0	0	0	0	0	0	0	0
Adjustable	0	0	0	0	+	+	-	0
Availability of fitting	0	0	0	0	0	0	0	0
Component availability with suitable port	0	0	0	0	-	0	0	-
Reusability	0	-	-	-	0	0	0	0
Approved by Classification Society	0	0	0	0	0	0	0	0
Price per assembly	0	0	0	+	0	0	0	0
Reliability factor from interviews	0	-	-	-	0	-	-	+
Low human error factor	0	0	0	-	-	0	-	-
Sum +´s	0	0	0	2	1	1	0	3
Sum 0´s	15	11	11	7	12	11	10	8
Sum -´s	0	4	4	6	2	3	5	4
Total	0	-4	-4	-4	-1	-2	-5	-1
Rank	1	4	4	4	2	3	5	2
Continue?	Yes	No	No	No	No	No	No	No

Form E

Each interviewee highlighted the Form E stud-end. Interviewee L commented that Form E is also the most common stud-end fitting, and the leak-proof connection is achieved by adding a locking agent thread. Interviewee L added that the plane surface must be straight at the port connection. Interviewee I pointed out that he had never heard of Form E leakages.

Form F

Form F is considered one of the most reliable and is used specifically in agricultural equipment, in which the operating pressures are high. Interviewee J stated that Form F is the most durable, and the operation is generally concretized at high-pressures. Interviewee I added that their company does not use Form F, since the manufacturing costs are higher due to the more precise machining requirement of the port form.

Form F only obtained better adjustability scores because the fitting model is available as an adjustable. Although the standard ISO 6149-1 only recommends the Form F stud-end for new designs, this was not in line with professional views. The situation would be different if the system were high-pressure. The weakest feature of Form F type connection is that the versatility of suitable components on the market, such as valves and actuators, is weaker than in Form E. In addition, port form of Form F type is the most challenging in its dimensions, which also increases the possibility of machining errors. Currently, machining problems have already been observed in the Form E type port, and if even more demanding machining were chosen, it would further increase the possibility of error. Therefore, Form F does not meet the established requirements.

Form C
All tapered stud-ends were graded according to Form C in Table 12. It was strongly pointed out in the literature that Form C is unreliable, and the views of each interviewee were consistent with this. Interviewee L mentioned that tapered fittings, BSPT, and NPT are still used, but in the design, it should always be considered that the port form is made of a suitable thread and cone. He specified that a locking agent that locks and seals should be used in the connections. Interviewee B wondered why Form C are still used in the current system and concluded that the fitting should be replaced with Form E. Interviewee I did not recommend the tapered fitting and concluded that these should be discarded, as they do not provide reliable sealing without elastic sealing. However, Interviewee H pointed out the compact size of NPT stud-ends, which is why they are still used in central lubrication systems. NPT stud-ends have a smaller key spacing than stud-end fittings with a separate seal.

The only requirements in whose terms Form C scored better than the current fitting was the price and the space required to install. However, tapered stud-ends have been found to be unreliable and to increase the possibility of installation error. The fitting model does not meet the established requirements for a leak-free connection, so the model should not be used.

Forms A, B, G, and bonded seal
Metal-to-metal sealed Form A and B fittings scored the least points due to their lack of reliability and reusability. Even small scratches on the port surface increase the risk of leakage. According to the literature and professionals, one of the features of a modern connection is the elastomeric seal, which Forms A and B lack. A bonded-seal fitting was not considered the most reliable in the interview, as the seal consists of layers that can fail over time. Interviewee J has found that a bonded seal gasket can be installed more easily in the wrong position than, for example, the ED seal. Forms A and B and bonded seal fittings did not score better in any section than the current fitting. Form G was not raised by any of the interviewers, although the fitting is also available as an adjustable model, from which the model received its only point. Form G also received lower scores for sealing reliability, as the manufacturers report the fitting sealing characteristic to be good, while Form E is rated as excellent (Parker 2005, p.59-61).

Flange
Interviewee L mentioned that flange fittings are very easy to install compared to threaded fittings, especially if a split pattern is used in flange fittings. The flanges are only set in place and tightened with a small torque. Interviewee I saw the flanges as providing security to the O-ring seal but emphasized their use only in larger tube connections. Interviewee G commented that flange fittings are good for leak-free operation, but the space required for installation is greater than for threaded fittings.

Each interviewee mentioned the flange as one of the most reliable fittings, especially in vibrating conditions. The flange connection emphasized zero-clearance installability, which allows the flanges to be installed side-by-side, unlike current threaded fittings. However, the installability of the flange is the weakest considering the physical size of the flange. In addition, the installation procedure increases the possibility of a human error. The flange O-ring must be lubricated, and the flange connection itself is tightened evenly crosswise with four bolts. When improperly tightened, this can cause a leaking connection. In addition, if the field has inadequate tools, tightening the flange to the correct torque is impossible. In addition, bolts would significantly increase the risk of installation, as these can drop in the tightest spaces. The poor versatility of adapters also reduced flange points compared to current fittings. Finally, the use of a flange is limited because the flange connection is only available for tube sizes larger than 13 mm OD and hoses from 12.5 mm ID (ISO 6162-1 2016, p.10, ISO 12151-3 2010, p.1).

Results

No concept scoring comparison was performed for the port fittings, as the concept screen comparison gave a precise result, as illustrated in Table 12. However, for port fittings, it was not possible to select only one connection for use. The components also influence the selection process in the propulsion system. In some cases, the use of a component such as a hydraulic pump may limit the choice of connection. The port end in the component is manufactured for a specific port only, limiting the range of fittings. The most reliable and suitable fittings based on the requirements would be Form E and the flange as port connections. In the Pugh comparison, Form E scored the highest number points. Comparable fittings received better scores for only one of the requirements. However, the reliability factor from the interviewers and the possibility of human error decreased the overall scores. The Form E stud-end meets the set requirements for both reliability and installability. Therefore, form C stud-ends should be replaced with Form E if components are available with the right thread end. Professionals preferred the flange as a very reliable connection. The flange connection would be suitable for use with several ports side by side, and the threaded connection would be challenging to install. Reliability is also supported by the fitting manufacturer's comparison of port connections, in which Form E and the flange received excellent value for connection reliability.

5.3 FMEA for design

As Stamatis mentioned, the FMEA team should be diverse, and this factor was thus considered when selected the interviewees. Team members consisted of research and development (R&D), service, product support, and production personnel. The people on the team all had deep expertise in hydraulics and various hydraulic projects. In addition, specific questions were asked to various employees in the case company and to the external professionals. The researcher used the results of the interviews to compile the FMEA. The FMEA table was created in an Excel file and was based on ready-made table templates proposed by Stamatis, which were modified to suit the company's use.

In the mapping of the current state, it was found that the connections with the most leakage were in the propulsion systems built according to Designs 1, 2, 4 and 10. Hose routing was found to be one of the root causes in Design 4. The hoses had incomplete routing, which was especially evident in the excessive bending radius. Hoses started to turn immediately after the crimp connection and had no straight section, as the hose manufacturers or SAE J517 standard recommend. Crimp connections are particularly affected by torque and tensile stress if routed incorrectly. In addition, the stud-end fittings for the components of Design 4 are NPT, which confirmed the findings in the literature and interviews that the connection is susceptible to leakage.

No design-related causes of the leakages were found in the Design 10 leakages. The findings directly referred to the installation procedure, particularly the lack of lubrication of threads and seals at DKO hose connections. Several similar design solutions were leak-free and were thus mapped out of the system, but the installation location of Design 10 is highly unfavourable, which complicates the installation procedure. In addition, these hoses are installed in the field and not in production. Internal interviews with the company also increased the certainty of inadequate lubrication, as it has already been stated in the past that field installations do not perform thread lubrication.

Designs 1 and 2 current design is very uniform, and these caused the most leakages in the system. The most significant difference in the designs was the number of fittings. Finally, Design 2, which suffered from the most leaking, was selected for closer inspection. The design subsystem was divided into component levels to identify the effects of different parts throughout the designs.

The FMEA was used to determine whether the design can prevent errors in the current installation procedure. The potential failure mode was known prior to the study, as the company had found that the fittings were leaking, but the causes were unknown. Initially, the potential effects of failures were identified using brainstorming and current-state mapping with interviewees. It was noted that one error during installation might have several negative effects on the reliability of the fitting. In addition, it was observed that the tubes increased the effects of several flaws. Finally, the potential causes of failures were investigated using brainstorming. It was found that the cause of the failure is rarely due to design alone; however, the most notable shortcoming related to the design is the incomplete manufacturing drawings. The causes and effects are listed in the FMEA table 15. After the causes and effects were recognized, the current detection methods were mapped; these are also listed in the FMEA table. In addition, once the design was created, it was reviewed using a separate design review.

The findings from the interviews were presented to an R&D representative, with whom the results were discussed. The problems that then arose were discussed in the various departments. The Fishbone diagram shows the potential causes and effects of the failure mode found in current designs. Figure 29 shows all the findings regarding what leads to the increase in the susceptibility to fitting leakage in the case company. In addition, most leaking designs have several serial connections.

The occurrences of leakages were determined in the FMEA table based on the current-state mapping. The severity of the effect of the fault was determined to be the same for flaws, with each leading to a problem of the same severity: 1) For contamination of the propulsion system; 2) reduce the oil level and, in the event of a significant leak, a low oil level alarm; 3) Risk of slipping. Eventually, the detection was determined based on the company's current control methods. After the risk assessment, the RPN was calculated for the probabilities. It was found that the highest RPN values are associated with rigid tubing and stud-end fittings in machined parts.

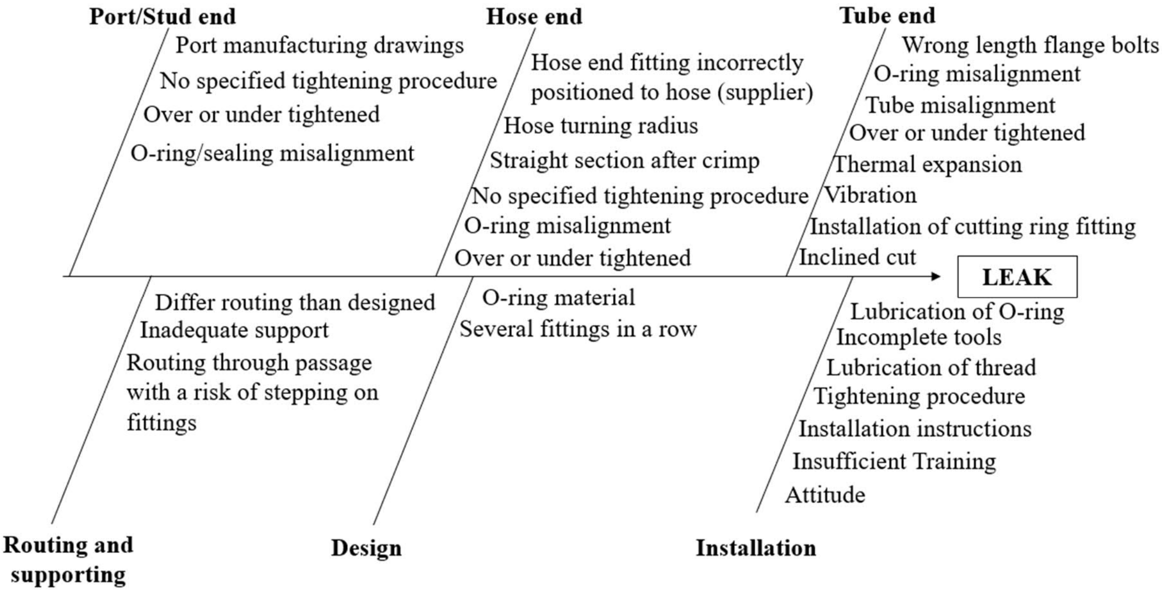


Figure 29. Cause and effect diagram of current design.

Next, how to reduce the critical RPN values was considered. The key findings of the interviews were used to determine recommendations for actions for FMEA and requirements for design. Design requirements were differentiated into nice-to-have and must have properties in the requirements of fitting (Table 13). Professionals favoured a reduction in the number of connections and hoses instead of tubes due to the cramped spaces and geometric shapes of the propulsion system. In addition, the design was required to meet the requirements previously outlined in Table 8. The recommended actions were set to change the current design and improve the manufacturing drawings.

Table 13. Requirements for design.

Type of requirement	Requirement
Nice to have	The minimum amount of fitting possible
Nice to have	Same fitting type in every connection
Must have	Fitting type is not sensitive for installation faults
Nice to have	Adjustable fitting facilitates installation
Must have	Tubes and hoses supported and routed correctly
Must have	Adequate manufacturing drawings

Following recommended actions, a proposed design was modelled using Siemens NX modelling software to replace Design 2. The intention was to develop a replacement design that would make it possible to mitigate the causes of leakage as efficiently as possible. The number of components in this design was reduced from 15 to 8, as illustrated in Figure 30. The adapters changed to different models and utilized valves with the same tube-ends to avoid separate adapters. The proposed design idea has only two different tightening procedures, while the current Design 2 has three. A rigid tube was found to be problematic and was replaced with a flexible hose. The correct length of the straight section after crimp considered in the hose design. The minimum bending radius was also checked from the manufacturer's brochure and was not exceeded in the design proposal. The changes were intended to reduce the problems that can be caused by incorrect installation and tension.

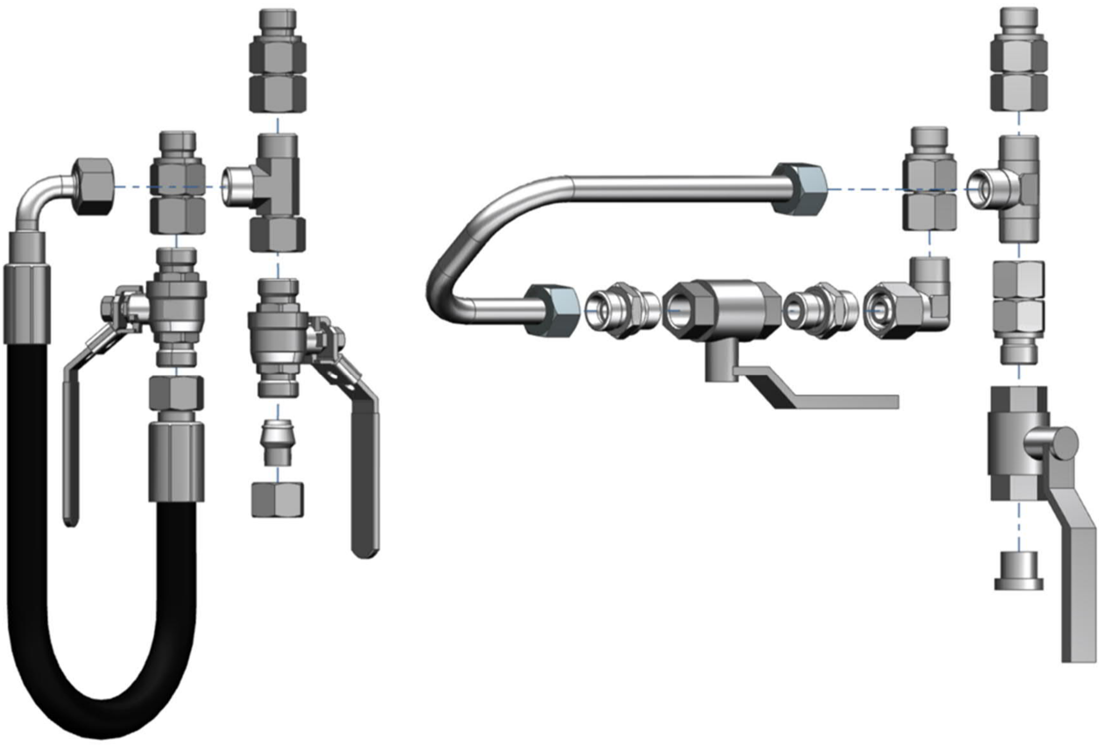


Figure 30. Proposed design idea on the left and current design 2 on the right.

Table 14 shows the errors that could lead to fitting leakage during the hose and tube installation phase. As can be seen from the table, rigid tubing errors cannot be mitigated as well as errors caused by hoses can be. The table considers the case company's current acquisition procedure. Hoses are purchased prefabricated with hose-end fittings, in which case the factory internal installation procedures do not affect the installation errors of the hose-ends. When components are purchased ready-made from a company specializing in them, the possibility of human error in the case company also decreases. The interviews highlighted several errors that occur during the installation phase itself. Hoses decrease the possibility of incorrect installation compared to the current method of tube preparation. In addition, the installation environment of a propulsion system is challenging due to its shape, giving the use of hoses an advantage. The hose facilitates service work, as the hoses are removed from the front by untightening the hose-end fitting, whereas, in rigid lines, the entire tubing must be disconnected, as it does not flex in the same manner as the hose. In addition, propulsion itself causes strong vibrations, transmitted from the structures directly to the fittings. The hoses compensate for the vibrations more effectively than the rigid tubes. This is particularly true if the tube supports are inadequate and vibrations are not considered at the design stage. Besides, it could be possible to prevent stresses in the connections due to the tube's unfavourable position utilizing a flexible hose.

The proposed design is intended to do the following:

1. Reduce the number of fittings and to simplify the design.
2. Reduce potential leakage paths, which also facilitates the detection of leakages.
3. Reduce the possibility of incorrect installation, as there are fewer parts to tighten.
4. Simplify and accelerate field and factory installations.
5. Reduce the number of threads and O-rings to be lubricated.
6. Mitigate the possibility that tightening one fitting will loosen the fittings attached to it—if there is only one fitting in the line, tightening will not affect the others.

Finally, the RPN value was recalculated for the design, as illustrated in Table 15 and Appendix 3. RPN values marked in green reflect how the design has affected one component, while RPN values marked in red indicate that design change has no effect. Based on the results of the FMEA, it can be observed that the causes of leakages are unlikely to be eliminated entirely at the design stage. However, the frequency of the faults could be reduced, thereby also reducing the number of leakages.

Table 14. Comparison between hoses and tubes.

Hose	Tube
• Inadequate straight length after crimp connection (D)	• Length changes due to thermal expansion (D)
• Wrong bend radius (D)	• Excessive vibration (D)
• Inadequate routing (D)	• Surface scratches
• Inadequate tightening	• Inadequate tightening
• Wrong material (D)	• Wrong material (D)
• Inadequate lubrication of fitting	• Inadequate lubrication of fitting
• Hose supplier has made the crimp connection incorrectly	• Inadequate tube sawing or surface quality or diagonally cut tube-end
• Fitting does not form a tight connection with another manufacturer (D)	• Tube is misaligned, giving tension to the connection
	• Incorrectly installed bite fitting

*D Errors can be mitigated at the design phase

Table 15. FMEA from Design 2.

Component	Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Detection method	D	RPN	Recommended action	Action Results				
										Action taken	S	O	D	RPN
LUBRICATION OIL PIPE	Leak	Tension to the fittings Increased leakage routes Tube does not seal to the fitting loosen the fitting	4	wrong lenght, wrong bending, tube sawing inadequate, scratches in the tube, vibration, design of tube	8	Leakage test Visual	7	224	replace tube with hose, improve production / service instructions	Replaced with a hose in a proposed design idea	4	3	5	60
ADJUSTABLE STUD COUPLING	Leak	incomplete port sealing thread galling / wrong tightness poorly positioned o-ring /ED over or undertightened fitting	4	manufacturing drawings, inadequate or non-calibrated wrench, unlubricated thread and o-ring, vibration, thread-locking compound not used, wrong sealing material	8	Leakage test, visual, mark tightening	7	224	complete the manufacturing drawings, improve production / service instructions, improve training		4	8	7	224
ADJUSTABLE STUD COUPLING	Leak	incomplete port sealing thread galling / wrong tightness poorly positioned o-ring /ED over or undertightened fitting	4	manufacturing drawings, inadequate or non-calibrated wrench, unlubricated thread and o-ring, vibration, thread-locking compound not used, wrong sealing material	8	Leakage test, visual, mark tightening	7	224	complete the manufacturing drawings, improve production / service instructions, improve training		4	8	7	224
ADJUSTABLE STUD COUPLING	Leak	thread galling / wrong tightness poorly positioned o-ring	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	8	Leakage test, visual, mark tightening	6	192	Improve production / service instructions, improve training, redesing	Removed from proposed design idea	0	0	0	0
ADJUSTABLE STUD COUPLING	Leak	poorly positioned o-ring thread galling / wrong tightness of fitting	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	8	Leakage test, visual, mark tightening	5	160	Improve production / service instructions, improve training, redesing	Removed from proposed design idea	0	0	0	0
STUD COUPLING	Leak	poorly positioned o-ring thread galling / wrong tightness, loosening	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	7	Leakage test, visual, mark tightening	6	168	Re-desing	Removed from proposed design idea	0	0	0	0
STUD COUPLING	Leak	poorly positioned o-ring, thread galling / wrong tightness, loosening	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	8	Leakage test, visual, mark tightening	6	192	Re-desing	Removed from proposed design idea	0	0	0	0
BALL VALVE	Leak	The valve stem seal is aging	4	Seal material	2	Leakage test, Visual	6	48	Re-desing	Changed valve from proposed design idea	4	2	6	48
BALL VALVE	Leak	The valve stem seal is aging	4	Seal material	2	Leakage test, Visual	6	48	Re-desing	Changed valve from proposed design idea	4	2	6	48
T-FITTING, ACID-PROOF	Leak	poorly positioned o-ring thread galling / wrong tightness of fitting	4	over or undertightened fitting Unlubricated thread and o-ring	8	Leakage test, visual, mark tightening	6	192	Re-design	Changed T-fitting from proposed design idea	4	8	6	192
FLANGED HEX SOCKET PLUG	Leak	poorly positioned o-ring thread galling / wrong tightness loosening	4	over or undertightened fitting, nlubricated thread and o-ring, thread-locking compound not used	2	Leakage test, visual, mark tightening	7	56	Improve production / service instructions, improve training, redesing	Changed plug from proposed design idea	4	2	7	56
TUBE NUT SS	Leak	thread galling wrong tightness of fitting No spring effect for the cutting ring	4	Unlubricated thread Over or undertightened fitting	7	Leakage test, visual, mark tightening	7	196	improve production / maintenance instructions, improve training, replace tube with hose	Replaced with a hose end fitting in a proposed design idea	4	7	7	196
TUBE NUT SS	Leak	thread galling wrong tightness No spring effect for the cutting ring	4	Unlubricated thread Over or undertightened fitting	7	Leakage test, visual, mark tightening	7	196	improve production / maintenance instructions, improve training, replace tube with hose	Replaced with a hose end fitting in a proposed design idea	4	7	7	196
CUTTING RING SS - VOSS	Leak	Incompletely bitten cutting ring	4	Improperly installed cutting ring	7	Visual	4	112	improve production / service instructions, replace tube with hose, maintenance instructions, improve training	Removed a proposed design idea	0	0	0	0
CUTTING RING SS - VOSS	Leak	Incompletely bitten cutting ring	4	Improperly installed cutting ring	7	Visual	4	112	improve production / service instructions, replace tube with hose, maintenance instructions, improve training	Removed a proposed design idea	0	0	0	0

6 Discussion

The section synthesizes the findings of the study into recommendations. The purpose of the study was to improve the reliability of connections in the design phase. The recommendations based on the findings aim to improve the propulsion system's reliability and quality so that the errors detected in the thesis can be prevented and mitigated in the future. In addition, the section contains suggestions for further research topics.

The research question was *How can leak-free hydraulic connections for the propulsion system be ensured in the design phase*. The answer to the question was sought through a literature review, a current-state mapping, and interviews and FMEA. The study revealed that the problems that cause leakages in fittings are well documented in the literature, in the brochures of component manufacturers, and in the interviewees' knowledge. Although these problems are recognized in hydraulic fields, these problems are strongly reflected in the operations of the case company. Current-state mapping revealed causes which increase the leakage sensitivity of the propulsion system. It is not possible to provide a completely leak-free system in the design phase, but the number of leakages can be significantly reduced. Selecting components in which installation errors are as minimal as possible will have a direct impact on the final product. This could mitigate several factors in the chain of influence, improving system reliability.

The main identified causes of leakages for which recommendations are proposed are as follows:

- installation procedure
- inadequate routing and supporting of tubes and hoses in design and installation phase
- inadequate manufacturing drawings for port machining.

6.1 Recommendations for installation procedure

The company expected the current connections to be unsuitable for the system and therefore to cause leakages. However, the findings suggest that the case company has particularly reliable connections, but as the professional interviews confirmed, the reliability of each fitting is directly reflected in the installation procedure. The interviewees consistently noted the importance of the skills of the installers and its effect on the reliability of the connections, and that there is no fitting that is not affected by the skill of the installer.

Currently, the case company does not have enough standardized operating procedures through which it would be possible to minimize systematic errors. Small fittings can be overtightened and large fittings under-tightened, and, as Hirvonen stated when studying bite fittings, the installation procedure affects durability. A leak-free system is the sum of many entities, and a completely leak-free system cannot be ensured at the design stage. Literature sources also mentioned that poor design accounts for only 20% of the causes of leakages.

The first action to mitigate connection leakages and increase system reliability would be to improve installation procedures. Field installers have no instructions on tightening fittings, and the factory did not produce instructions until early 2020 for DKO fittings. As it is, the Form E stud-end fitting still lacks a tightening instruction, and inadequate lubrication of fitting threads and seals was revealed as one of the root causes of leakages.

- It is recommended to develop uniform tightening and lubrication instructions for each fitting model for factory and service installations. When using fittings from different manufacturers, the correct tightening method of the manufacturer should always be ensured.
- The current tightening procedure for bite fittings is incorrect and should be corrected according to the manufacturer. In addition, the instructions should mention the lubrication of the thread and the O-ring.
- It is recommended to obtain adequate tools to tighten the connections.

An additional recommendation relates to installer skills, given their effect on the reliability of the fitting and the risk of leakage.

- The company is recommended to provide periodic training on the installation of hydraulic components. Training is recommended for production as well as field installers. Fittings should only be installed by a trained installer. The training should be organized in the same way as occupational safety training, which is currently required.

The problems of a large organization were also noted in the findings. The flow of information is not completely seamless across departments, and the same mistakes can be repeated several times if everyone is not aware of these errors.

- Shortcomings due to field installations should also be brought to designers' attention so that problems can be mitigated at the design phase. This recommendation would help prevent the spread of design errors on different vessels.

6.2 Guideline for designers

The final objective of the study was to create guidelines for designers. The guidelines were created based on the research findings and served as a recommendation for the case company’s designers. The guidelines are intended to reduce the number of systematic errors by providing standard operating procedures for the connection design phase. Current state mapping revealed that leakages occur more frequently in four designs than in others, even though similar fittings are used. As a result, the following recommendations for guidelines were created for the company.

6.2.1 Design tube-end connections

To achieving a leak-free system, designers should have guidance on how the tubes should be routed and supported and tube-end fittings selected. Tubing vibrations can potentially loosen the fittings, increasing the possibility of leakage, as a study by FPRC showed.

- Tubes are preferred for use when the vibrations of machinery or a propulsion system and the required tube bends are minimal.
- It is preferred to use Metric 24° cone fitting for tube-end connections (ISO 8434-1).
- The preferred sealing material is Fluoro Rubber, e.g., FPM (DIN/ISO), FKM (ASTM), or fluoro-elastomer (for example, Viton®).
- The design should aim for as few connection points as possible.
- The design should use different adapters and swivels to reduce the number of fittings. Adjustable stud-end fittings give the freedom to set the fitting to the desired angle with just one connection.

- Components such as valves with an appropriate connection type should be selected to avoid the use of additional adapters. The valves that are used should be verified in a standard item folder.
- The minimum dimensions of the straight tube-end required for a fitting installation must be considered.
- Tubing must be supported to prevent vibrations and stresses at the fittings.
    - The recommended spacing for the fastening clamp based on ISO 4413 was added to the guidelines.
- The use of DIN 3015-1/3 type clamps, which permit longitudinal movement and reduce vibration, is preferred.
- The clamp must not prevent the movement of the S or U bend.
- The use of tubes in areas in which a tight turning radius is required is preferred.
- Straight tube lines are non-preferred, as small sizing errors can cause leakage.
- Designing U and S bends is preferred in order to prevent strain to the fittings due to the length changes of tubes (Figure 31).

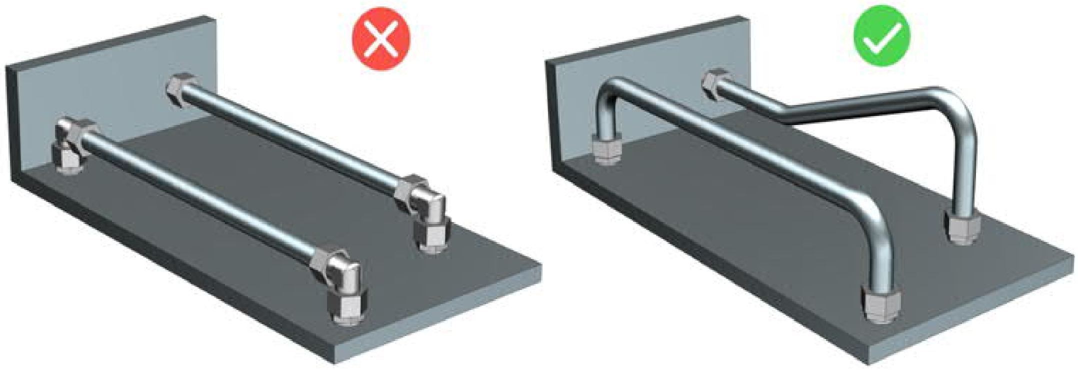


Figure 31. Modelled design recommendation to prevent strain to connections.

6.2.2 Design hose-end connections

Production has guidance on hose support spacing, but designers lack comparable information. The guidelines introduce elements from the production guidelines directly to the designers, with the intention of creating a standardized operating procedure. In this case, the hoses' support locations have already been considered from the design phase, and there is no need to plan how the hoses would be supported in production. Inadequate routing of the hoses increases the stresses in connections. However, it should be noted that hoses are not as long-lasting as rigid tubing. In addition, when selecting a hose, the operating environment and pressure must be appropriate, as with other hydraulic components.

- Hoses are preferred in areas which are exposed to vibration and in which the installation of rigid tubing and fabrication would be challenging due to the confined and geometric shapes of the propulsion system.
- It is preferred to use a metric male 24° cone and a female 24° cone with an O-ring seal (DKO) for hose-end connections (ISO 12151-2/ISO-8343-1).
- It is recommended to avoid designing hoses with two bended hose-end fittings.
- The number of fittings can be reduced by using hose fittings. Hoses must be equipped with a suitable hose-end to avoid stresses on the hose and fitting (Figure 32).

- Hoses should be routed and supported so that no stress is applied to the crimp fitting or hose.
- Hoses should be routed such that they are not in the passageways and are thus not stepped on.
- Hoses should be designed to bend on one plane. Clamps are recommended for use to prevent flexing and twisting on more than one plane.
- If hose clamps are designed as a retrofit kit, consider whether the clamps are safe to install without dropping parts into critical parts of the propulsion system.
- The minimum bending radius of the hose should not be exceeded. In addition, the minimum straight length after the crimp should be at least 1.5 times the hoses outer diameter.

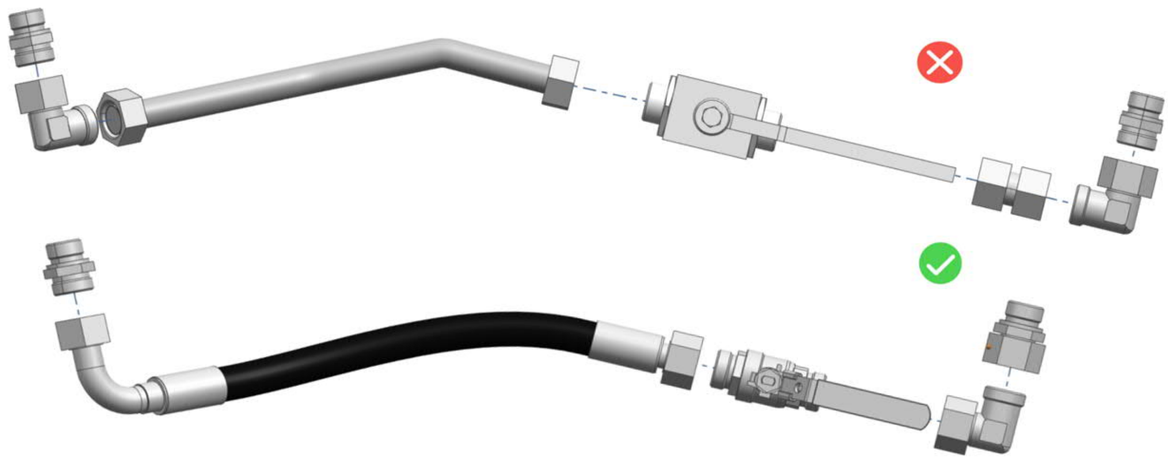


Figure 32. Modelled design recommendation to reduce the number of fittings.

6.2.3 General recommendations for design

The company's bill of material lists mainly contains the company's specific item name for the fitting. When a new employee enters the company, it is difficult for him or her to identify the fitting model, as no clear identification list of items has been created. Deficiencies were found in the manufacturing drawings, and the company did not have a clear rule as to which port fitting to use.

- An identification list of the fittings and adapters provided in the guidelines should be used to recognize different fitting models.
- The company's most important instructions, documents, and specifications related to hydraulics, which added to the guidelines should be utilized. In addition, sections in which the hydraulic requirements of the classification societies can be found should be checked.
    - The purpose of this is to locate information from one place.
- Precise manufacturing drawings are required for machined port-end connections. Accurate information for all surfaces should be included in the manufacturing drawings to ensure leak-free connections.
- A Form E stud-end is preferred, and the NPT stud-end should be avoided unless the component is not available with another type of form.
- A flange (SAE J518 & ISO 6162-1/2) is recommended for use in confined spaces in which it is difficult to tighten the threaded fitting. It should also be verified that flange bolts are the correct length and that the bolts do not bottom out.

- Tightening torques for fittings should not be added to the manufacturing drawings, as the tightening torques vary across fitting manufacturers and materials.
- In confined spaces, the installability of the connection must be ensured. One method to illustrate installability is to model the adequate tool and test whether it is possible to install the connection, as shown in Figure 33.
- It is recommended that the finished design be inspected using the checklist provided in the guidelines (Figure 34).

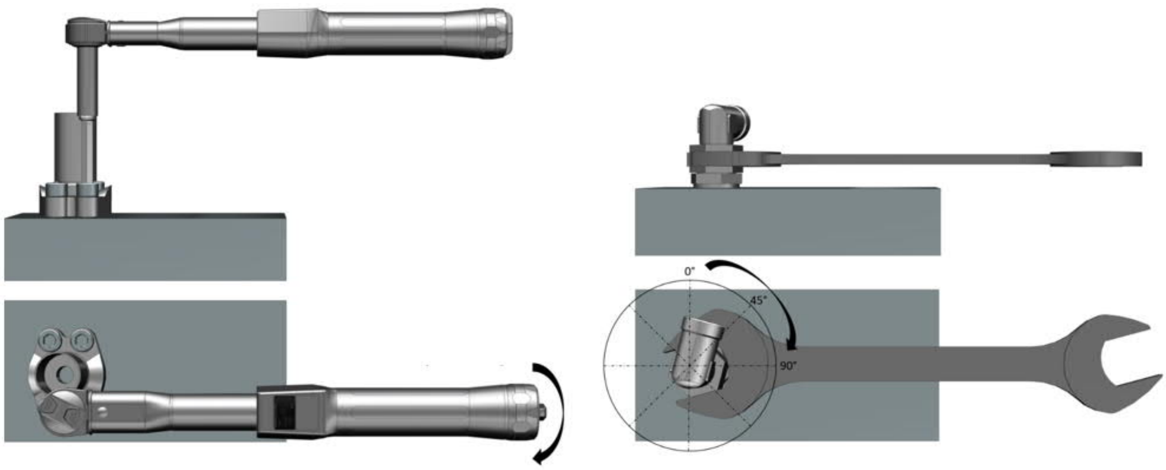


Figure 33. Tightening space illustration in guideline.

Checklist				
Project Number		Module number and revision		
	Check	Results Yes	No	Done by [Name / Date]
1	Is the number of connections minimized?	☐	☐	
2	Pipes are supported and routed according to the guideline?	☐	☐	
3	Hoses are supported and routed according to the guideline?	☐	☐	
4	Are all dimensions in the manufacturing drawings?	☐	☐	
5	Is it possible to tighten connections at the planned space?	☐	☐	
6	Design fulfil the requirements of classification society?	☐	☐	
Skipped steps				
Design phase is completed		☐	☐	

Figure 34. Checklist in design guideline.

6.2.4 Summary of the guidelines

Initially, a draft version of the guidelines was prepared and shared among the case company's departments in Finland for comment. Extensive dissemination of the guideline had the same purpose as FMEA. When the guidelines were shared among several employees, discussion was sparked and cross-functional ideas for improvement from different professionals proposed. The development ideas generated by the sharing were added to the latest version of the guidelines. As a result, the guidelines became a 21-page document illustrating the design guidelines using modelled images. The guidelines are currently in final design review in the case company, but the company has a clear need for them. Guidelines have already utilized in the service department in the design of retrofit kits.

6.3 Suggestions for future research

This section presents the areas for future research identified in the study.

The findings of the study suggested that the root causes of the leakages focus on the installation phase and instructions.

- The case company's current installation procedure at the factory and field should be investigated.

The purpose of the study was to find out how to improve the reliability of the propulsion system in the design phase. The study found that the company's current tube-end fitting is most prone to installation errors. A replacement connection was found that could reduce installation errors and improve system reliability.

- In further research, the formed tube-end fitting should be tested at the case company premises, and accurate cost calculations should be investigated for the connection.

The propulsion system is a confined space, and currently, it is not possible to replace all fittings without removing other components.

- Whether the use of machined parts or hydraulic blocks to replace multiple connections in the system and the accessibility of the installation could be facilitated at the design stage should be researched.

Several fitting manufacturers do not recommend locking agents for threads, but the views of the interviewees differed as to the use of locking agents. Two professionals highlighted the utility of locking agents for highly vibrating objects.

- Future research should investigate whether locking agents weaken or improve the reliability of stainless steel fittings in vibrating conditions.

The fittings have been tested according to standardized vibration tests. The vibrations of the fittings in the propulsion systems have not been measured.

- In further research, the kind of vibrations to which the company's connections with the greatest leakage are exposed should be investigated.

7 Conclusions

This master's thesis conducted a case study using a company that specializes in propulsion systems. The aim of the study was to investigate how leakages in hydraulic connections can be mitigated at the design phase, to determine the needs of the company for the required fitting and design, to use these needs to select the most reliable fitting for the propulsion system, and to map the current leaking connections and designs and thus identify the root causes of leakages. The final objective was to develop, based on the findings of the study, design guidelines for the designers of the case company and provide recommendations for the company. The need for the study arose as a result of the case company's increased hydraulic fitting leakage observations. This study concentrated on hydraulic fittings on the market.

The literature review, divided into two sections, provided a strong basis for the study. The first section examined the causes of leakages, the properties of different fittings models, and the design requirements of hydraulic connections. The second part of the literature review examined the requirements for hydraulic connections set by classification societies.

The empirical part began with an introduction to current design of the company models and the fitting models used. This was followed by mapping the current state and identifying which fittings and designs were leaking and what the different departments required from the fittings and designs. Data on leakages was not previously stored in one place, so all leakages were mapped using old service reports, site survey reports, and customer complaints. The root causes of the leakages were investigated by interviewing personnel from the case company and external professionals and exploring the current installation procedures and instructions. The interviews were used to determine the features of a reliable connection and which features different departments within the company want from the design. Furthermore, the views of external professionals were used to find the root causes of leakages as well as to clarify whether other companies have found a way to prevent leakages with a particular type of fitting or design.

After the interviews, the fittings were scored based on the requirements found in the interviews and literature. First, the characteristics of a reliable connection, then the requirements of the company for the fittings were determined. The fittings were scored using the Pugh screening method, and if this method did not provide the most suitable fitting model clearly, the fittings were compared more closely using the concept-scoring method. The comparison covered eight types of tube-end fittings, six types of hose-end fittings, and eight types of port-end fittings. Based on these requirements, a formed tube-end (ISO 8434-1) fitting was selected as the most suitable tube-end connection. The most suitable hose-end connection was determined to be a 24° cone and a 24° cone with an O-ring (ISO 12151-2), which is also the company's current fitting model. The most suitable port connection was selected as Form E (ISO 1179-2), which is also used by the company along with other port fittings. The current tube-end fitting, a bite with an elastomer seal, was found to be reliable if installed correctly. However, the company's current connection is one of the most challenging fittings to install, and the reliability was affected by several human error possibilities. Four types of connections on the market offer a more reliable tube-end connection, and the installer's experience does not have the same effect on the reliability of the connection as the bite with elastomer seal.

At the end of the study, an FMEA was created for the most critical design. The FMEA considered the root causes of the current leakages and enabled corrective design suggestions to be made to mitigate similar errors. The FMEA analysis found that it is not possible to mitigate all leakages in the design phase. However, leakages can be minimizing by reducing the number of fittings and by using hoses instead of rigid tubing. The creation of uniform installation instructions for production and service and the same type of fittings results in an identical installation phase, which reduces uncertainty in the installation phase.

The company had an expectation that the current hydraulic connections would be unsuitable for the propulsion system. However, the current-state mapping and the root cause investigation revealed that the leakages were reflected in the installation procedure and the lack of guidance. Current state mapping revealed that leakages occur very systematically in specific designs. The four designs of the company cause 80% of leakages from all mapped leaking designs. The stresses caused by connections of the rigid tubes increase the risk of leakage to the fittings connected to the hydraulic line. In addition, the study highlighted problems with the installation phase of these designs. Design changes that can be utilized to reduce leakages are straightforward, and with a little consideration, the number of fittings can be reduced. Reducing fittings would affect the number of leakages and reduce possible installation errors.

The goal was achieved by finding out the requirements for the leak-free design and the company's requirements for the desired design. The company lacked complete guidelines on the design and selection of fittings. The guidelines that were created provide recommended fitting types and instructions on when to use the tube or hose. The guidelines include recommendations on how to reduce connections and instructions on supporting and routing tubes and hoses. All essential company documents related to hydraulics were also compiled in the guidelines, with the aim of bringing all the company's current operating methods and installation instructions into one place. The guidelines aimed to harmonize the operating methods of the company's design, service, and production departments so that leakages could be eliminated and mitigated in the early phase before they reach the customer.

The study provided valuable information on hydraulic connection leakages for the case company. The study revealed that the properties of reliable connections and the causes of leaking connections are very well known in the literature and by external professionals. Nevertheless, these errors are reflected in the company's hydraulic leakages. The study addressed clearly which designs cause leakages and identified the root causes of leakages. With this information, the company can improve and develop incomplete work instructions and installation procedures in the future, making it possible for the case company to prevent and mitigate leakages.

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List of Appendices

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Appendix 1. Interview questions

1. Design
    a. What is desired of the design?
    b. Is there a maximum number of fitting in the design that can be connected?
    c. Is there a rule when to use a tube and when to use a hose?

2. Space and installation
    a. Hose and tube connection installability, do these have specific features that should be considered in the design?
    b. Does the installability of the fitting vary?
    c. How the installability affects the reliability of the connection?
    d. How the difference in tightening procedures affects the reliability of the connection?
    e. Are there differences in the same standard fittings from different manufacturers?

3. Environment
    a. How do temperature variations affect the choice of fitting?
    b. The propulsion system causes vibrations. Are there connections that reliably withstand vibration and do not require retightening?
    c. Installation conditions vary. What effect does cleanliness have on the leakproofness of the connections?
    d. The propulsion system connections consist mainly of lubrication lines, and the pressures are less than 10 bar. How does low-pressure affect the reliability of the connection?

4. Case company current leakages
    a. The company uses cutting ring with elastomer seal in tube-end connections that have been found to be challenging to install and cause leakages. What factors cause leakages in that connection?
    b. The hose-end and adapter connections use 24° cone and 24° cone with O-ring fitting, which leaks often. Have similar leakages been encountered in the past?
    c. Form E stud-end has been found in the literature to be highly reliable, but what factors cause leakages in that connection?

5. Fittings
    a. Characteristics of tube-end fittings?
    b. Characteristics of hose-end fittings?
    c. Characteristics of port-end fittings?

Appendix 2. Concept scoring for tube-end connections

		Fitting type							
		ISO 8434-1 elastomer seal (Current)		ISO 8434-1 (formed tube)		ORFS		Compression (Swage)	
Requirement	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Seal reliability	15 %	4	0,60	5	0,75	5	0,75	5	0,75
Vibration resistance	15 %	4	0,60	5	0,75	5	0,75	5	0,75
Required space install	2,5 %	5	0,13	4	0,10	3	0,08	5	0,13
Ease factory assembly	5 %	4	0,20	5	0,25	5	0,25	5	0,25
Ease site assembly	5 %	4	0,20	2	0,10	2	0,10	5	0,25
Ease verify correct tightness	5 %	3	0,15	3	0,15	4	0,20	5	0,25
Stainless Steel	2,5 %	5	0,13	5	0,13	5	0,13	5	0,13
Removable	2,5 %	5	0,13	5	0,13	5	0,13	5	0,13
Availability of fitting	5,0 %	5	0,25	4	0,20	2	0,10	1	0,05
Reusability of fitting	2,5 %	4	0,10	4	0,10	4	0,10	4	0,10
Versatility	7,5 %	5	0,38	5	0,38	5	0,38	2	0,15
Approval by Classification	5 %	5	0,25	5	0,25	5	0,25	5	0,25
Price	7,5 %	5	0,38	3	0,23	2	0,15	2	0,15
Reliability factor from interviews	10 %	3	0,30	5	0,50	5	0,50	5	0,50
Human factor to reliability	10 %	3	0,30	4	0,40	4	0,40	5	0,50
	Total	4,075		4,400		4,250		4,325	
	Rank	4		1		3		2	
	Select?	No		Yes		No		No	

Appendix 3. FMEA chart

Component	Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Detection method	D	RPN	Recommended action	Action Results				
										Action taken	S	O	D	RPN
LUBRICATION OIL PIPE	Leak	Tension to the fittings Increased leakage routes Tube does not seal to the fitting loosen the fitting	4	wrong lenght, wrong bending, tube sawing inadequate, scratches in the tube, vibration, design of tube	8	Leakage test Visual	7	224	replace tube with hose, improve production / service instructions	Replaced with a hose in a proposed design idea	4	3	5	60
ADJUSTABLE STUD COUPLING	Leak	incomplete port sealing thread galling / wrong tightness poorly positioned o-ring /ED over or undertightened fitting	4	manufacturing drawings, inadequate or non-calibrated wrench, unlubricated thread and o-ring, vibration, thread-locking compound not used, wrong sealing material	8	Leakage test, visual, mark tightening	7	224	complete the manufacturing drawings, improve production / service instructions, improve training		4	8	7	224
ADJUSTABLE STUD COUPLING	Leak	incomplete port sealing thread galling / wrong tightness poorly positioned o-ring /ED over or undertightened fitting	4	manufacturing drawings, inadequate or non-calibrated wrench, unlubricated thread and o-ring, vibration, thread-locking compound not used, wrong sealing material	8	Leakage test, visual, mark tightening	7	224	complete the manufacturing drawings, improve production / service instructions, improve training		4	8	7	224
ADJUSTABLE STUD COUPLING	Leak	thread galling / wrong tightness poorly positioned o-ring	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	8	Leakage test, visual, mark tightening	6	192	Improve production / service instructions, improve training, redesing	Removed from proposed design idea	0	0	0	0
ADJUSTABLE STUD COUPLING	Leak	poorly positioned o-ring thread galling / wrong tightness of fitting	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	8	Leakage test, visual, mark tightening	5	160	Improve production / service instructions, improve training, redesing	Removed from proposed design idea	0	0	0	0
STUD COUPLING	Leak	poorly positioned o-ring thread galling / wrong tightness, loosening	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	7	Leakage test, visual, mark tightening	6	168	Re-desing	Removed from proposed design idea	0	0	0	0
STUD COUPLING	Leak	poorly positioned o-ring, thread galling / wrong tightness, loosening	4	over or undertightened fitting, unlubricated thread and o-ring, thread-locking compound not used	8	Leakage test, visual, mark tightening	6	192	Re-desing	Removed from proposed design idea	0	0	0	0
BALL VALVE	Leak	The valve stem seal is aging	4	Seal material	2	Leakage test, Visual	6	48	Re-desing	Changed valve from proposed design idea	4	2	6	48
BALL VALVE	Leak	The valve stem seal is aging	4	Seal material	2	Leakage test, Visual	6	48	Re-desing	Changed valve from proposed design idea	4	2	6	48
T-FITTING, ACID-PROOF	Leak	poorly positioned o-ring thread galling / wrong tightness of fitting	4	over or undertightened fitting Unlubricated thread and o-ring	8	Leakage test, visual, mark tightening	6	192	Re-design	Changed T-fitting from proposed design idea	4	8	6	192
FLANGED HEX SOCKET PLUG	Leak	poorly positioned o-ring thread galling / wrong tightness loosening	4	over or undertightened fitting, nlubricated thread and o-ring, thread-locking compound not used	2	Leakage test, visual, mark tightening	7	56	Improve production / service instructions, improve training, redesing	Changed plug from proposed design idea	4	2	7	56
TUBE NUT SS	Leak	thread galling wrong tightness of fitting No spring effect for the cutting ring	4	Unlubricated thread Over or undertightened fitting	7	Leakage test, visual, mark tightening	7	196	improve production / maintenance instructions, improve training, replace tube with hose	Replaced with a hose end fitting in a proposed design idea	4	7	7	196
TUBE NUT SS	Leak	thread galling wrong tightness No spring effect for the cutting ring	4	Unlubricated thread Over or undertightened fitting	7	Leakage test, visual, mark tightening	7	196	improve production / maintenance instructions, improve training, replace tube with hose	Replaced with a hose end fitting in a proposed design idea	4	7	7	196
CUTTING RING SS - VOSS	Leak	Incompletely bitten cutting ring	4	Improperly installed cutting ring	7	Visual	4	112	improve production / service instructions, replace tube with hose, maintenance instructions, improve training	Removed a proposed design idea	0	0	0	0
CUTTING RING SS - VOSS	Leak	Incompletely bitten cutting ring	4	Improperly installed cutting ring	7	Visual	4	112	improve production / service instructions, replace tube with hose, maintenance instructions, improve training	Removed a proposed design idea	0	0	0	0