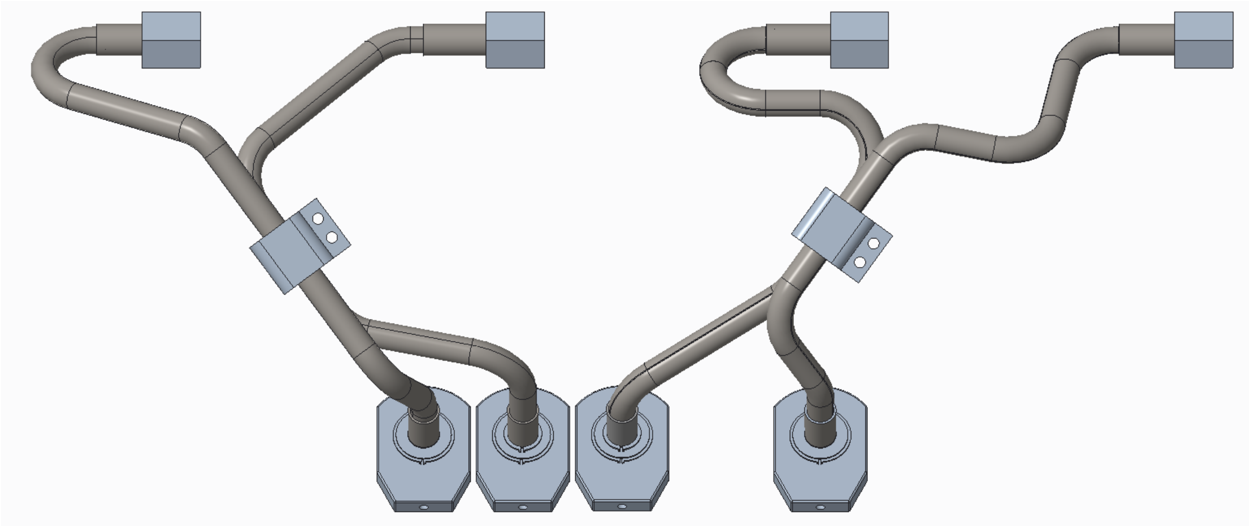

Future System for High-Pressure Fuel Leakage Detection in Marine Commercial Engines

Degree project report in MSc Product Development

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Cover: CAD model of fuel pipe assembly, Volvo Penta

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Abstract

The project explores the development of novel double-walled high-pressure fuel injection pipes used in marine commercial engines. Current double-walled pipes meet the safety standard, but they suffer from higher costs and increased manufacturing complexity.

The project aimed to offer the industry a superior alternative to existing solutions in certain Volvo Penta engines, with the intent of improving the manufacturability of the components, reducing costs, and improving tolerances. The project was driven towards developing a robust leak detection and containment mechanisms to mitigate hazards such as fuel spray or contamination in the engine room. It also investigates on potential suppliers for procuring the materials and components for the system. It also aims to propose recommendations for future systems.

The project was conducted using a stage gate product development process. Initially, an analysis of existing systems and Volvo Penta marine engines was performed, followed by a review of the regulations applicable to current engines, as these regulations played a major role in the concept development. The final design was validated through Finite Element Analysis (FEA) while cost calculations were performed and material alternatives were explored.

Keywords: Design, optimization, double-walled pipes, product development, cost optimization, flexible metallic hoses, marine commercial engines, safety, additive manufacturing, 3D printing, classification society, high- pressure fuel injection pipes, FEA simulation, leakage detection.

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Aswin Madhav Narendrakumar & Gowtham Raj Sowrirajan, Gothenburg, 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

IMO - International Maritime Organization
SOLAS - International Convention for the Safety of Life at Sea
RINA - Registro Italiano Navale
DNV - Det Norske Veritas
CCS - China Classification Society
ABS - American Bureau of Shipping
BV - Bureau Veritas
LR - Lloyd's Register
HPF - High-Pressure Fuel
HPP - High-Pressure Pump
CR - Common Rail
DED - Directed Energy Deposition
PBF - Powder Bed Fusion
PBF-LB - Powder Bed Fusion - Laser Beam
DMLS - Direct Metal Laser Sintering
CAD - Computer-Aided Design
AM - Additive Manufacturing
3D - Three Dimensional
ISO - International Organization for Standardization
DFM - Design for Manufacturability
PTFE - Polytetrafluoroethylene
WP - Working Pressure
BP - Burst Pressure
FEA - Finite Element Analysis
FOS - Factor of Safety
HIP - Hot Isostatic Pressing
MH - Metallic Hose
MC - Modified Cross-section
CC - Common Collection Unit
CAE - Computer-Aided Engineering
RPM - Revolutions Per Minute

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1

Introduction

This chapter provides a brief introduction to the company and its background, as well as the purpose and expected outcome of the master's thesis project conducted at Volvo Penta. It also addresses the scope and limitations of this project.

1.1 Background

Volvo Penta is a Swedish company that manufactures engines and power systems for marine and industrial applications. It was founded in 1907 in Gothenburg, Sweden, originally as a separate company and is now a joint stock company within the Volvo Group [1]. Volvo Penta operates globally, with its headquarters located in Gothenburg, Sweden. Its manufacturing facilities are located in Sweden and China. It has regional offices in Europe, North America, and Asia, and service centres to cater to its customers in various regions.

Volvo Penta focuses primarily on 2 main businesses, "On land" and "At sea". In the “On land” business segment, Volvo Penta develops future-focused industrial solutions like industrial engines, power generation engines, electric power solutions, and energy storage solutions. Whereas in the “At sea” business unit, Volvo Penta focuses more on marine engines and propulsion systems for leisure boats and commercial vessels [2].

Generally, Volvo Penta develops engines for marine applications that are type approved by marine classification societies (e.g., RINA, DNV, GL, NV, Transportstyrelsen), adhering to stringent safety and legal requirements [3]. High-pressure fuel injection pipes are one of the most significant components of the engine, which deliver high-pressure fuel from the common rail to the injectors in the high-pressure fuel injection system. These high-pressure fuel delivery pipes are also used to transfer fuel from the high-pressure pump to the common rail.

Traditionally, Volvo Penta's D4 and D6 engines utilized the single-walled fuel injection pipes. However, evolving regulations from classification societies now mandate the use of jacketed (double-walled) fuel injection pipes to enhance safety by preventing fuel leakage in the engine room in the event of a pipe failure [3]. In this design, the outer pipe acts as a protective shield, containing any leaks from the inner pipe, which carries high-pressure fuel.

The production of high-pressure fuel injection pipes is outsourced, and although existing market solutions for double-walled designs meet safety standards, they are associated with high production complexity and costs. Overcoming these challenges is crucial in the engine development process, as it also helps eliminate production redundancies.

1.2 Purpose

The purpose of this thesis is to investigate the challenges associated with the designs offered by the current market and propose to the industry a superior alternative to those already in use, with the intention of enhancing the manufacturability of the components, reducing costs, and improving production tolerances. The primary objective is to develop a promising new concept for the double-walled fuel injection pipes represented as detailed CAD models. The secondary objectives are to validate the proposed design through simulation, optimize the design, and identify potential suppliers for procuring or manufacturing the component. The solution will also include advanced leak containment and detection mechanisms to prevent risks such as fuel spray or contamination in the engine room.

1.3 Research scope and delimitations

The study includes examining the design of existing double-walled high-pressure fuel injection pipes and also the problems associated with it. It also involves a study of the regulations related to the design and development of high-pressure fuel injection pipes. The project will also look into proposing suitable manufacturing methods for producing these components. Cost parameters related to the existing product and the proposed product will also be looked into. In addition, the study investigates potential alternative alarm or monitoring systems in case the new design is incompatible with the current fuel leakage detection system.

However, physical prototyping and experimental validation of the evolved designs are not within the project scope due to budget constraints. The design of high-pressure fuel delivery pipes used to transfer fuel from the high-pressure pump to the common rail is also not included in the scope of the project. The positional shift or design alteration of the common rail and injectors will not be undertaken since these are outsourced from external suppliers, and their design cannot be altered. Since Volvo outsources the design and production of the double-walled pipes, detailed information on the manufacturing process and accurate cost breakdown is not available, which is a study limitation.

1.4 Deliverables

The thesis aims to deliver these goals:

- Documentation of the regulations related to the design and development of high-pressure fuel injection pipes provided by the classification societies.

- CAD modeling of the proposed design with all documentation from conceptual design to detailed design.

- Validation of the proposed design by conducting a finite element analysis simulation and optimizing the design based on the results.

- Development of plastic prototypes of the proposed solution using the facilities at Chalmers University or the Volvo Penta workshop, demonstrating the design's feasibility and functionality.

- Propose future recommendations for the developed concepts to enhance product viability and market readiness.

1.5 Research questions

The following research questions were selected based on the purpose and scope of the project. This thesis work mainly aimed to address these questions:

- RQ 1: What are the main challenges and limitations associated with the double-walled pipes available in the market?

- RQ 2: How are the double-walled pipes manufactured? And are there any alternate manufacturing methods?

- RQ 3: What factors influence the design of the double-walled pipes?

- RQ 4: What makes them costly compared to single-walled pipes?

- RQ 5: What regulatory and safety standards must be considered when developing alternative designs for high-pressure fuel injection pipes?

- RQ 6: What are the materials used in the system, and what can be best suited for the future solution, considering performance, cost, and feasibility?

- RQ 7: How should the proposed design perform under structural loading conditions, based on Finite Element Analysis (FEA)?

1.6 Report outline

The report starts with a basic introduction to this thesis, including background information about the company and the context of the project. This is followed by a brief description of the project's objectives and requirements. The development activities leading to the final design selection are elaborated, and the final design is explained in detail. The report concludes with future recommendations and a summary of key findings.

2

Theory

This chapter explains the technical foundation and scientific principles, like concept development methodology, design for manufacturing, and fundamentals of structural analysis, that are necessary to develop and understand the proposed high-pressure fuel leakage detection system. It also addresses the current fuel injection system in D4 & D6 engines.

2.1 Concept development

Concept development is a structured engineering process for generating and evaluating design ideas to meet specific functional goals. This process starts with analyzing the problem statement and conducting interviews with experts and customers. Functions are defined based on key points from interviews, requirements, and desires. Then this function is decomposed and broken down into subfunctions. A morphological matrix is then used to brainstorm multiple solution alternatives for each sub-function, helping explore a wide design space and ensuring no option is missed. These sub-solutions are combined into complete concept variants, offering a broad set of ideas for comparison [4].

To refine these options, a Pugh selection matrix is used, where concepts are compared to a reference (datum) concept across several qualitative criteria. This method helps to find the strengths and weaknesses of each concept at an early stage. In the next stage, each criterion is given a specific weight based on its importance in a weighted decision matrix called the Kesselring matrix, and each concepts are scored. Based on the scores, the top concepts are chosen for the next detailed design phase. Pugh matrix is a qualitative evaluation method where whereas the Kesselring matrix is a quantitative evaluation method; these methods helped to eliminate bias and support rational design choices.

Based on the concept evaluation, the final concept is chosen. Detailed design is performed for the final concept, and necessary simulations are also done to check if the design satisfies all the necessary design requirements.

2.2 Design for manufacturing (DFM)

When a concept is selected, it must be developed with manufacturing feasibility in mind. Design for Manufacturing (DFM) is the practice of designing products so they are easy to manufacture at high quality and lower cost. A few good DFM practices are selecting compatible materials for the chosen process and designing the component for ease of assembly. DFM mainly focuses on reducing the number of parts, minimizing the complexity of the design, and applying tolerances that are practical and cost-effective. Using standard components is also one of the good practices in DFM [5].

Since additive manufacturing (AM) is considered, Design for Additive Manufacturing (DFAM) principles are also applied. Material selection, orientation optimization, support structure generation, surface finish, and print time estimation are considered early in the design phase to optimize and reduce the cost of the product.

2.3 Structural analysis

Finite element analysis (FEA) is commonly used to model geometries, simulate stress distributions and deformation. Structural analysis gives us the ability to evaluate if a mechanical design would fail or withstand applied loads without failure. For high-pressure fuel systems, analysis is generally composed of two parts: static analysis and dynamic (vibration and fatigue) analysis.

Static structural analysis evaluates how well the system performs under constant pressure and temperature loads in the pipe. For pressure-containing components like pipes, this includes calculating stresses using methods such as the von Mises yield criterion, which predicts material yielding under complex loading. FOS is determined as the ratio of material yield strength to maximum operational stress (applied load). The required FOS value from international standards for fuel pipes should exceed 2 in most cases.

Dynamic analysis addresses loads that vary over time, including vibrations and cyclic pressure fluctuations. Modal analysis determines natural frequencies together with corresponding mode shapes, ensuring avoidance of resonance with engine excitations. Fatigue analysis determines the consequences of recurring load applications over millions of cycles using S-N curves or endurance limits.

2.4 Powder bed fusion

Powder bed fusion is an additive manufacturing process that uses either laser, thermal, or electron beam energy to melt and fuse powder material together layer by layer to form a three-dimensional object [6]. It can be used to melt plastic and also metal powders based on the requirements, and for this project, a Direct Metal Laser Sintering (DMLS) process is employed to work with metallic powders. DMLS uses a high-power laser beam to produce metal components. Materials suitable for this process include aluminum, stainless steel, titanium, cobalt chrome, and inconel. Products with high complexity, high accuracy, good surface finish, and excellent thermal, mechanical, and electrical properties can be produced through this method.

In this process, A thin layer of metal powder is applied to the build platform and is melted layer by layer with a laser according to the part's digital cross-section. When one layer is done, the build platform lowers, a new layer of powder is spread on top, and the process continues until completion. Components are often printed with low-resolution support structures which can be removed by machining or by hand, depending on their strength. Post-processing treatments such as stress-relief heat treatment or Hot Isostatic Pressing (HIP) improve their properties. Regardless of these challenges, powder bed fusion (PBF) is still widely used in aerospace, medicine and engineering for additive manufacturing owing to its capability of producing complex geometry parts with superior performance features.

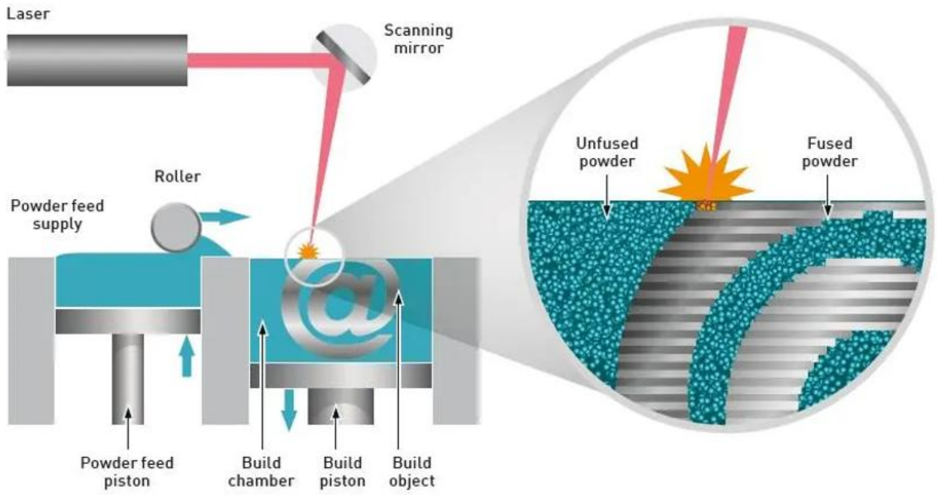


Figure 2.1: Powder bed fusion [7]

2.5 Directed energy deposition method

Directed energy deposition (DED) is a method of additive manufacturing that involves the application of heat via a laser, electron beam, or plasma arc to a material, which is simultaneously being deposited [8]. In this case, wire or powder form feedstock is injected into the energy source's melt pool through a nozzle. DED builds parts layer-by-layer sequentially according to a computer-aided design (CAD) model. This technique is employed to perform repairs and modifications on large components.

Commonly used metals in DED are stainless steel, titanium, inconel, and cobalt-chrome. Unlike powder bed fusion, which yields finer feature resolution and smoother surface finish, DED results in a rougher texture. This process often requires secondary steps of machining or heat treatment in order to achieve dimensional precision as well as improve mechanical strength. The benefits of DED include faster machining speed for precisely shaped parts due to the shorter time spent on construction stages. This process is widely used in aerospace, defense, and heavy industries for producing and repairing high-value components with complex geometries and tailored material properties.

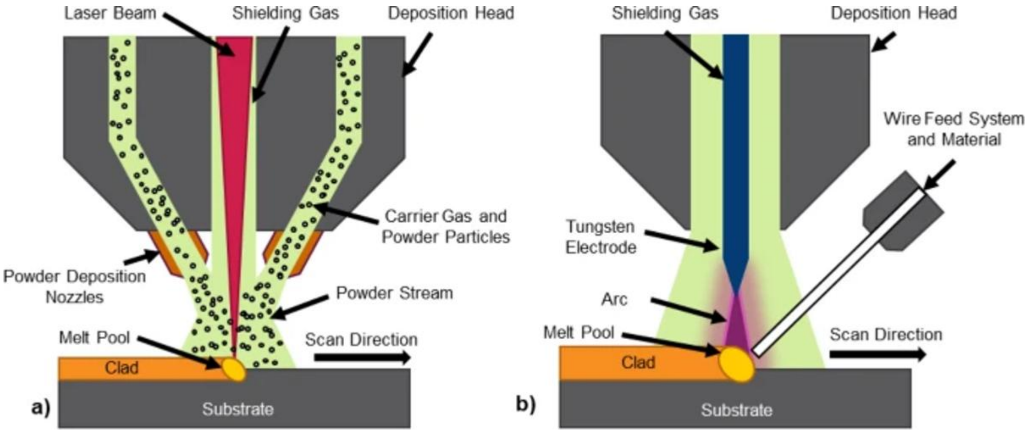


Figure 2.2: Direct Energy Deposition method [9]

2.6 Fuel system - current D4/D6 engines

The fuel system of a D4/D6 engine consist of the fuel tank, filters, high-pressure pump, common rail, injector, inlet fuel pipes, fuel injection pipes, hoses, fuel chamber, rail pressure sensors and fuel return lines.

The inlet fuel pipes help to transfer the fuel from the fuel tank to the filters and then to the high-pressure pump. The pre-filters and fine filters are used to remove larger and smaller contaminants from the fuel and ensure that the fuel is clean. After filtration, the fuel enters the high-pressure pump, where the pressure can be up to 2000 bars. This pump consists of 2 portions, low pressure section and a high-pressure section. A balance pipe is used between the low-pressure section and high pressure section of the pump, which balances the pressure between the two portions. Initially, the fuel from the filters enters the low-pressure section of the pump and then moves to the high-pressure section of the pump. In the high-pressure section, the pressure of the fuel can be raised up to 2000 bars by ensuring proper atomization for efficient combustion. The fuel from the high-pressure pump is then directed to the common rail system with the help of inlet fuel pipes.

The common rail acts as a reservoir for the high-pressure fuel. The fuel injection pipe acts as a connection between the common rail system and the injectors and helps to transfer fuel from the rail to the injectors. These fuel injection pipes are single-walled. Rail pressure sensors are used to monitor the pressure of the fuel inside the common rail.

Based on regulations, for engines greater than 375 kW, the fuel injection pipes are

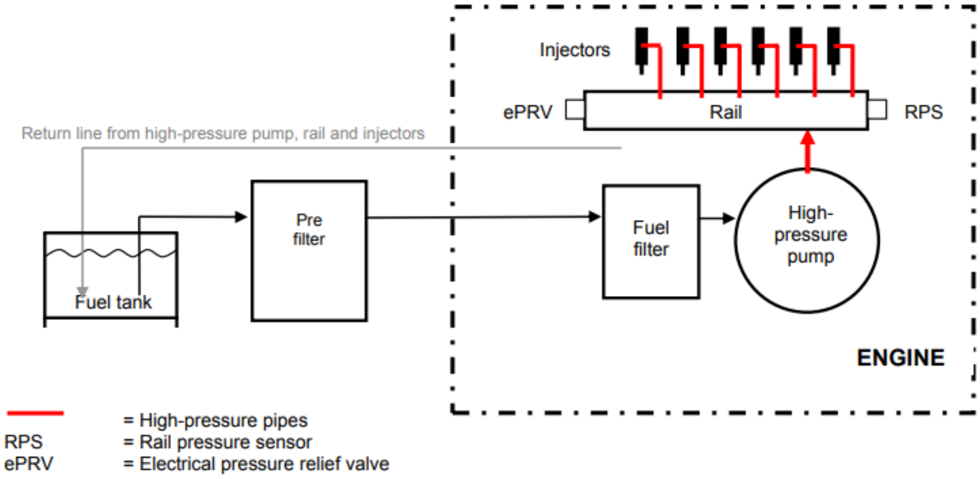


Figure 2.3: Layout of fuel injection system

supposed to be jacketed or double-walled system. These fuel injection pipes have 2 pipes in them; The inner pipe is used to transfer high-pressure fuel from the common rail system to the injectors, whereas the outer pipe serves as a safety feature to collect the fuel leakage in case of a crack in the inner fuel injection pipe. An alarm is triggered in case of fuel leakage.

3

Methodology

This chapter explains the various stages involved in the development process. It also gives an overview of the methods and tools used and their effect on the final result.

3.1 Product development methodology

The product development process was carried out using a stage gate process as proposed in the book Product Design and Development by Ulrich, K. T., Eppinger [4]. The planning phase was carried out extensively and involved analyzing the existing design, understanding legal and user requirements, establishing objectives and constraints, and formulating the mission statement. As this is a research project, the production ramp-up phase was eliminated and the prototype development phase was planned to be carried out.

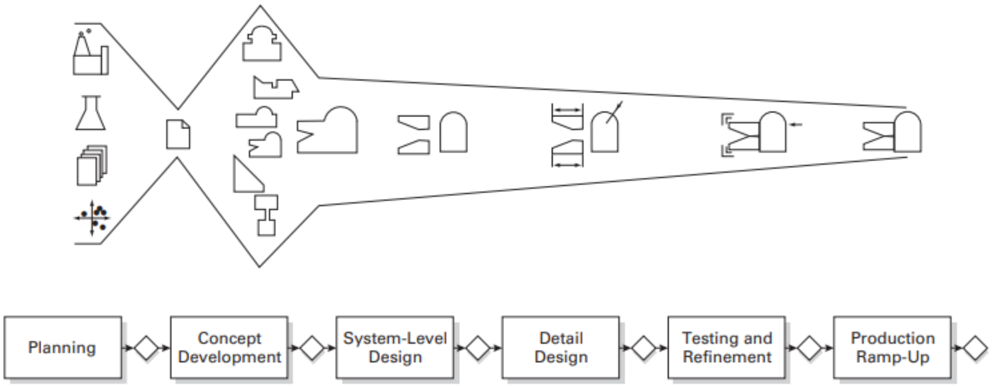


Figure 3.1: Generic product development process [4]

The proposed approach involves:

- Study and understand the existing industry standards for designing marine engines and their sub-components.
- Conduct a market and competitor analysis of current double-walled pipe solutions and identify limitations.
- Conduct interviews with Volvo Penta design engineers and fuel system engineers to define requirements and perform functional analysis.

- Generate ideas and concepts, and select the most promising concepts for detailed design.
- Design an improved high-pressure double-walled fuel injection pipe and the overall fuel delivery system using advanced CAD tools.
- Perform material selection based on manufacturability and cost. Engage with potential suppliers to evaluate feasibility and implementation potential.
- Perform relevant FEA analysis using simulation tools and optimize the design.
- Explore alternative leakage detection and alarm systems if needed.
- Develop a plastic prototype to validate the design effectiveness and functionality of the proposed solutions.

In a real-world scenario, based on the thesis requirements, the detailed development process would be as illustrated below:

Figure 3.2: Detailed development process

3.2 Literature study

The literature study was carried out to analyze existing products and patents, thereby gaining insights into existing systems. The research questions played a vital role in identifying areas for exploration. Initially, the focus was on the design of existing high-pressure double-walled pipes, and later in the process, the study expanded towards exploring manufacturing processes and materials used. Additionally, the investigation into potential leakage detection and alarm systems used in high-pressure fuel delivery systems was also carried out in this process.

3.3 Regulations study

The regulatory study was carried out by looking into the necessary regulations established by the classification societies that helped to establish the requirements and identify the areas where improvements were possible. This study was useful in establishing the do's and don'ts and played a crucial role in driving the development process in the right direction.

3.4 Requirement specification

The requirement specification was performed to integrate the legal, internal, and user needs and establish the characteristics of the product to be developed. The legal requirements were determined following the relevant regulations, while interviews and problem analysis with Volvo Penta employees were used to identify the user and internal needs. Using this information, the essential requirements and desirable features for the product were established, aiding in the identification of key areas with wishlists.

3.4.1 Function analysis

The functional analysis was performed to define what a system should do and served as a foundation for generating ideas. Methods such as process flow modeling and function tree modeling helped perform the function analysis. In both methods, the primary function was decomposed into a number of sub-functions, which provided a structured approach for the identification of all functions of the system to be designed and improved in performing the primary function. It also led the way for unbiased idea generation.

3.5 Idea generation

This phase involved generating ideas by performing an external search, an internal search, and employing a morphological matrix. The idea generation phase was carried out primarily by using the morphological matrix as the base, where all the sub-functions of the system, identified by function analysis, were listed, and ideas were generated for each. The five-step concept development method proposed in the book Product Design and Development by Ulrich, K. T., Eppinger [4] helped generate ideas for each sub-function.

3.5.1 External search

An external search was performed by conducting interviews(consultation) with experts at Volvo Penta, exploring patents, performing a literature study, and benchmarking competitor products. The external search is a continuous process and was started during the problem analysis phase and continued throughout the concept development and evaluation phase.

Interaction with design engineers, fuel system specialists, manufacturing engineers, and material engineers proved fruitful in understanding the challenges with critical sub-functions. Their expertise helped to understand functional requirements and refine the idea generation process. During external search, existing solutions were explored, and this helped in realizing the intent of design amongst competitors' double-walled fuel injection pipes. This exploration also helped identify the subproblems that did not have satisfactory solutions.

3.5.2 Internal search

Various methods were employed to generate ideas for each function, including both individual and group brainstorming sessions with the team responsible for the fuel pipes design and development. Organizing a group brainstorming session facilitated the generation of new ideas and the enhancement of existing ones. Additionally, design catalogs were utilized during these sessions to draw inspiration from established designs and to explore how other designers have tackled similar challenges.

3.5.3 Morphological matrix

Initially, function decomposition was carried out to identify several key sub-functions of the system. This analysis was further examined to uncover all the sub-functions that required idea generation to enhance the feasibility of the final concept. The ideas generated from both external and internal searches were then compiled into a morphological matrix, which outlined all the alternative solutions for each sub-function

3.6 Concept generation and screening

Concept development was carried out to collect and combine fragments of ideas in order to generate new concepts for double-walled fuel delivery pipes. The concepts developed were sketched to provide a visual illustration, enhancing the understanding of each concept.

3.7 Concept evaluation

Concept evaluation was performed to systematically narrow down the large pool of concepts generated and rank them to identify the most promising solution to be developed further. The two formal methods used in the evaluation process were concept screening and concept scoring. Concept screening was carried out by evaluating each concept against an established set of criteria related to the customer needs, functional, manufacturing, and regulatory requirements of the product using a Pugh matrix. After screening, concept synthesis was performed to combine similar concepts.

This was followed by a more sophisticated concept scoring performed by a Kesselring matrix, whereby weight was assigned to each criterion in relative impact towards the determination of the success and feasibility of the ultimate design. Concepts were ranked, and the top-ranking concepts were selected for development.

3.8 Detail design

The detailed design was performed for the final concepts that were selected in the concept development phase using PTC Creo software. In this phase, material selection and optimization of the manufacturing process were also carried out. In addition to this, an approximate cost calculation was also performed. Some of the parts in the final design were prototyped to ensure that the final product would match the design intent. The assembly process, purpose, and functionality of each component in the design are described and illustrated.

3.9 Simulation and validation

To validate the proposed design concept, an in-depth finite element analysis was performed. Simulations such as static structural, Fatigue analysis, transient structural, and modal analysis were performed using the Ansys workbench software in order to analyze the ability of the design to withstand internal pressures, mechanical loads, thermal effects, and engine vibration. The analysis was carried out using different materials for each component of the product to study the cost vs. efficiency trade-off. The results were validated through discussions with Volvo Penta experts and benchmarking with scientific literature and industry standards.

4

Literature study

This chapter reviews research and patents related to double-walled fuel pipes, focusing on material behavior, fatigue, corrosion, and leak detection. It explores about the conventional manufacturing challenges and additive manufacturing opportunities for double-walled pipes. The discussion also highlights key findings, limitations, and gaps in current studies.

4.1 Academic research paper

The academic paper titled Additive Manufacturing of Steels was chosen because it addresses the consideration of process parameters for PBF and DED technologies to manufacture fuel system components [10]. While DED is able to accommodate large, intricate geometries, it has a tendency towards rougher surfaces; conversely, PBF offers smoother surfaces but may introduce residual stress. The important tradeoff in these 2 methods for double-walled pipe construction, are the internal precision and concentricity of the pipe. It is evident from the review that post-processing HIP (Hot Isostatic Pressing) and machining are required; however, those processes have to be performed to meet vital structural integrity requirements. This review also describes the microstructure and mechanical properties of steels used in high-pressure applications.

The next academic paper titled fatigue properties of additively manufactured metals was selected because of its cross-alloy comparison on fatigue response tendencies over a wide range of materials like stainless steel, nickel alloys and titanium [11]. The study points out that the build orientation, surface finish, and defect density hold greater value than the material itself when considering overall fatigue life–often shifting attention away from the material composition entirely. This information is critical in applications such as double-walled fuel pipes where cyclic loading alongside constant vibrations occurs. That paper supports the thesis focused on optimizing process parameters alongside post-processing techniques to yield desired results.

4.2 Patent review

The patent US4149568A, known as double-walled fuel line for injection engines, describes an initial design for double-walled pipes or jacketed fuel pipes [12]. It describes a concentric pipe system where the outer sleeve captures potential leaks from the inner high-pressure line and directs them safely to a vent or collection point. This system enhances safety in diesel engine applications since it mitigates fuel spray interacting with hot surfaces. The patent matters for marine safety regulations because it captures the geometry and philosophy of passive safety systems that are still used today. For this thesis, the design principles presented here inform the structural arrangement of the containment layer, which must balance reliability, manufacturability, and regulatory compliance even when transitioned to additive manufacturing methods.

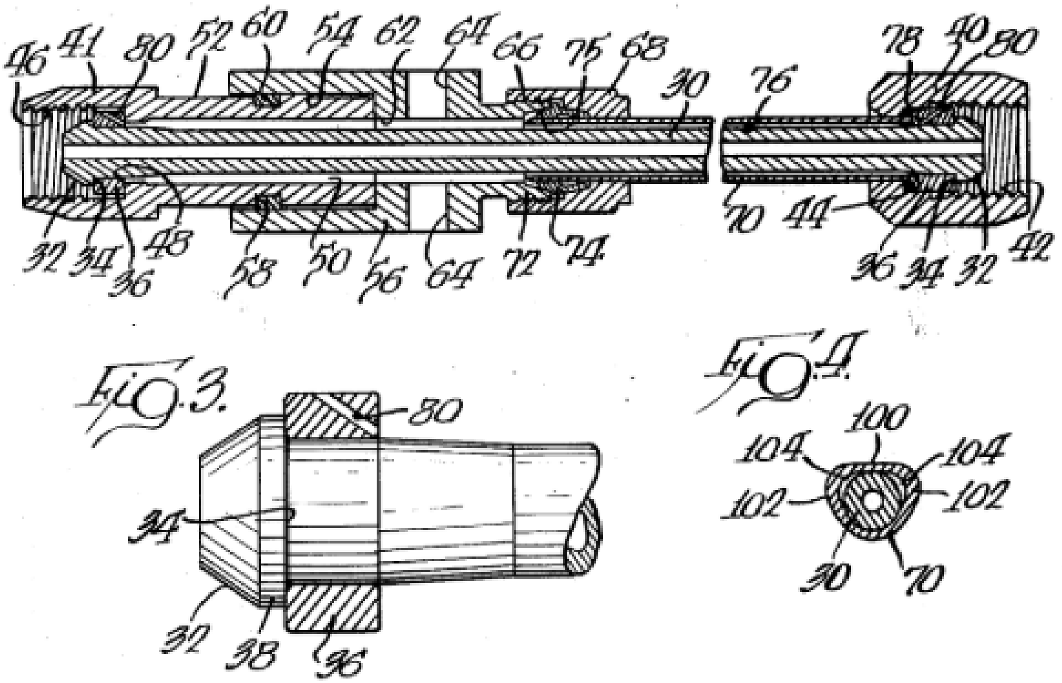


Figure 4.1: Patent review 1: US4149568A [12]

The patent US7770602B2 “Double wall pipe with grooved outer sleeve” describes an improvement of previously existing double-walled pipe systems [13]. Instead of having a circular cross-section for the outer pipe, a star-shaped structure (longitudinal grooves), that directs leaked fuel toward a monitoring or drainage point. This design improves leak transport without significantly increasing pipe diameter or complexity. It is especially advantageous for systems where prompt detection of minor leakage is necessary before catastrophic failure occurs. From a design perspective, the integration of defined flow paths into the outer wall helps manage small-volume leaks while minimizing the risk of pressure buildup. This is very important in additive manufacturing, where such designs can be incorporated directly into the print, eliminating the need for extra steps like secondary machining and assembly. The patent demonstrates not only mechanical innovation but also integration driven by AM that is functional.

The patent WO2005/038232A1, Leak alarm integrated in a high-pressure line takes a more proactive stance toward safety against fuel leakage [14]. This specific design

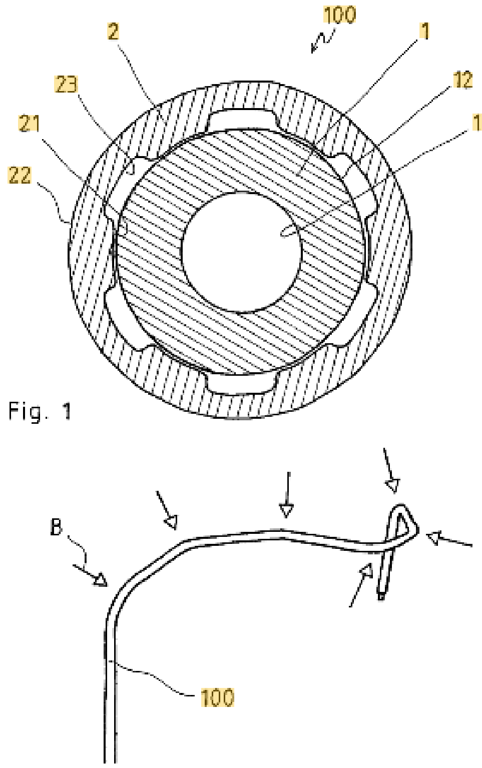


Figure 4.2: Patent review 2: US7770602B2 [13]

places a pressure sensor at the annular leak zone of a double-walled pipe. If the inner pipe breaks due to a crack, the fuel is then sprayed into the outer pipe, which also builds up pressure between layers and would trigger an alarm. This patent is significant because it merges containment with leak detection and active monitoring. It goes further to ensure that leaks not only remain contained but also generate alerts on time to prevent escalation. For purposes of this thesis, the patent backs the argument for incorporating mechanical or sensor-based monitoring into AM-manufactured parts. It reinforces the notion that containment and detection should not be treated as separate systems but rather as a combined design challenge that can benefit from AM's capacity for embedded functionality.

4.3 Summary and research gaps

The reviewed papers and patents provide important information on the additive manufacturing of steels, fatigue performance, and double-walled pipe designs. In the paper The Additive Manufacturing of Steels (2020), issues with PBF versus DED were discussed and post-processing was emphasized due to its importance for the part's integrity. Yi et al. (2023) discussed that build orientation, surface finish, as well as defect density are more critical than material selection for fatigue life, which is particularly important for components subjected to cyclic loading. Patent US4149568A describes a basic double-walled pipe system designed to contain leaks safely from a structural perspective. Patent US7770602B2 improves this with outer sleeves that have grooves which guide leaks more efficiently while

WO2005/038232A1 adds active detection through pressure sensors. Together these sources provide critical design, process and safety parameters needed for constructing dependable double-walled fuel pipes with AM techniques.

These contributions are important, but there are still gaps that need to be addressed. There is no research that focuses on double-walled pipe geometries made from AM and examines them under cyclic pressure, vibration, and marine environment conditions. Existing literature address portions of the problem, such as focusing on fatigue or leak detection, but not how they work within AM-manufactured pipes. Moreover, integrating features for containment and sensing with AM remains largely unexplored, leaving uncertainty about how to optimize designs for durability, safety, and manufacturability in real-world marine applications.

5

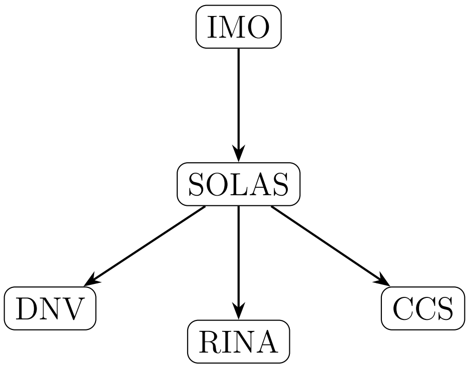
Regulation study

This chapter aims to describe the framework regulations and their impact on the project. It also discussess the regulatory requirements that are important in the design and development of the high-pressure fuel delivery pipes.

5.1 Framework of regulatory bodies:

The thesis mainly originates from changes in regulations with respect to the high-pressure fuel delivery system. To understand the nature of these regulations and their importance in the approval of marine engines, a comprehensive study of the regulations is carried out. It is found that there are classification societies that outline the rules and regulations for the construction of ships and their components.

Different regions follow various classification societies, which are established according to the specific requirements of those areas. These classification societies utilize the SOLAS convention and the IMO as a foundational reference to develop their regulations. To gain a better understanding of this, a detailed study of the framework and purpose of each of them was conducted, as is illustrated below.



5.2 Overview of regulatory bodies:

The International Maritime Organization (IMO) is a specialized agency of the United Nations that provides a framework of global standards for the safety, security, and environmental performance of international shipping among member states in the maritime sector [15].

The International Convention for the Safety of Life at Sea (SOLAS) is one of the key conventions developed and maintained by the IMO. It is continuously updated to address emerging safety concerns and technological advances in the maritime industry. It also establishes minimum safety standards for the construction of ships, the equipment used, and the operation of vessels. The IMO is tasked with reviewing and updating SOLAS to incorporate advancements in technology, changes in operational practices, and emerging safety concerns [16].

Classification societies are independent organizations that establish and maintain technical standards to assist shipowners in the design, construction, and maintenance of vessels, ensuring their safety for operation [17]. They play a crucial role in ensuring the safety, reliability, and environmental compliance of ships operating in international waters.

These societies issue classification certificates, which indicate that a vessel meets the required safety and performance standards. This certification is often essential for ships to operate legally and obtain insurance. Classification societies align their rules and standards with regulations established by the IMO, including SOLAS. There are many classification societies, and some of the prominent societies are DNV, RINA, ABS, LR, CCS, and BV. These classification societies are differentiated based on their geographical location and specialization.

5.3 Key takeaways from maritime regulations:

As these regulations play a crucial role in the design and development of high-pressure fuel delivery pipes, an in-depth study of these regulations is conducted, and some key takeaways related to current issues are [15]:

- All external high-pressure fuel delivery lines between the high-pressure fuel pumps and fuel injectors are required to be protected with a jacketed piping system capable of containing fuel from a high-pressure line failure [15].

- For engines of less than 375 kW where an enclosure is fitted, the enclosure is to have a similar function to jacketed pipes, i.e. prevent spray from a damaged injector pipe impinging on a hot surface [15].

- The enclosure should completely surround the injection pipes except that existing “cold” engine surfaces may be considered as part of the enclosure [15].

- Two systems - rigid sheathed fuel pipe and flexible sheathed fuel pipe. In both systems the sheathing is to fully enclose the pipe [15].

- The drainage system should have leakage detection alarm [15].
- Fuel system is designed to accommodate the high-pressure pulses which will be generated by the injection pumps [15].

Scandinavian countries such as Norway, Sweden, and Denmark follow DNV regulations as they integrate into their national maritime laws and practices. Many shipowners, operators, and manufacturers in these countries adhere to DNV standards to ensure compliance, and it is also widely recognized in the maritime industry for its stringent safety and quality standards. The DNV also clearly states that [3]:

- All external high-pressure fuel injection lines between injection pumps and injection valves shall be screened by jacket pipes in such a way that any leaking fuel is safely collected, drained away unpressurized, and alarmed upon leakage [3].
- The high-pressure fuel pipe and the outer jacket pipe shall be of permanent assembly [3].

6

Requirements and functions

This chapter discusses the requirements and desires for high-pressure fuel injection pipes. It also involves function analysis using the process flow model and the function tree model.

6.1 Requirement specification

The requirement specification serves as the basis for the development of double-walled high-pressure fuel injection pipes. These requirements were derived primarily from the regulations set forth by international classification societies. In addition to that, the technical specifications of the existing single-walled high-pressure fuel injection pipes, user and customer needs were also used to formulate a comprehensive list of both mandatory requirements and desirable features.

6.1.1 Product requirements

The table 6.1 displays the set of target requirements that the final design must satisfy to ensure regulatory approval, safety, and functional reliability. The requirements such as R1, R2, R3, R5, R6, R7 and R10 must be satisfied to gain approval from the classification societies. Other requirements such as R4, R8 and R9 are framed based on the technical specifications of existing single-walled high-pressure fuel injection pipes developed by Volvo Penta.

ID	Requirement description
R1	Inner pipe must be made of steel or other approved materials
R2	Inner pipe must withstand approximately 3000 bar pressure
R3	Both inner and outer pipes must be corrosion resistant
R4	Outer pipe must withstand approximately 10 bar pressure
R5	All materials must meet fire resistance regulations
R6	Leaked fuel must be safely collected and drained away
R7	Connection between pipes must be a permanent joint/assembly
R8	Pipes must withstand high-pressure pulses from the engine
R9	Both pipes must withstand temperatures up to 70-80°C
R10	The leakage detection system must have an alarm

Table 6.1: Product requirements

6.1.2 Product desires

In addition to the mandatory requirements, a set of desires as illustrated in table 6.2 are formulated based on the user needs, problem definition, and discussions with Volvo Penta engineers. These desires play a key role in enhancing the manufacturability, cost, performance, and ease of assembly of the final design.

ID	Desirable features description
D1	The solution should be cheap
D2	The solution should be easy to manufacture
D3	It should have sufficient tolerance for easier assembly
D4	It should be easy to assemble
D5	The number of joints should be minimal

Table 6.2: Product desires

Problem analysis and the aim and objectives of the thesis work also contributed significantly to the formulation of requirements and desires. The final specifications of these double-walled high-pressure fuel injection pipes were established after developing the most promising concepts. Trade-offs were necessary between certain requirements and desires to balance performance, manufacturability, and compliance with regulations. The resulting specification forms the basis for simulation, evaluation, and future development.

6.2 Function analysis

Design challenges in general are complicated and solving them as a whole can be tricky. To counteract this, the problem is effectively broken down into several simpler sub-problems, which is known as problem decomposition. This section provides a structure for problem decomposition using established function analysis models.

6.2.1 Process flow model

The function analysis is performed using the process flow model, where the black box incorporates the main functions of the double-walled high-pressure fuel injection pipes. The main functions are the step-by-step working process of the fuel system, and this breakdown served as a foundation for concept generation during the design phase.

The fuel supply to the high-pressure pump (HPP) is considered as the input, and directing the leaked fuel to the tank is considered as the output. The inputs and outputs of the system are defined outside the black box as illustrated in figure 6.1. In this model, the focus is limited to the sections of the fuel system where high-pressure fuel (HPF) is involved, rather than representing the entire fuel system process.

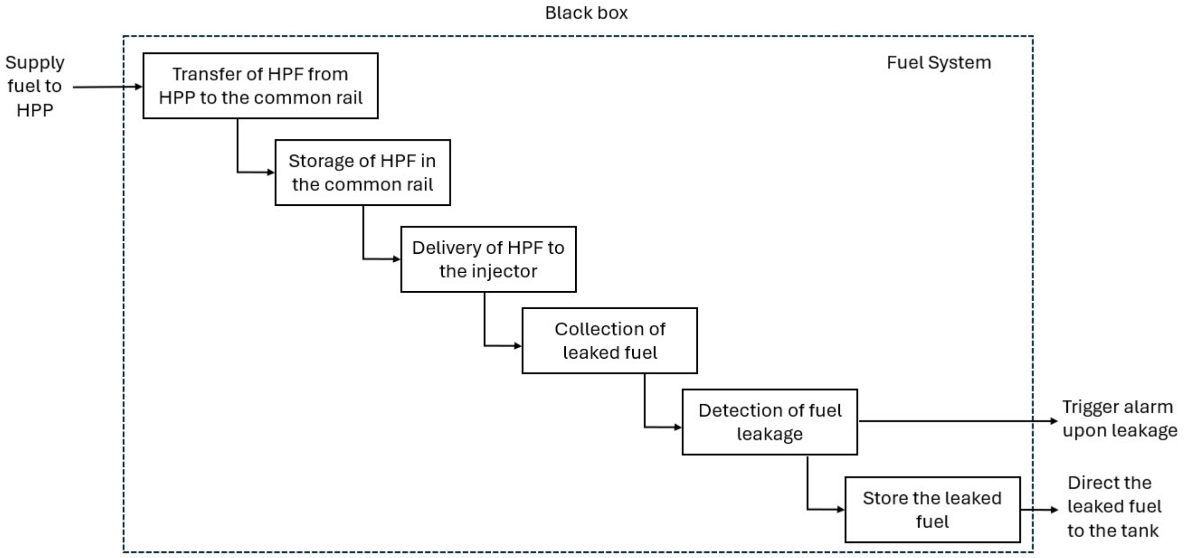


Figure 6.1: Process flow

6.2.2 Function tree model

While the process flow model establishes the major sub-functions of the system, certain other functions are difficult to illustrate within its structure. To counter this better, a function tree model is utilized (Fig 6.2) as a tool to develop a more comprehensive and hierarchical description of the system functions so that no critical functions are omitted at the concept development phase.

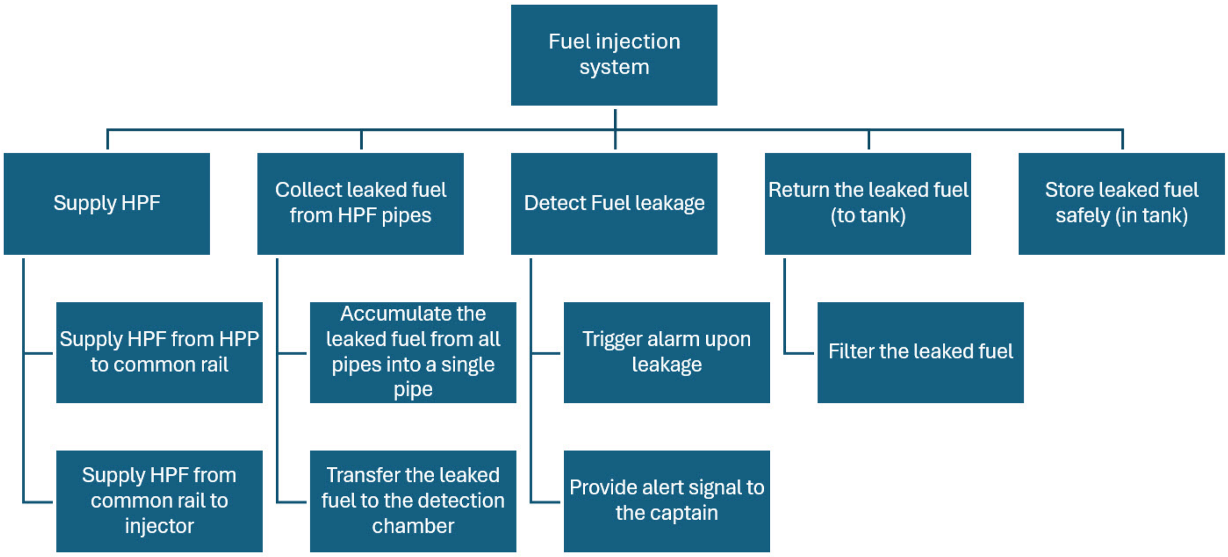


Figure 6.2: Function tree

7

Concept development

This chapter represents a crucial part in the life cycle of product development, where initial ideas for performing each function are generated and transformed into possible concepts that serve as a potential solution to the problem.

7.1 Idea generation

By performing the external search and internal search, several ideas for the key sub-functions were generated and are illustrated in the appendix A. The morphological matrix proved to be a useful tool in visualizing the ideas, allowing for a clear comparison of alternative solutions for each sub-function. The important sub-functions for which ideas are developed are:

- Supply high-pressure fuel
- Connect the HPF pipe to the collection unit
- Suppress vibrations
- Collect leaked fuel
- Detect leakage
- Return leaked fuel
- Store leaked fuel in the tank

The ideas generated during this phase were further analyzed in subsequent phases.

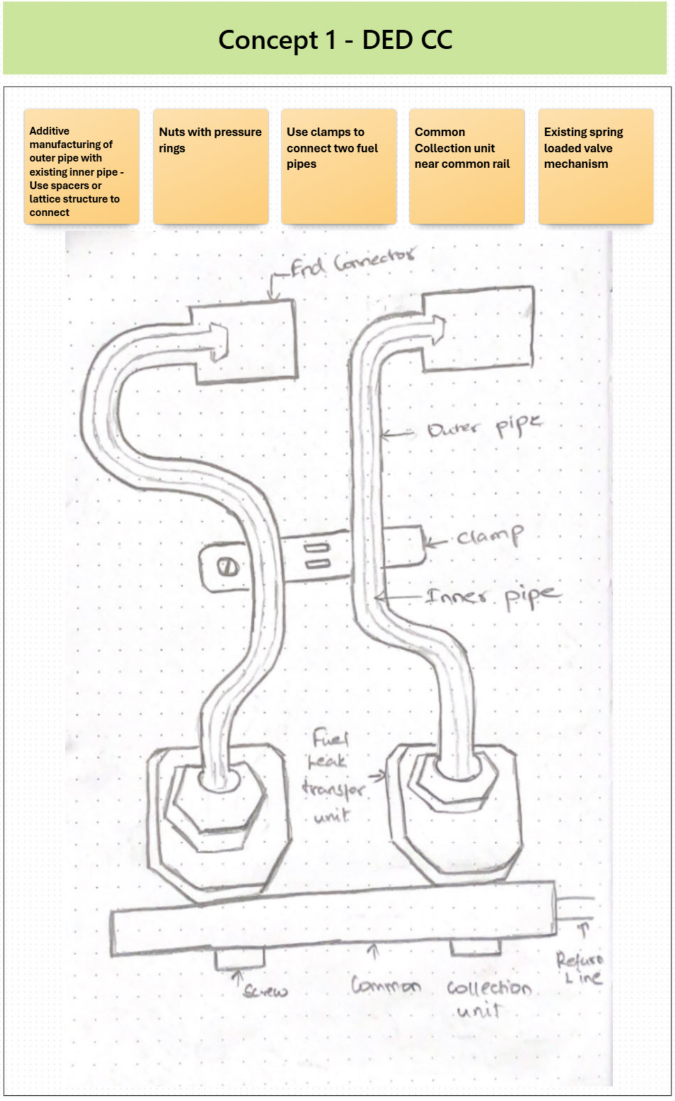
7.2 Concept generation

The concept generation phase played an important role in the development of all concepts. In this, a complete concept is developed by integrating alternative solutions from the idea generation phase for each sub-function. The SCAPMER method provided by Osborn [18] was useful in this concept generation process. the SCAMPER technique is a creative thinking framework based on seven strategies: Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse [18]. Each of these prompts was used to challenge conventional thinking and explore new possibilities. The concepts are sketched out to determine if they can work and if they are a feasible solution. This phase is particularly exciting, as it allows the generation and visualization of potential product concepts.

7.2.1 Concept 1: DED of outer pipe

The first concept focuses on the utilization Directed Energy Deposition (DED) process [8], an additive manufacturing method that enables the outer pipe to be printed around an existing inner pipe. The design incorporates standard nuts equipped with pressure rings as end connectors. These connectors are intended to apply pressure to the flare end of the inner pipe, ensuring a secure fit with the common rail and injectors. In addition, a dedicated leakage transfer unit is attached to each pipe to facilitate the transfer of leaked fuel from the outer pipe to a common collection unit.

The leaked fuel in the collection unit flows to the sensor through a return line. The sensor is a spring-loaded valve sensor that detects fuel leakage whenever the leakage pressure exceeds 5 bar. Upon reaching this threshold, the valve opens, allowing the leaked fuel to be returned to the fuel filter and tank, thereby enhancing safety and efficiency. Clamps are also added to secure the two pipes, ensuring that vibrations are kept to a minimum.


Concept 1 - DED CC

Additive manufacturing of outer pipe with existing inner pipe - Use spacers or lattice structure to connect

Nuts with pressure rings

Use clamps to connect two fuel pipes

Common Collection unit near common rail

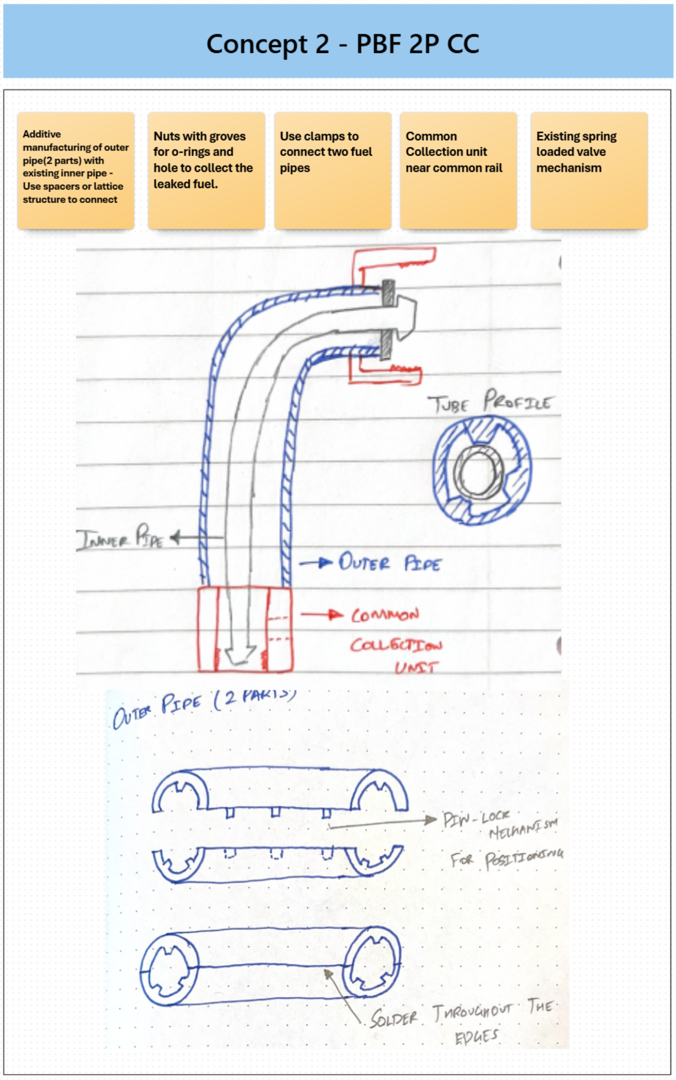
Existing spring loaded valve mechanism

Figure 7.1: Concept 1

7.2.2 Concept 2: PBF of outer pipe in 2 halves

The second concept is based on the powder bed fusion additive manufacturing process [6]. In this approach, the outer pipe will be printed in two halves, allowing for assembly over an existing inner pipe. The two halves, after being assembled, will be attached together using clamps or by employing any joining activity. A customized end connector is planned for use in this concept. This end connector will feature grooves for o-rings and a hole to transfer any leaked fuel to the collection unit.

The difference between this concept and concept 1 is that there is no separate fuel leakage transfer unit; instead, the leaked fuel is directly transferred through the end connector. The fuel leakage collection unit and the sensor system will remain the same as in concept 1.



Concept 2 - PBF 2P CC

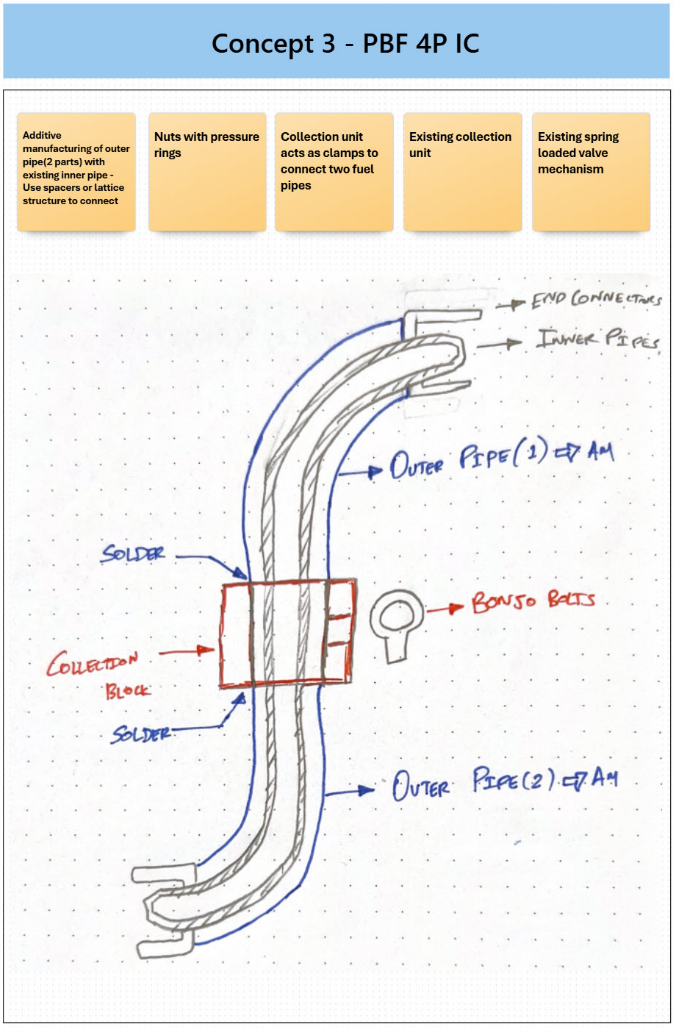
- Additive manufacturing of outer pipe(2 parts) with existing inner pipe - Use spacers or lattice structure to connect
- Nuts with groves for o-rings and hole to collect the leaked fuel.
- Use clamps to connect two fuel pipes
- Common Collection unit near common rail
- Existing spring loaded valve mechanism

Figure 7.2: Concept 2

The rationale behind this concept is that products can be produced with high accuracy over the traditional method of bending two pipes together which causes deformation and ovality to the outer pipes, which are intended to maintain a circular form. The tube features an internally ribbed circular profile that separate the inner and outer walls. This geometry aids in structural stability, leak channeling, and precise spacing between components.

7.2.3 Concept 3: PBF of outer pipe in 4 halves

The third concept also uses the powder bed fusion process [6] to make the pipes. In this approach, the pipes are produced in four halves instead of two, with all four halves connected to a central collection unit. The pipes are planned to be made of metal, and the connections can be made by soldering or welding, whichever is more preferable. This collection unit is designed to house and collect leakage from two individual double-walled high-pressure fuel injection pipes while also acting as a clamp to limit vibrations. This system is similar to the existing double-walled prototype pipes.



Concept 3 - PBF 4P IC

Additive manufacturing of outer pipe(2 parts) with existing inner pipe - Use spacers or lattice structure to connect

Nuts with pressure rings

Collection unit acts as clamps to connect two fuel pipes

Existing collection unit

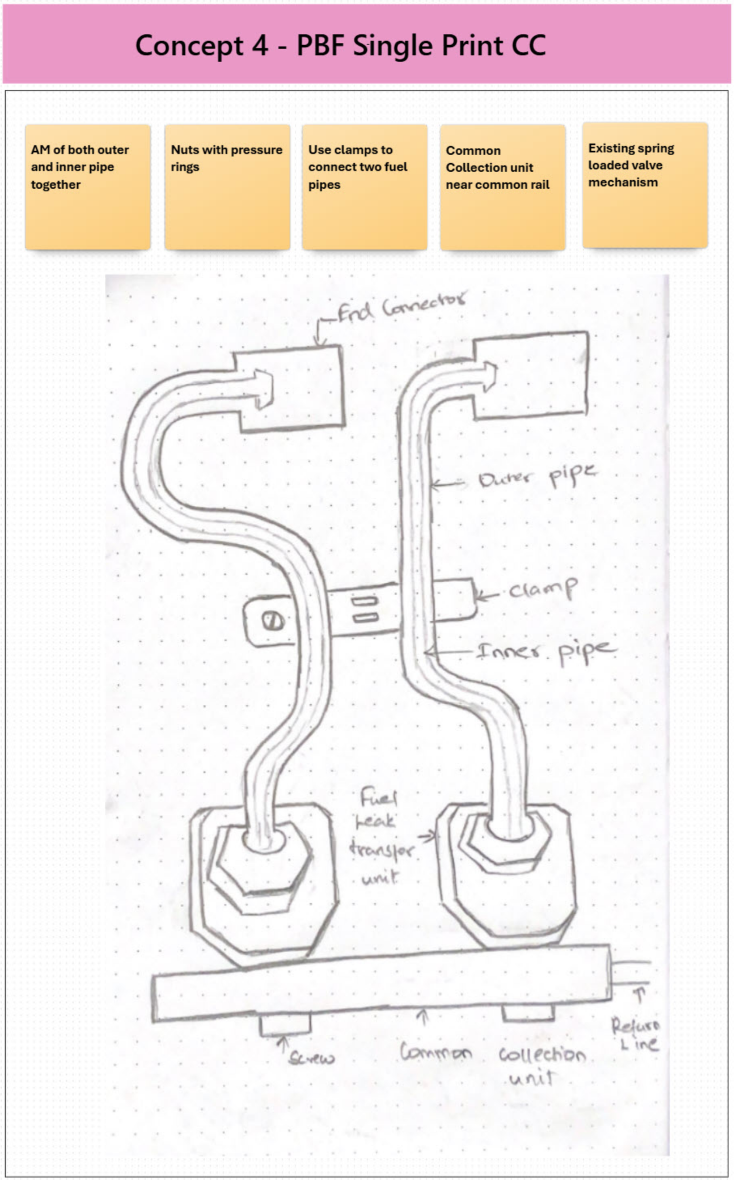
Existing spring loaded valve mechanism

Figure 7.3: Concept 3

7.2.4 Concept 4: PBF single print

This concept employs the powder bed fusion method for manufacturing both the inner and outer pipes, as they can be produced with the same material. It significantly differs from concepts 2 and 3, as both the inner and outer pipes are produced in a single print, eliminating the need for assembly. End connectors with pressure rings and fuel leakage collector will also be printed along with the pipes in this design, reducing assembly operations and design complexity.

Fuel leak transfer unit and the collection unit remains the same as in concept 1. In addition, clamps are used to suppress the vibration of the pipes. Existing spring-loaded valve sensors are designed to be used in this concept.



Concept 4 - PBF Single Print CC

- AM of both outer and inner pipe together
- Nuts with pressure rings
- Use clamps to connect two fuel pipes
- Common Collection unit near common rail
- Existing spring loaded valve mechanism

Figure 7.4: Concept 4

7.2.5 Concept 5: PBF with polymer spacer

In concept 5, the design of the system is mostly similar to that of concept 2, where the outer pipe is printed in 2 halves and is assembled over an existing inner pipe. The major difference in this concept lies in the cross-section of the outer pipe. In earlier concepts, the outer pipe profile is not circular and includes an internally ribbed circular profile.

In this concept, instead of modifying the pipe profile, a circular profile is maintained and an external spacer is planned to be used as a structural support to reduce vibration. This reduces manufacturing complexity because the projection is minimal, thereby decreasing the likelihood of overhang deformation. Depending on the system's requirements, either rubber or plastic polymer spacers can be utilized. The fuel leak collection and detection system remains the same as of concept 2.

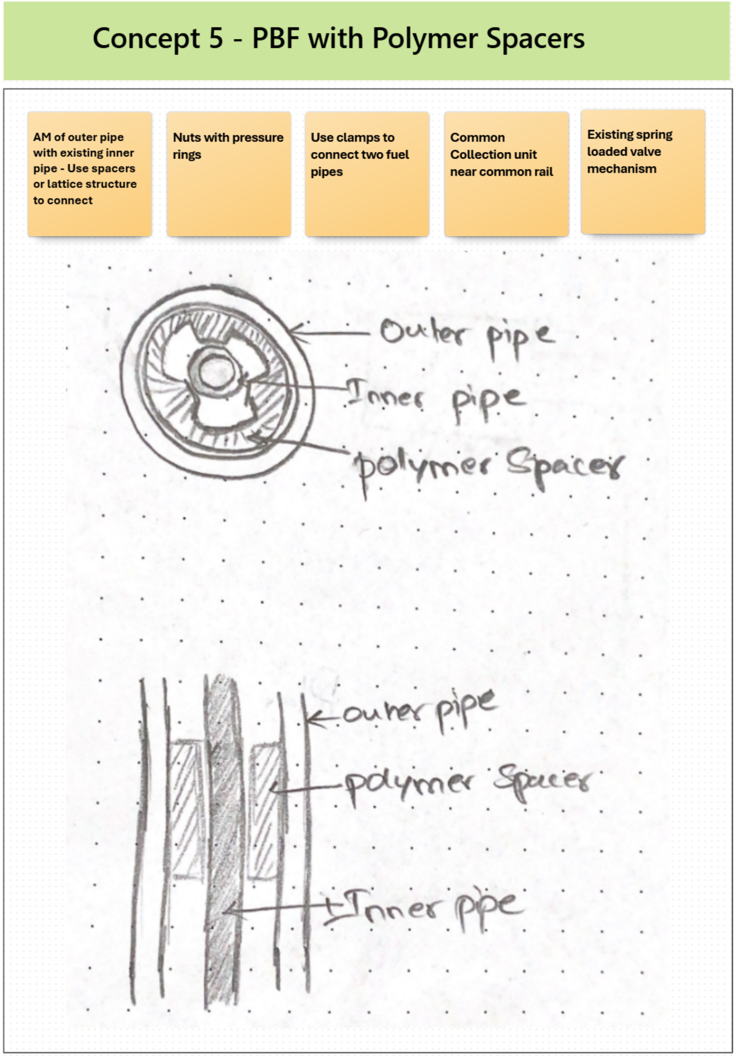
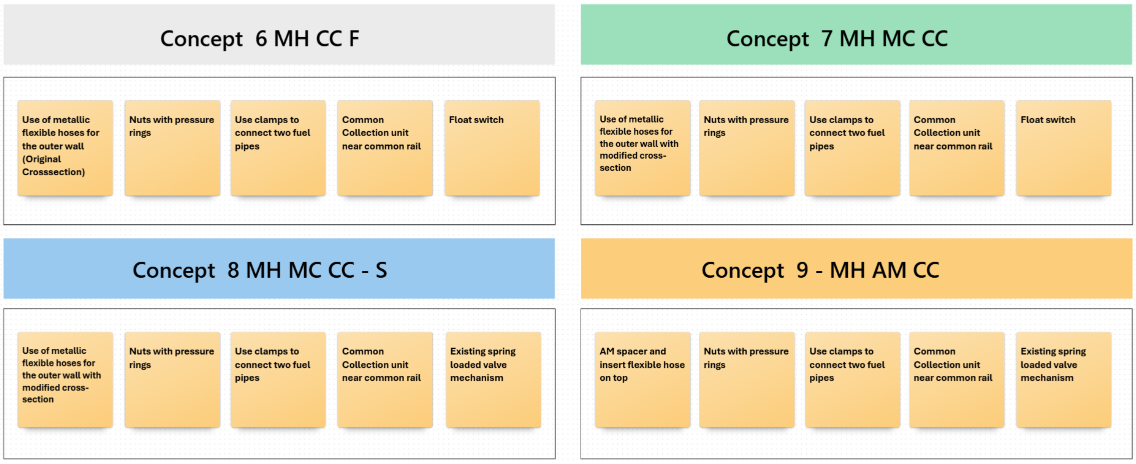


Figure 7.5: Concept 5

7.2.6 Concepts 6 to 9: Flexible metallic hoses

Concepts 6 to 9 are different from the concepts discussed earlier. These concepts are based on utilizing metallic flexible hoses instead of rigid metal pipes. As discussed earlier during the regulations study phase, rigid and flexible sheathed pipes can be used in the double-walled high-pressure fuel injection pipes. These flexible hoses are made of a number of layers, which can be customized to various materials and configurations.



Concept 6 MH CC F	Use of metallic flexible hoses for the outer wall (Original Crosssection)	Nuts with pressure rings	Use clamps to connect two fuel pipes	Common Collection unit near common rail	Float switch
Concept 7 MH MC CC	Use of metallic flexible hoses for the outer wall with modified cross-section	Nuts with pressure rings	Use clamps to connect two fuel pipes	Common Collection unit near common rail	Float switch
Concept 8 MH MC CC - S	Use of metallic flexible hoses for the outer wall with modified cross-section	Nuts with pressure rings	Use clamps to connect two fuel pipes	Common Collection unit near common rail	Existing spring loaded valve mechanism
Concept 9 - MH AM CC	AM spacer and insert flexible hose on top	Nuts with pressure rings	Use clamps to connect two fuel pipes	Common Collection unit near common rail	Existing spring loaded valve mechanism

Figure 7.6: Concepts 6 - 9

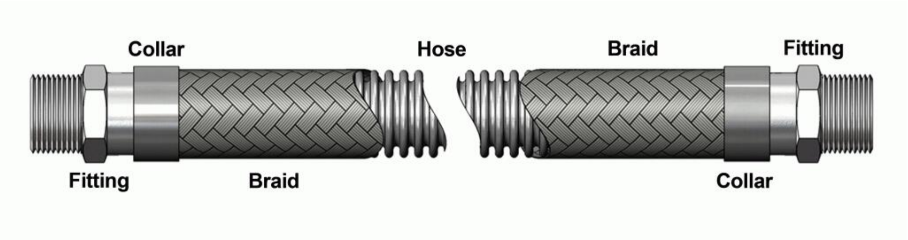


Figure 7.7: Flexible metallic hose [19]

7.2.6.1 Concept 6

In this concept, standard flexible metallic hoses available in the market can be directly bought and assembled over existing inner pipes. This concept reduces the complexity and customization of the components of the system. The detection system is different from the concepts discussed before. Instead of a spring-loaded valve sensor, a float detector is planned to be used in this system. The advantage of using a float sensor is that it does not cause pressure build-up within the sensor, which in turn reduces the pressure build-up in the pipes, thereby lowering the overall system pressure resistance requirements [20]. However, the fuel leak transfer unit and collection unit remain the same in this concept.

7.2.6.2 Concept 7

In concept 7, the flexible metallic hoses are customized with a modified cross-section. This cross-section serves as one of the layers of the flexible hose, where the outer layer is metal and the inner layer, made of polymer or rubber, acts as a protective layer to prevent metal-to-metal contact between the flexible hose and the inner pipe. Additionally, it facilitates the passage of leaked fuel. A float switch is employed as the sensor in this concept, while the fuel leak transfer unit and collection unit remain unchanged.

7.2.6.3 Concept 8

Concept 8 is similar to concept 7 in all aspects except for the sensor used. In this concept, the existing spring-loaded valve sensor was planned to be used instead of the float switch.

7.2.6.4 Concept 9

In this concept, standard flexible hoses are planned to be assembled over the inner pipe with polymer spacers placed between the flexible hose and the inner pipe. The purpose of these spacers is to avoid constant contact between the pipes. The metallic flexible hoses consists of corrugated metal tube as the inner layer, which can cause wear and tear to the inner pipe due to vibrations, which can be eliminated with the help of these polymer spacers.

7.3 Concept selection

To determine the most suitable design alternative for the jacketed fuel piping system, a Pugh matrix analysis was used. In this process the nine concepts were compared with the current market alternative based on the predefined evaluation criteria derived from system requirements. In this analysis, the current market alternative was selected as the datum, i.e., the baseline for comparison. The datum served as a neutral reference point, enabling each new concept to be evaluated relative to what is already in use.

The five main criteria with which the concepts were evaluated are functionality, manufacturability, cost, durability, and quality, each representing key performance and feasibility parameters. The first and foremost criteria was the functionality, it focused on factors like controlling leaked fuel, eliminating leakage from various joints (outer pipe, end connections, collection unit), ease of assembly, and time taken to assemble were assessed. Manufacturability involved criteria like ease of manufacturing and the number of components, while cost parameter focused on manufacturing cost and material cost. Finally, quality included aspects like durability, longevity, and surface finish for both outer and inner pipes.

The Scoring was based on expert input from Volvo Penta, existing benchmarks from the current market alternative, and estimations derived from interviews and supplier feedback. Each concept was evaluated on a relative scale where a score of +1 indicated superiority over the current market alternative, 0 indicated equivalence, and -1 indicated inferiority. The sum of positive scores, negative scores, and net values was calculated to rank each concept and provide clear guidance on whether a concept should be proceeded with, combined with others, or eliminated.

This helped rank the concepts and determine their suitability for further development. The key outcomes were as follows:

- Concept 4 (PBF Single Print CC) received the most number of +'s and had the netscore of +8. And hence it was ranked 1. It dominated the other concepts in both functionality and manufacturability criteria. It also had the potential to integrate multiple parts into a single print and reduce leakage paths.

- Concept 8 (MH MC CC S) and Concept 9 (MH AM CC) received the next maximum net score of +6. Both these concepts used metallic hoses, which are very flexible, and they dominated the other concepts in assembly factors of the functionality criteria. These concepts were much cheaper than the current market alternative with a lot of number of suppliers around the globe.

- Concept 1 (DED CC) and Concept 2 - PBF 2P CC - These concepts were pretty promising ones, and they received a net score of +5, indicating clear improvements over the datum in areas like functionality and manufacturability, and these concepts had a low manufacturing cost when compared to the datum.

- Concept 7 (MHI MC CC F) also used metallic flexible hoses and received a net score of +4. Though not outstanding, it demonstrated unique strengths in targeted functional benefits. It was also cheap to manufacture and also has better surface finish.

- In contrast, Concept 3 (PBF 4P CC) and Concept 5 (PBF with spacer) were pretty decent concepts, when compared to datum, they ranked the least with less net scores -5 and +2, respectively. Concept 3 was similar to concept 2, where in concept 2 there were 2 parts that were manufactured in AM and welded along the seam, whereas in concept 3 we have 4 pieces that would be manufactured in AM and welded along the seam. This increases the number of parts, assembly time, and fixtures when compared to concept 2. Concept 3 also lacked in both functionality and manufacturability point of view, whereas concept 5 was pretty equal to the current market alternative in almost all criteria.

Based on the net scores the below decisions were made,

- Concept 1 (DED CC), Concept 2 - PBF 2P CC, Concept 4 (PBF Single Print CC) and Concept 6 - MH CC F were proceeded to the next concept scoring

Criteria	Datum	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8	Concept 9
Functionality										
Collect Leaked fuel	0	0	0	0	+	0	0	0	0	0
No leakage from outer pipe	0	0	0	0	0	0	0	0	0	0
No leakage from end connectors	-	+								
No leakage from the collection unit	0	0	0	-	+	0	0	0	0	0
Direct the leaked fuel to fuel chamber	0	0	0	0	+	0	0	0	0	0
Manufacturability										
Easy to assemble between pipes	-	+	+	-	+	0	+	+	+	0
Easy to assemble with system	-	+	+	-	+	+	+	+	+	+
Less number of tools to assemble	-	+	+	0	+	0	+	+	+	+
Less time taken to assemble	-	0	0	0	+	0	+	+	+	+
Manufacturing Ease										
Easy to manufacture	-	+	+	-	+	+	+	-	-	+
Less number of components	0	+	+	-	+	0	-	-	+	0
Cost										
Low manufacturing cost	-	+	+	+	+	+	+	+	+	+
Low material cost	0	-	-	-	-	-	+	+	+	+
Durability										
Longevity	0	0	0	0	0	0	0	0	0	0
Quality										
Surface finish at outer pipe	+	-	0	0	0	0	0	0	0	0
Surface finishing at inner pipe	+	0	0	0	-	0	0	0	0	0
Sum of +	2	7	6	1	10	3	7	6	7	6
Sum of -	7	2	1	6	2	1	1	2	1	0
Sum of 0	5	5	6	6	2	9	5	5	5	8
Net Value	-5	5	5	-5	8	2	6	4	6	6
Rank	6	3	3	6	1	5	2	4	2	2
Decision		Proceed	Proceed	Eliminate	Proceed	Eliminate	Proceed	Combine	Combine	Combine

Table 7.1: Concept evaluation - Pugh matrix

phase.

- Concept 7 (MHI MC CC F), Concept 8 (MH MC CC S) and Concept 9 (MH AM CC) were similar in almost all function but was varying in either one or two function, so it was decided to combine these concepts into 1 and proceed it to the next concept scoring phase.

- Though Concept 3 (PBF 4P CC) and Concept 5 (PBF with spacer) had its own advantages, the net scores of these concepts were not promising and few parts of these concepts would be integrated in the other concepts in the detail design phase if needed.

7.4 Concept synthesis

Based on Scores from the Pugh matrix, it was decided to combine concept 7 (MHI MC CC F), concept 8 (MH MC CC S), and concept 9 (MH AM CC) to form a new concept for the next concept scoring phase. The new concept was synthesized by consolidating the functional strengths of all three concepts, along with implementing several enhancements to improve performance and feasibility.

All these concepts are towards the use of metallic flexible hoses with modified cross sections. Both concept 7 and concept 8 used a modified cross-section of inner PTFE tubing, whereas concept 9 used flexible hoses with circular cross-sections and additional spacers that are manufactured by additive manufacturing.

To improve functionality and manufacturability, some design features from additive manufacturing (AM) concepts were retained. For example, the insertion of the leak transfer unit and specialized sleeves was integrated to make a compact geometry with ease of assembly. Furthermore, the additive manufacturing-inspired geometries with optimized cross-sections of the inner pipe and o-ring grooves for sealing were incorporated to enhance leak containment.

The other difference in these concepts was the leak detection mechanism. Concept 7 used a float mechanism, concept 8 and concept 9 used a spring-loaded valve mechanism. One of the key aspects of the system is to reciruclate the fuel leaked from the injection pipes to the fuel tank. In case of the float mechanism, it would be difficult to send back the leaked fuel to the fuel tank as it was a separate system without recirculation. whereas the spring-loaded valve mechanism was compatible with fuel recirculation, and hence it was chosen. The resulting concept would use metallic flexible hoses with a modified cross-section and spring-loaded valve mechanism.

7.5 Concept scoring

A Kesselring matrix was used to evaluate the 5 chosen concepts. For more clarity, the concepts that were selected from the Pugh matrix and the concepts that were combined to form a single concept in the concept synthesis phase were renamed as below.

- Concept A – DED CC
- Concept B - PBF 2P CC
- Concept C - PBF single Print CC
- Concept D - Metallic flexible hose
- Concept E - Metallic flexible hoses with MC

Similar to the Pugh matrix, the Scoring was based on expert input from Volvo Penta, existing benchmarks from the current market alternative, and estimations derived from interviews and supplier feedback. The criteria that are used to evaluate the concepts were given specific weights according to their importance. All these criteria were given weights between 0 to 15.

The criteria related to functionality, such as collecting leaked fuel, no leakage from outer pipes, no leakage from end connectors, and no leakage from the collection unit, are assigned high weights. Since factors like the absence of leakage from the outer pipe, end connectors, and collection unit in the functionality criteria are very important, these were given a high weight of 10. whereas the other factors, like the ability to direct leaked fuel to the fuel chamber, have a relatively lower weight of 2.5.

Criteria related to assembly, such as ease of assembly between pipes, ease of assembly with the system, the number of tools required for assembly, and the time taken to assemble, are each given a weight of 2.5. Though these criteria were important, they were secondary requirements and not primary requirements. Manufacturability, including ease of manufacturing and the number of components, received notable attention, with "easy to manufacture" weighted at 10 and "fewer number of components" at 5.

Factors like low manufacturing cost and low material cost are assigned weights of 10 and 5, respectively, in the cost criteria. Durability is considered through the criteria of longevity and surface finishes. Longevity received a smaller weight of 2.5, indicating that although important, it is less important than performance characteristics. Surface finish is notably prioritized, especially for the inner pipe, which carries the highest weight of 15 among all the criteria. This shows that the internal surface quality is a key performance driver, since the inner wall of the inner pipe has direct contact with flammable fuel (diesel), and it should not contaminate the fuel.

The scores assigned to each concept reflect the performance of the designs across these weighted criteria. Concept A, the DED CC received a very high score on all the functionality-related aspects, consistently receiving the highest ratings of 5,

Criteria	Weight	Concept A		Concept B		Concept C		Concept D		Concept E	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Functionality											
Collect Leaked fuel	5	5	25	5	25	5	25	5	25	5	25
No leakage from outer pipe	10	5	50	4	40	5	50	3	30	3	30
No leakage from end connectors	10	5	50	4	40	5	50	3	30	3	30
No leakage from the collection unit	10	5	50	4	40	5	50	4	40	4	40
Direct the leaked fuel to fuel chamber	2.5	5	12.5	5	12.5	5	12.5	5	12.5	5	12.5
Easy to assemble between pipes	2.5	3	7.5	3	7.5	5	12.5	5	12.5	5	12.5
Easy to assemble with system	2.5	4	10	4	10	5	12.5	5	12.5	5	12.5
Less number of tools to assemble	2.5	5	12.5	3	7.5	5	12.5	5	12.5	5	12.5
Less time taken to assemble	2.5	5	12.5	3	7.5	5	12.5	5	12.5	5	12.5
Manufacturability											
Easy to manufacture	10	3	30	4	40	4	40	5	50	2	20
Less number of components	5	5	25	3	15	5	25	4	20	4	20
Cost											
Low manufacturing cost	10	2	20	4	40	4	40	5	50	4	40
Low material cost	5	2	10	3	15	3	15	5	25	5	25
Durability											
Longetivity	2.5	5	12.5	5	12.5	5	12.5	3	7.5	3	7.5
Quality											
Surface finish at outer pipe	5	3	15	4	20	4	20	4	20	4	20
Surface finishing at inner pipe	15	5	75	5	75	0	0	5	75	5	75
Net Value	100		417.5		407.5		390		435		395
Rank			2		3		5		1		4

Table 7.2: Concept scoring - Kesselring matrix

as it had the ability to prevent leakage and collect fuel effectively. But in case of manufacturability and cost, it scored 2 and 3 because, in this concept, the outer pipe is created by a unique technique called direct energy deposition. It is one of the costliest additive manufacturing techniques. Additionally, its internal surface finishing is good, which helped to maintain a strong total score. Overall, Concept A achieved a high net value of 417.5, ranking it second among the five.

Concept B, PBF 2P CC, performed a bit lower than Concept A in functionality, receiving a score of 4, which indicates it has a slight risk of leakage. In this concept, the outer pipe would be produced into 2 halves, and it would be joined with the help of glue or by soldering it, and hence it received a score of 4 rather than 5. However, its manufacturability and cost ratings were stronger, suggesting a more economical and practical production process. The surface finishing also remained strong. And hence Concept B received a total score of 407.5, and it ranked 3rd overall.

Concept C, the PBF Single Print CC, initially seemed promising, with strong scores in functionality and exceptional ease of assembly. As per the criteria, the internal surface finish of the inner pipe was the heavily weighted criterion with a score of 15, a critical issue raised in this concept due to the poor surface finish of the inner pipe, and hence this concept received a score of 0 in that particular criterion. This flaw significantly dragged down the total score. Despite otherwise good performances, this single major weakness causes Concept C to achieve the lowest net value of 390, ranking it fifth and making it the least preferred option.

Concept D, the metallic flexible hose with standard circular cross section, received very good scores in manufacturability and cost, whereas it received a low score in functionality when compared with concept A and B due to its risk of leakage. Assembly is very easy, which further boosts its practical value. It had a very high-quality internal and external surface finishes of the outer pipe. Overall, Concept D achieved the highest net value of 435, ranking first among all concepts due to its balance in manufacturing ease, cost efficiency, and sufficient functionality.

Concept E, Metallic flexible hoses with modified cross section, mirrors Concept D closely but scores slightly lower in manufacturability and cost, since it is difficult to find a manufacturer that could produce pipes with a modified cross section. But it has a lower cost and better manufacturability when compared with the traditional pipe manufacturing processes. Although the differences are subtle, they result in a net value of 395, placing Concept E fourth overall.

Based on the Kesselring matrix, Concepts 4 and 5 would be combined to form one concept with metallic flexible hoses. Finally, Concept 1, 2, and 4 would proceed to the next iteration, whereas Concept 3 would be eliminated due to its lower surface finish of the inner pipe, as that was one of the most important factors.

In the next iteration feasibility, potential suppliers and cost were taken more into consideration. In Concept 1, DED has only a few suppliers around Europe and was found to be the costliest among the 3 concepts. Concept 4 metallic flexible hoses had design constraints; it was a bit difficult to find a flexible hose that had a minimum bending radius of 18 mm and could withstand a pressure of 10 bar. Concept 2 did not have any major constraints. So at the end of concept scoring and feasibility check, Concept 2 proceeds to the detail design phase where whereas Concept 1 was eliminated, and Concept 4 was kept on hold and would be considered as a future work for Volvo Penta to deep dive into suppliers. Details regarding the design of metallic hoses are discussed in the future work section.

8

Final design

8.1 Detail design - Concept PBF

From the Concept screening phase, the concept PBF 2P CC was selected and proceeded in the detailed design phase. Creo Parametric was used to design the parts and assemble them.

The main aim of this concept is to reduce the overall cost of the double-walled fuel injection pipes and to improve the ease of assembly. The current double-walled fuel injection pipes are difficult to assemble. To achieve it, all the parts of this concept would be produced by the powder bed fusion method, except the use of standard inner pipe and end connectors.

This concept mainly focuses on printing the outer pipe into 2 halves and soldering them along the seam. With specialized end connectors and a leak transfer unit at each end of the pipe.

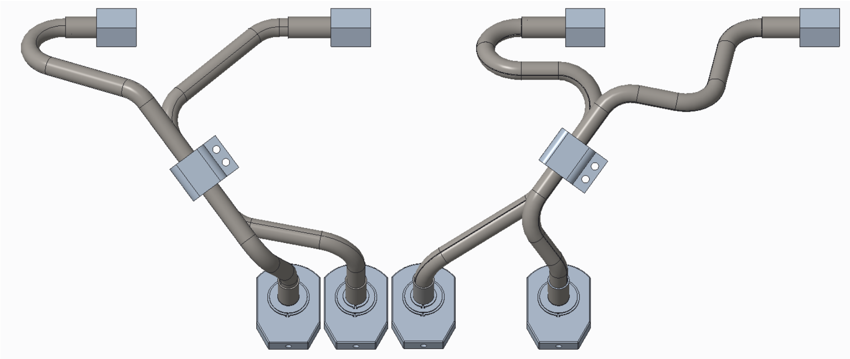


Figure 8.1: CAD model - full assembly

The parts of this concept are as follows,

- Standard Inner Pipe
- Customized Outer pipe
- Specialized sleeves
- Fuel Leak Transfer Unit
- Fuel collection unit
- Customized end connectors

- Snap rings
- Clamp
- Circlip

8.1.1 Standard inner pipe

This concept uses the Today's fuel pipe from the supplier. This is because the inner pipes are very crucial in the fuel injection system, as these pipes should be manufactured in a clean room environment to prevent surface contamination. They also need to be manufactured with high precision and surface finish. An autofrettage process is required for these pipes to improve their mechanical strength and fatigue resistance to withstand a minimum of 2000 bars. Finally, these inner pipes require a corrosion-resistant coating. Keeping all these factors in mind, it was decided to use the standard inner pipes from the supplier.

Figure 8.2: Inner pipe

8.1.2 Customized outer pipe

In this concept, the outer pipes are printed into 2 halves in the powder bed fusion additive manufacturing technique. The main reason for this is the ease of assembly. Outer pipes would be positioned above the inner pipe and would be soldered along the seam. These outer pipes have a different cross-section from the standard circular cross-section. The change in cross-section is used for positioning the inner pipe and outer pipe, as well as to collect the leaked fuel from the inner pipe and to direct it to the collection unit. The outer pipes do not have contact with the inner pipe; they have a very small clearance of about 0.3mm. This is to avoid metal-to-metal interaction, which reduces wear between the pipes.

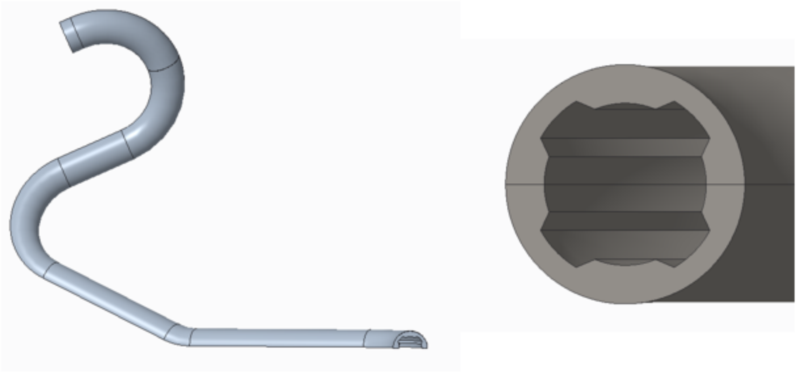


Figure 8.3: One half of outer pipe and cross section

8.1.3 Specialized sleeves

These Sleeves are soldered at each end of the outer pipe. Sleeves are with normal circular cross-section. The inner diameter of the sleeves would be the same as the outer diameter of the outer pipes. And the sleeves are designed with a step feature that helps to place the outer pipe and the sleeves in the right position, and then it would be solved around the edges. The sleeve at the common rail side has a small hole of 1.5 mm diameter to transfer the leaked fuel from sleeve to the collection unit. The end connectors and the collection unit are placed in the sleeves, and both the end connectors and the collection unit can rotate and translate along the sleeve.

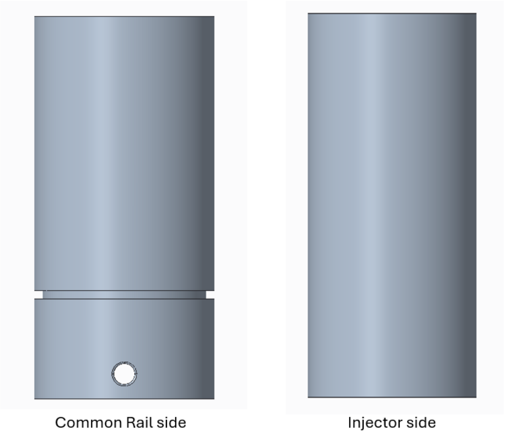


Figure 8.4: Specialized sleeves

8.1.4 End connectors and O-rings

The end connectors are used to connect the fuel injection pipes to the injector and the common rail. These end connectors are nothing but specialized nuts. The end connector in the injector end is a specialized M12 nut and on the common rail side is a specialized M14 nut. These nuts have O-rings inside it, which help for the relative motion of the nut on the sleeve and prevent fuel leakage from it.

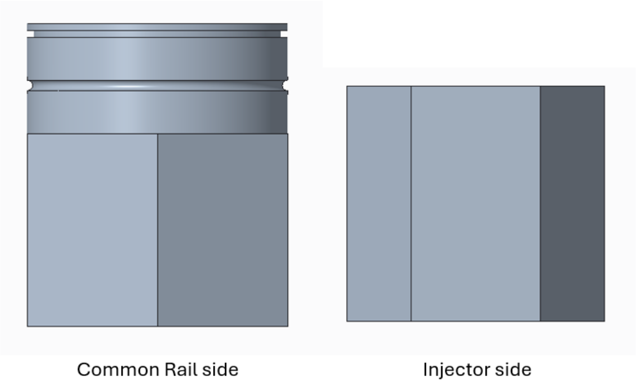


Figure 8.5: End connectors

8.1.5 Fuel leak transfer unit

The fuel leak transfer unit is placed on the top of the end connector. It is designed in such a way as to direct the leaked fuel from the sleeves to the common collection unit. The fuel leak transfer unit has a 5 mm through hole through which the leaked fuel passes. These fuel leak transfer units also have two O-rings above and below the hole to prevent fuel leakage from both ends.

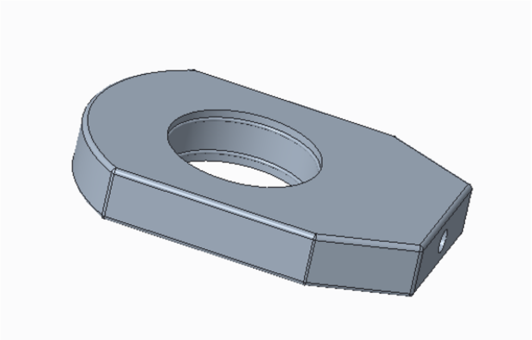


Figure 8.6: Fuel leak transfer unit

8.1.6 Common collection unit

A common collection unit is used to collect leaked fuel from the leak transfer unit and then direct it to the fuel tanks with the help of fuel hoses. In this concept, the four fuel leak transfer unit is connected to the common collection unit with a help of line banjo bolts, these are special bolts that have passage for the fuel to flow.

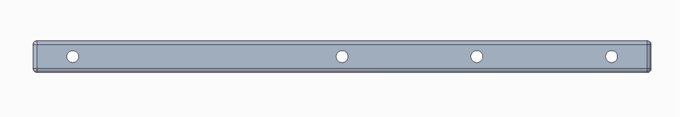


Figure 8.7: Common collection unit

8.1.7 Snap rings

Snap rings are used to pressurize the flared end of the inner pipe. The end connectors have a projection that hits the snap rings, and the snap ring hits the flared part of the inner pipe when the end connector is tightened with the common rail and injector.

8.1.8 Clamp

The clamps are used to arrest the movement of the injection pipes due to engine vibrations. The clamp consists of two parts: the inner pouch and the clamp housing. The inner pouch of the clamp is made up of rubber or polyurethane, whereas the clamp housing is made up of steel. The clamp is tightened with the help of fasteners. Typically, one clamp is used to arrest the motion of two fuel injection pipes.

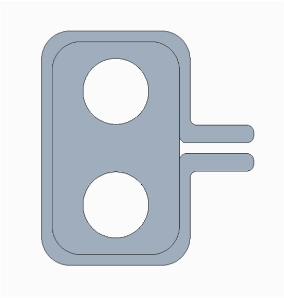


Figure 8.8: Clamp

8.1.9 Assembly

The assembly process of this concept is described below and is also illustrated in Figure 8.9.

- **Step 1:** Place the standard inner pipe in the jig.
- **Step 2:** Place both the customized outer pipe above the standard inner pipe and weld it along the seam.
- **Step 3:** Insert the sleeves through the flared part of the inner pipe, position it at the end of the outer pipe in both ends, and solder it along the edges.
- **Step 4:** Insert the fuel collection unit in the common rail side of the inner pipe.
- **Step 5:** Insert the common rail end connector in the common rail side, Position the fuel collection unit, and use a circlip to arrest the motion of the collection unit in the + Y direction.

- **Step 6:** Now translate both the common rail nut and the collection unit till the end of the sleeve and place the snap ring. This arrests the motion of the common rail nut and the collection unit in the -Y direction.

- **Step 7:** Insert the injector nut in the other end, translate it to the end of the sleeve, and place the snap ring.

- **Step 8:** Place the 2 fuel injection pipes and clamp them to prevent the motion of the pipes from engine vibration.

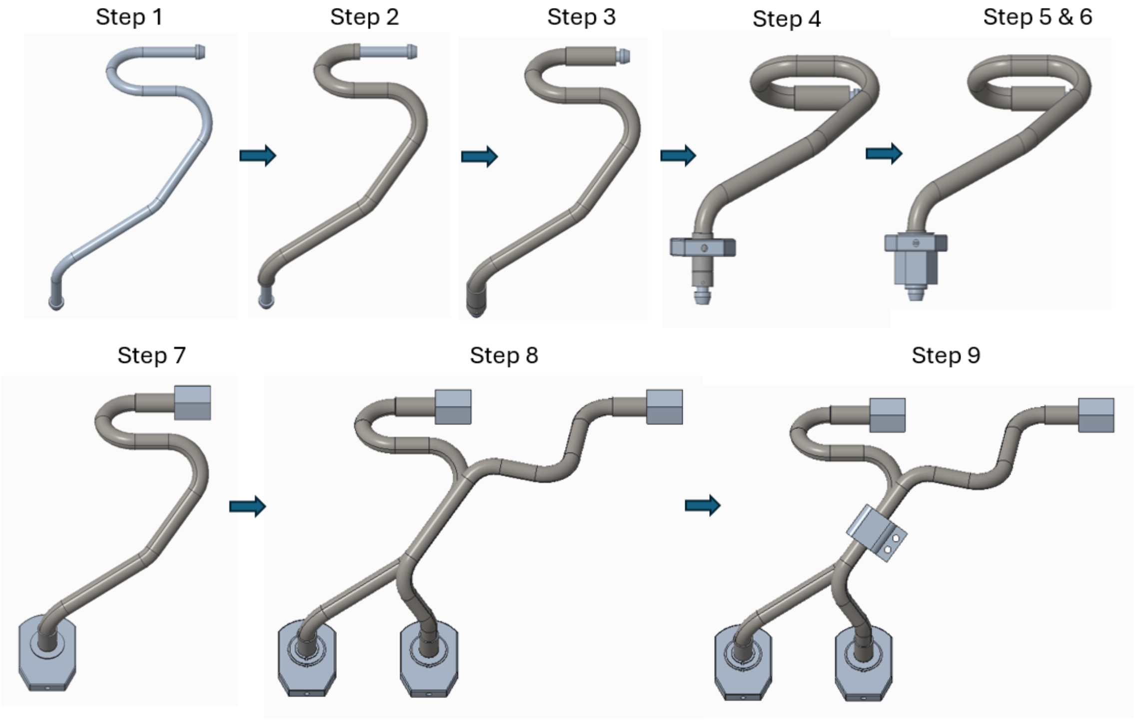


Figure 8.9: Assembly process

8.2 Material selection

The material selection process played a vital role in selecting materials which can potentially drive the performance of the system. This phase began after the finalizing the design of the whole system, including all the components. This section outlines the material selection procedure and explains the rationale behind the final material choice.

8.2.1 Material benchmarking

The material benchmarking process initially began during the literature review and the benchmarking of existing products. During the interviews with experts at Volvo Penta inquiries about current materials and potential alternatives were made. More information on materials used in existing systems was gathered, and their properties were examined to identify the desired characteristics for materials suitable for the system. Since the manufacturing process plays an important role in material selection, a study of available materials for the powder bed fusion process, the relevant suppliers, and the costs of these materials was investigated.

The identified materials were compared with performance criteria such as strength, stiffness, weight, cost, weldability, fatigue resistance, thermal conductivity, thermal stability, and corrosion resistance. The benchmarked materials were validated with the assistance of material experts and through research of existing studies. This combined approach ensured that material selection depended not only on raw facts but also on practicability and specialist advice.

8.2.2 Final selection process

Design requirement for outer pipe	
Function	• To collect the leakage from inner pipe • To trigger alarm upon leakage
Constraints	• Must withstand pressure from leaked fuel (upto 10 bars) • Must be corrosion resistant • Must be fire resistant • Must not contaminate the fuel • Must not leak • Must have high fatigue resistance • Must be compatible with additive manufacturing process
Objectives	• Minimize cost • Maximize thermal conductivity • Maximize stiffness
Free variables	• Choice of material

Table 8.1: Material requirements specification

The key objective of the material selection process is to satisfy the requirements of the system and also to find areas where innovative materials can improve performance and reduce cost. After benchmarking, an initial idea of a list of probable materials and required properties from valid materials for the system was gained. To validate this, a systematic material selection process is carried out using Asbhy's methods outlined in the book Material Selection in Mechanical Design [21]. In the first step, the design requirements of the component are translated into a prescription for the material. It is expressed as functions, constraints, objectives, and free variables as illustrated in Table 8.1.

Following the creation of material specification requirements, the materials are screened from the material universe using the constraints in Ansys Granta Edupack software. The materials that are selected are ranked according to the objectives, and the top-ranked materials are chosen to be simulated to check if they satisfy the thermal and mechanical requirements of the component.

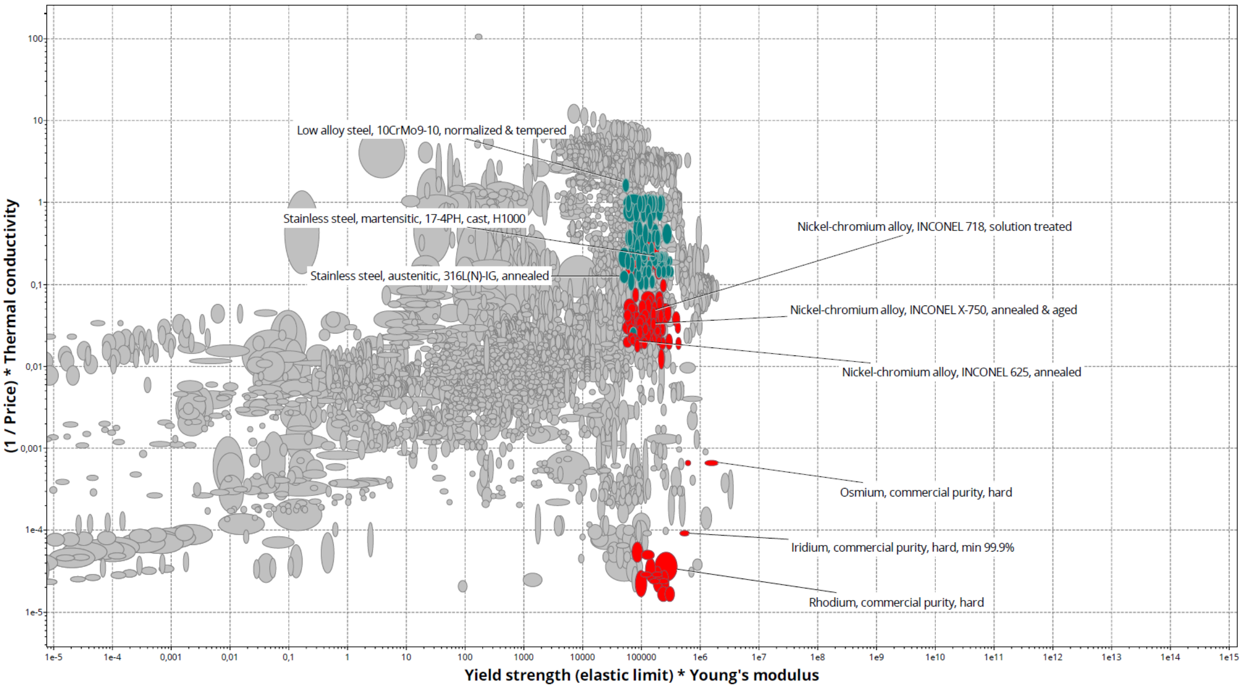


Figure 8.10: Material selection chart

Figure 8.10 displays the final list of materials that fulfilled all the conditions. The attributes on the X-axis are used to rank materials with high stiffness and strength, aiming to minimize deformation. The Y-axis represents materials with low cost and high thermal conductivity. High thermal conductivity is a key parameter as it facilitates faster production during additive manufacturing, where the build speed greatly contributes to the manufacturing cost of the pipes.

From the list, the commercially available powders suitable for additive manufacturing include Stainless steel 316L, Inconel 625, and Inconel 718. Other materials are excluded due to their high cost and lack of commercial availability. Overall, Stainless steel 316L and Inconel 718 emerged as the most suitable materials for this concept.

8.3 Manufacturing process

The manufacturing process selection played a vital role in concept generation. Customer needs and product specifications served as the primary drivers for concept generation. However, the design phase is conducted with a focus on design for manufacturability. The manufacturing process selected for producing the pipes, fuel leak transfer unit, fuel collection unit, sleeves, and the snap ring is powder bed fusion.

8.3.1 Materialize magics

Materialize magics software is used in the build preparation for additive manufacturing of the fuel pipes and its components. The software is used for converting the CAD files into 3D printable format. The workflow in this software involved a number of steps as displayed in Figure 8.11.

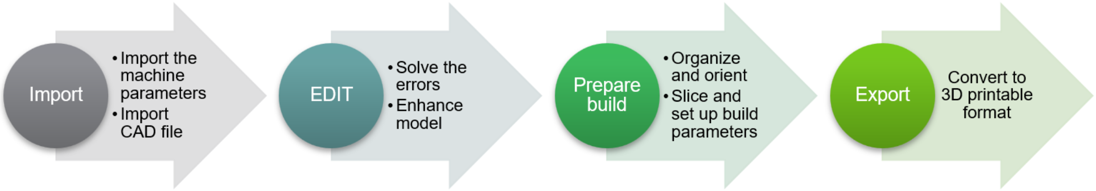


Figure 8.11: Magics workflow

In the initial step, the EOS M290 3D printing machine is selected for its suitability, and its parameters are imported into the Magics software. The machines accommodates a build volume of 250 x 250 x 325 mm. After setting up the machine properties, the CAD models of all the components are imported into the software. The models are initially analyzed to identify and rectify any errors or disruptions that might have occurred while importing.

Subsequently, the parts are nested and oriented to optimize the build process, and the necessary supports are generated as illustrated in 8.12. The orientation of the parts is specifically optimized to minimize the height in the Z direction.

This approach is adopted to reduce the print time, minimize material consumption, enhance stability, and lower printing costs. Reducing build time is particularly crucial, as it significantly impacts the overall cost, with build time being a primary cost-driving factor in 3D printing. Following these activities, the parts are sliced and the build parameters are set up before converted them into a 3D printable format.

In the figures below, the sleeves are not included in the build due to limitations of the software for the student version. In real cases, the sleeves will be included as the idea is to manufacture all the components required for a D4 engine at once.

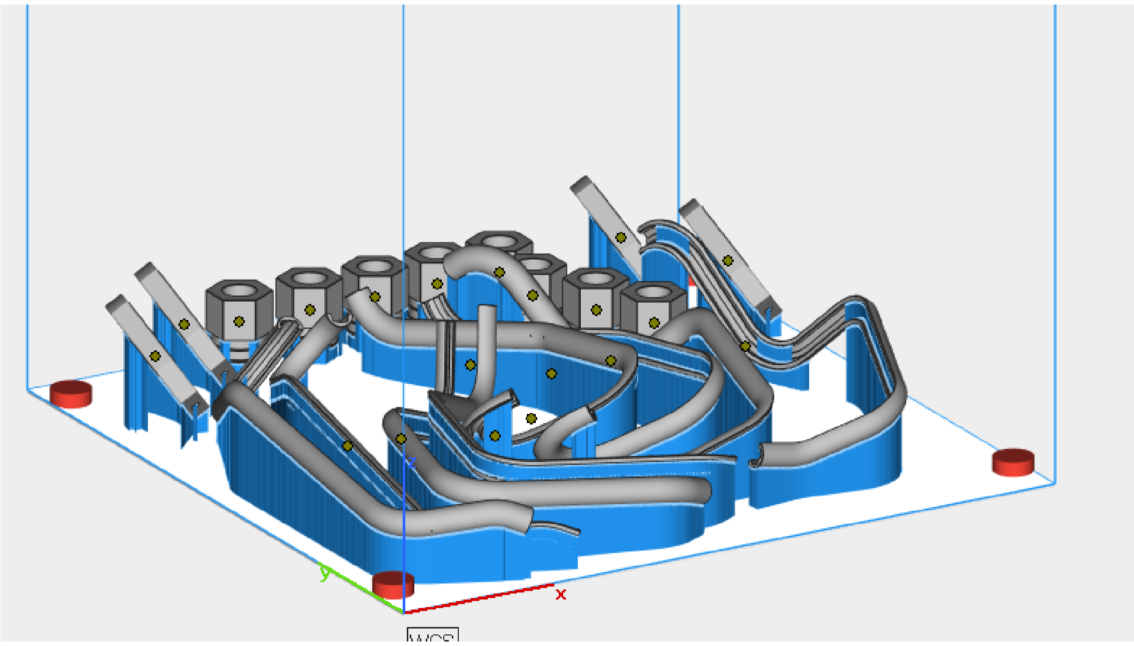


Figure 8.12: Nested fuel pipes and components

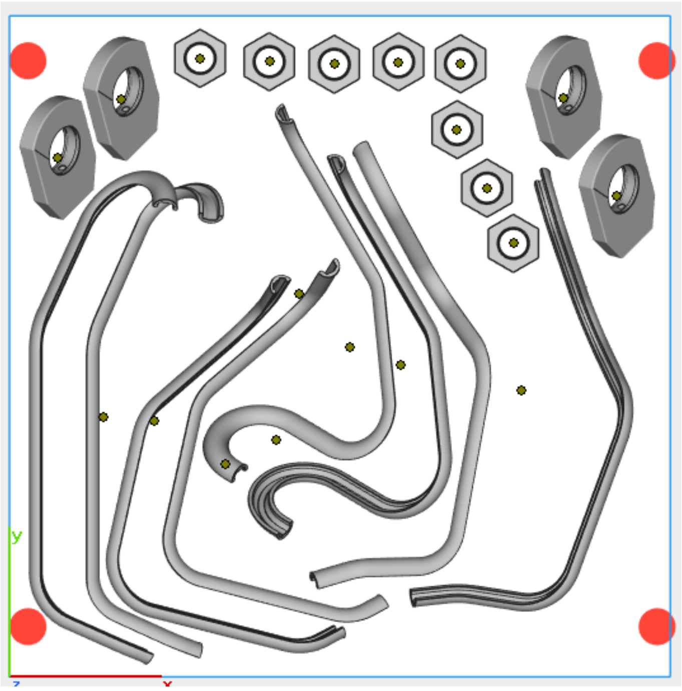


Figure 8.13: Top view

Figure 8.14: Front view

8.4 Cost analysis

Reducing the cost is one of the primary objectives of this research and acts as a key criterion on which the concept selection is made. Manufacturing cost is considered to be a primary factor in the success of the product. DFM was carried out with an intent to reduce the cost of the final product compared to the existing product. The DFM process started by following the steps illustrated in the book Product Design and Development [4]. The steps are:

- Estimate the manufacturing cost.
- Reduce the cost of components and assembly.
- Reduce the cost of supporting production.
- Consider the impact of DFM decisions on other factors.

8.4.1 Manufacturing cost estimation

There are a lot of models developed for cost calculation for laser additive manufacturing process which are differentiated in terms of accuracy of prediction. In DMLS, cost is driven by a combination of material, machine, energy, labour and overhead expenses. Direct costs include raw powder, support material, machine operation, energy, and required labour. Indirect costs include factory overhead, administration and other fixed expenses. To streamline the cost calculation process, the method proposed by di Angelo and di Stefano[22] is taken as a reference, and the cost equation employed is represented in 8.1.

$$C_{TOT} = C_{Build} + C_{Post} + C_{Material} + C_{Pre} \tag{8.1}$$

where,

$$C_{Build} = C_{opertion} * T_{Build} \tag{8.2}$$

$$C_{Material} = C_{Powder} * V_{Build} \tag{8.3}$$

Nomenclature description	
C_{Tot}	Total cost [SEK]
C_{Build}	Cost of one build operation [SEK/build]
$C_{Operation}$	Operating cost of machine per hour [SEK/h]
C_{Post}	Cost for post-processing activity [SEK]
C_{Pre}	Operation costs before build [SEK]
T_{Build}	Total time of build [h]
V_{Build}	Total volume of build [mm^3]
C_{Powder}	Material cost [Kg]

Table 8.2: Nomenclature description of presented equations

Initially, a study on commercial assessment of materials was conducted from which the cost of materials were collected and are tabulated below:

Material	**Supplier**	**Cost/10Kg**
Nickel Alloy IN625	EOS	9,446
Nickel alloy IN718	EOS	8,694
Titanium Ti64	EOS	26,664
Cobalt chrome	EOS	15,138
Maraging steel ms1	EOS	7,857
Tool steel	EOS	13,821
Stainless steel 316L	EOS	4,897

Table 8.3: Material cost data sheet [23]

As discussed earlier in the material selection phase, Inconel 625, 718, and Stainless steel 316L are the materials given importance. After the commercial assessment of materials, the post-processing requirement and cost for the final products were studied. As the outer pipes act as a protective layer and the fuel flow characteristics are not a major concern, the surface finish requirements of final product are not considered.

The Inconel 625, 718, and stainless steel 316L materials have adequate thermal, mechanical, electrical, and corrosion resistance properties; no heat treatment or coating activities are required. Support removal is the only post-processing process that needs to be carried out. The material cost is calculated using the build volume, which is generated with the help of Materialize Magics software.

After calculating the material cost, supplier identification was carried out, and a manufacturing quote was requested to get an idea of the overall printing cost. It was identified that for manufacturing these pipes with Inconel 718 and Stainless steel 316L, the cost is around 12000 - 15000 SEK. The higher cost of Inconel is compensated for with a faster build time than stainless steel.

8.5 Finite element analysis

After the detailed design phase, CAE analysis was performed to validate the performance of our design. Ansys Workbench was used to perform analyses like pressure, temperature, fatigue, and modal. Analysis phase was started by converting the 3D model from a Creo assembly file to a STEP file. The converted STEP file was used to import geometry in Ansys Workbench, and the following analyses were performed:

- Static structural – To validate pressure and temperature loads in both inner and outer pipes
- Transient Structural – To validate engine pulses in the pipes
- Modal analysis – To validate its resonance performance

8.5.1 Materials

The current material for the inner fuel injection pipes is high-strength, low-alloy structural steel. It is set as the same throughout the analysis. The chosen materials such as Stainless steel 316L, Inconel 625 and 718 are applied to outer pipes, specialized sleeves, and the fuel leak transfer unit in separate simulations. Structural steel is used for both the end connectors and for clamp housing. Concerning material properties, they are briefly discussed in the material selection section. The Table 8.4 provides data related to the materials used in the analysis.

In the Figure 8.15, the outer pipe, specialized sleeve, and the fuel leak transfer unit are assigned with Inconel 718. And for the next set of iterations, the material are switched to Stainless steel 316L and Inconel 625 respectively, and its performances are assessed.

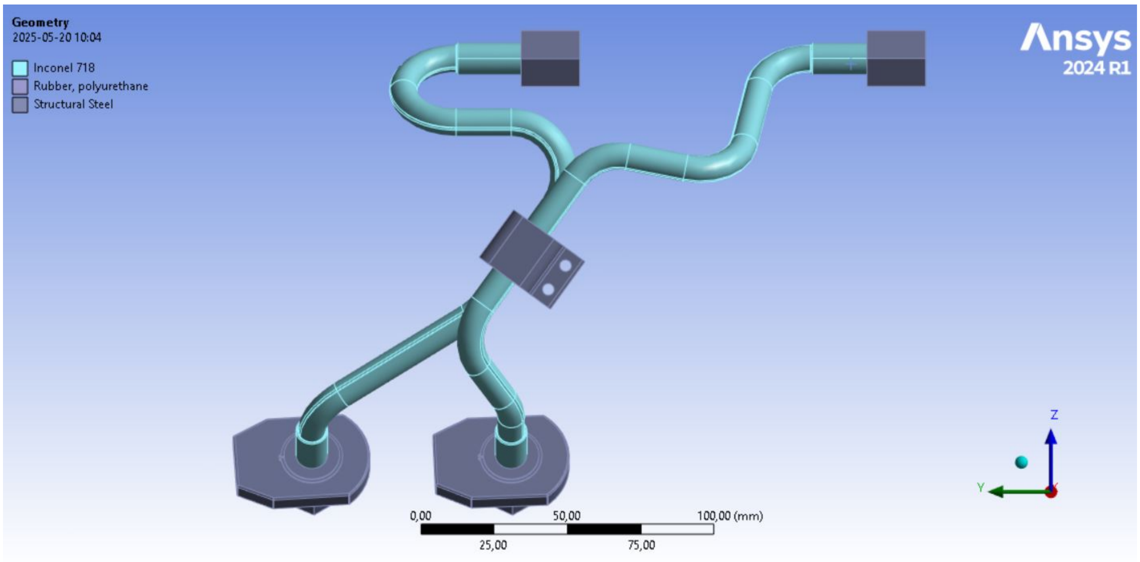


Figure 8.15: Material Assignment

Parts	**Materials**
Inner pipe	High strength, low alloy structural steel
Outer pipe	Stainless steel, Inconel 625, Inconel 718
Specialized sleeves	Stainless steel, Inconel 625, Inconel 718
Fuel leak transfer unit	Stainless steel, Inconel 625, Inconel 718
End connectors	Structural steel
Clamp inner	Polyurethane
Clamp housing	Structural steel

Table 8.4: Materials for FEA analysis

8.5.2 Meshing & connection

After assigning the materials, the next step is to mesh the components. 1.5mm and 1mm are used as mesh sizes for the components, and a mesh refinement is performed in some of the critical places, such as the bends and the high-stress areas to find the maximum stresses and deformation. Since the component is imported as an assembly in Ansys Workbench, connections between the parts are automatically generated by the software itself. But to double-check it, an automatic connection feature is inserted to find all the missing connections between the parts.

8.5.3 Static structural and fatigue analysis

In static structural analysis, both temperature and pressure loads are applied to the fuel injection pipes. Based on interviews with Volvo fuel injection experts, the

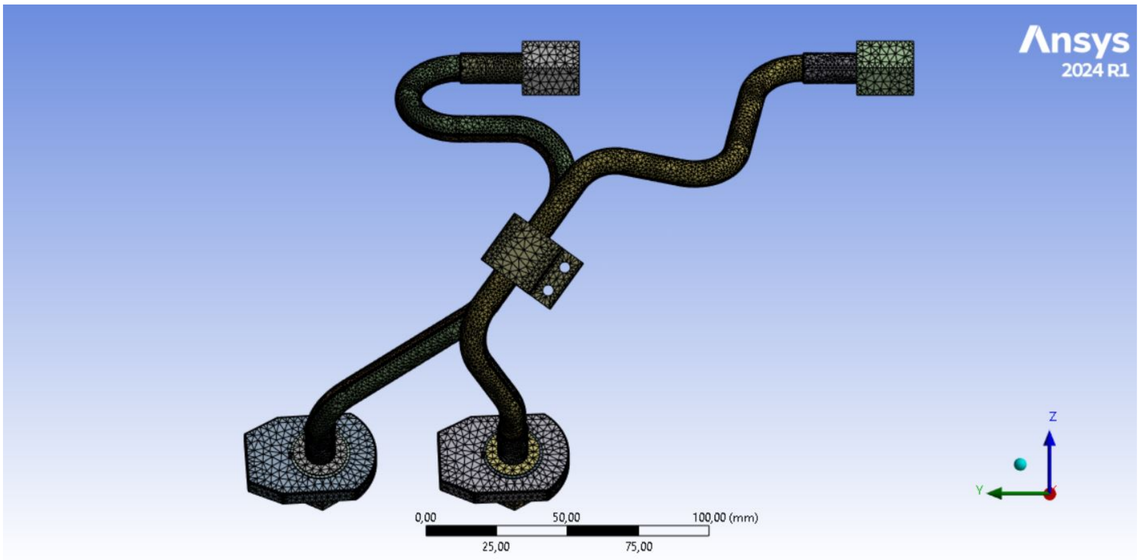
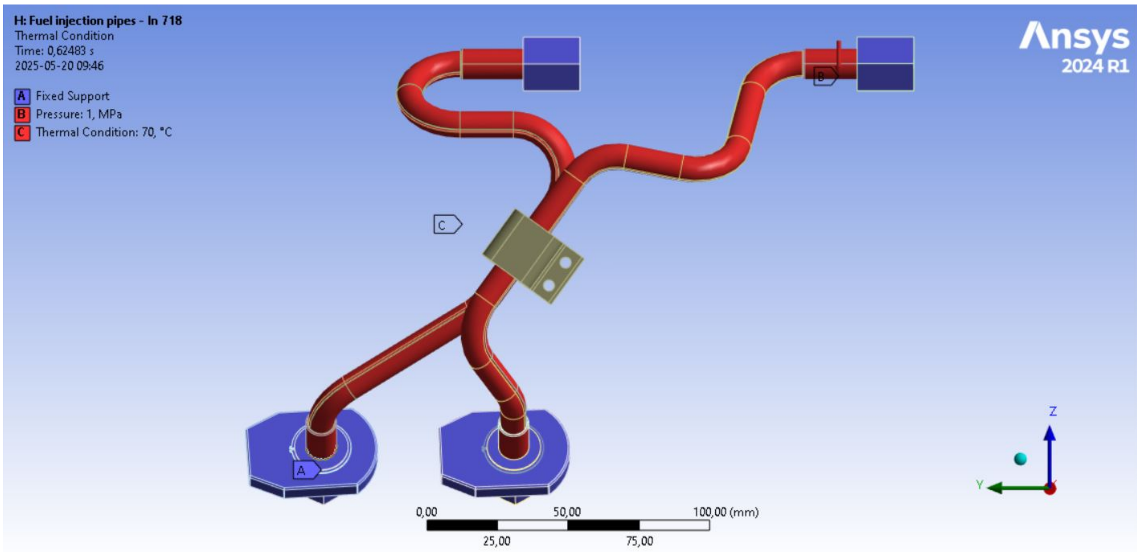


Figure 8.16: Meshing


H: Fuel injection pipes - In 718
Thermal Condition
Time: 0,62483 s
2025-05-20 09:46

A Fixed Support
B Pressure: 1, MPa
C Thermal Condition: 70, °C

Figure 8.17: Boundary conditions for static structural analysis

boundary conditions are applied as illustrated in Figure 8.17. The end connectors, the fuel leak transfer unit, are applied with fixed support. The maximum temperature that would act on the pipes is 100 degrees, and the operating temperature of the system is around 60 - 70 degrees, based on the technical product specification published by Volvo Penta. The simulations are performed by applying 70 degrees as an initial limit. A pressure load of 10 bar is applied to the inner wall of the outer pipe. A large number of iterations are performed and the final results are tabulated in Table 8.6.

Boundary Conditions	Parts	Values
Fixed support	End connector & fuel leak transfer unit	NA
Thermal condition	Outer pipes & specialized sleeves	70 Degrees
Pressure load	Inner diameter of outer pipes & specialized sleeves	10 bar

Table 8.5: Boundary conditions and parameters for static structural analysis

8.5.3.1 Results of static structural analysis

Results are generated based on the boundary conditions, mesh and material assignment. In the first iteration, Stainless steel 316L is used; Inconel 625 and Inconel 718 are simulated in the second and third iterations, respectively.

The Table 8.6 shows the results in terms of total deformation, equivalent stresses, factor of safety, and fatigue life for each iteration.

Iteration	Yield strength (MPa)	Von Mises stress (MPa)	Total deformation (mm)	FOS	Fatigue (cycles)
Iteration 1 – SS 316	290	459.39	0.005	0.63	low
Iteration 2 – IN 625	414	380	0.005	1.08	57266
Iteration 3 – IN 718	1030	407	0.005	2.5	69810000

Table 8.6: Static structural results for different material

- In Iteration 1, the use of Stainless steel 316L resulted in a Von-mises stress of 459.39 MPa. The yield strength of Stainless steel 316L is 290 MPa and when comparing the equivalent von Mises stress with the yield strength of the material, it is way higher; this means that the is likely to undergo plastic deformation under the applied load. The total deformation due to the applied load is 0.005mm and which is way less and this would not be a problem. The Factor of Safety (FOS) is only 0.63, which is well below the safe threshold of 1.0, and fatigue life is low. So, the design fails when Stainless steel 316L is used.

- In Iteration 2, the use of Inconel 625 resulted in a von Mises stress of 380 MPa. The yield strength of Inconel 625 is 414 MPa, and when comparing the equivalent von Mises stress with the yield strength of the material, it is a bit less, and hence there is no plastic deformation due to the applied load. The total deformation of about 0.005 is also way lesser. The Factor of Safety (FOS) is only 1.01, which is just above the safe threshold of 1.0, and fatigue life is 57266 cycles, which is approximately around 15 mins. This means that the design satisfies the factor of safety, equivalent stress and total deformation criteria but not the fatigue life criteria when Inconel 625 is used.

- In Iteration 3, the use of Inconel 718 (aged) resulted in a von Mises stress of 407 MPa, which is one-third of the yield strength of the material. The total deformation is also 0.005 mm, and the factor of safety is around 2.5, which is above the allowable limit of 1. The fatigue life is $6.9x10^7$ cycles, which approximately equals 320 hours. Based on Volvo's technical specification of fuel

> pipes, it achieves the pleasure duty engine specification. This material combination with the current design meets all the required criteria, hence Inconel 718 is selected for the next set of iterations.

The Figures 8.18,8.19, and 8.20 show the result of the static structural analysis of Inconel 718.

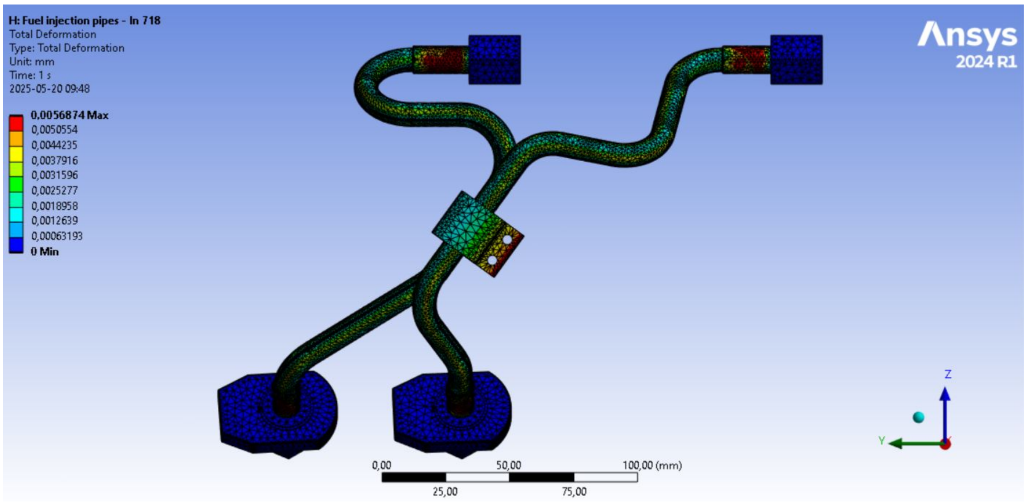


Figure 8.18: Total deformation of IN 718

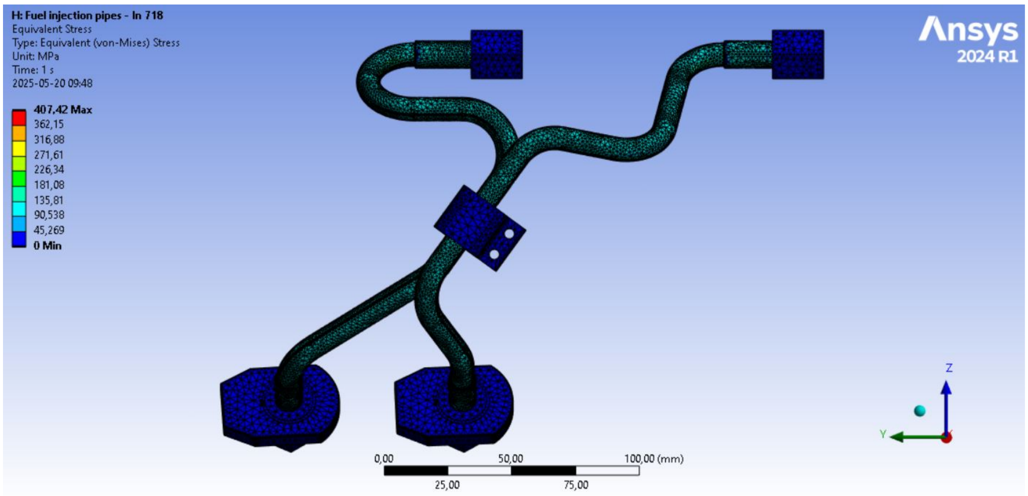


Figure 8.19: Equivalent stress of IN 718

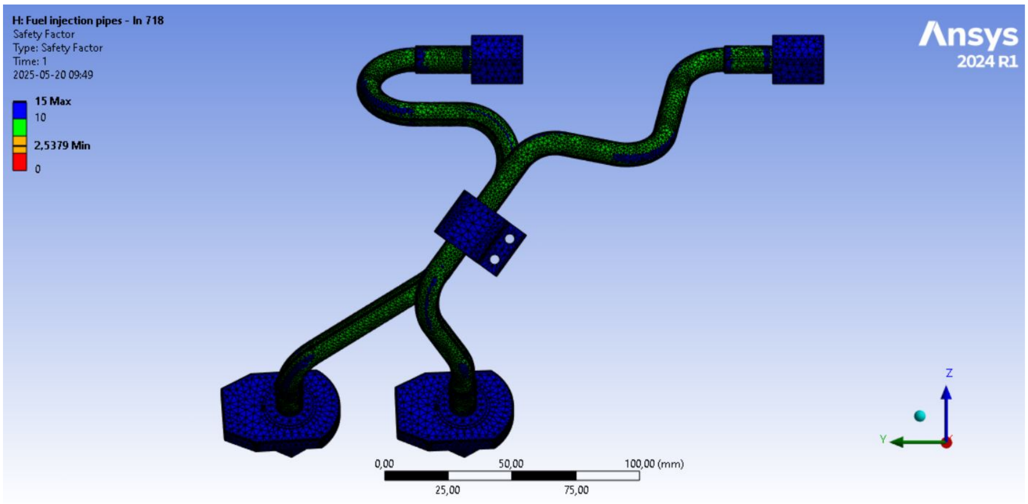


Figure 8.20: Factor of safety of IN 718

8.5.4 Transient structural

In Transient Structural analysis, the loads due to engine pulse are validated. The same fixed support from the static structural analysis are used, and a thermal condition of 70 degrees is applied to the whole system. The pressure pulses applied to the outer pipe are varied with respect to time. From ISO 18770 [24], it is found that the fuel pipes should be designed to withstand a varying pressure of 16 bars, and hence the same is simulated.

The main difference between static and transient structural is that the pressure is constant throughout the whole time in static structural, whereas in transient structural the pressure varies with respect to time. The Table 8.7 represents how the pressure was varied with respect to time.

Time (Seconds)	Pressure (MPa)
0	1.6
2	0
4	1.6
6	0
8	1.6
10	0

Table 8.7: Time vs Pressure

8.5.4.1 Results of transient structural analysis

In the transient structural analysis, only Inconel 718 is used for the outer pipe, specialized sleeves, and the fuel transfer unit. The total deformation due to engine pulsation is around 0.005, which is very less. The equivalent stress is around 465 MPa, whereas the yield strength of Inconel is 1200 MPa. The fatigue life was around $6.4x10^7$ approximately equals to 297 hours. When compared to the fatigue life in the static structural analysis, there is a minimum drop in the no. of cycles, but it is still in the acceptable range. The Figures 8.21 and 8.22 show the results of the transient structural analysis of Inconel 718.

Iteration	**Von Mises Stress (MPa)**	**Total deformation (mm)**	**Fatigue (Cycles)**
Iteration 3 - IN 718	465	0.005	64000000

Table 8.8: Transient structural results

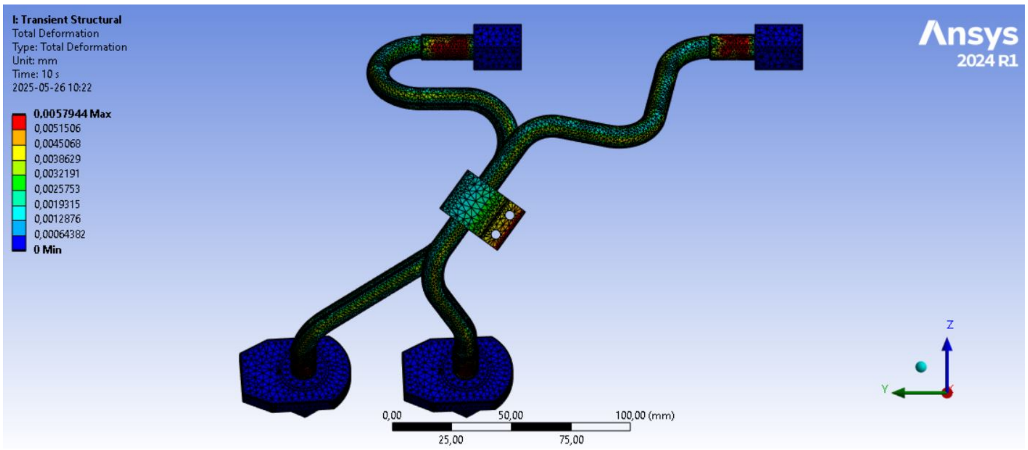


Figure 8.21: Transient structural - Total deformation of IN 718

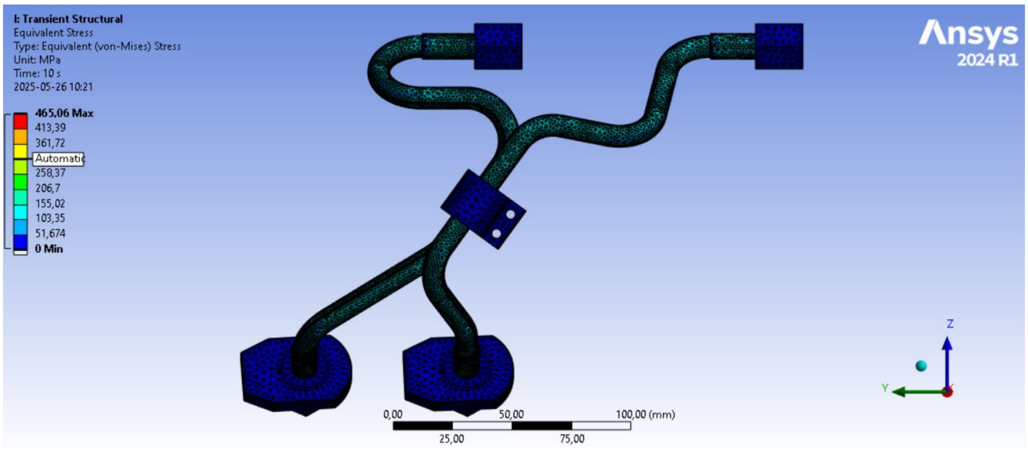


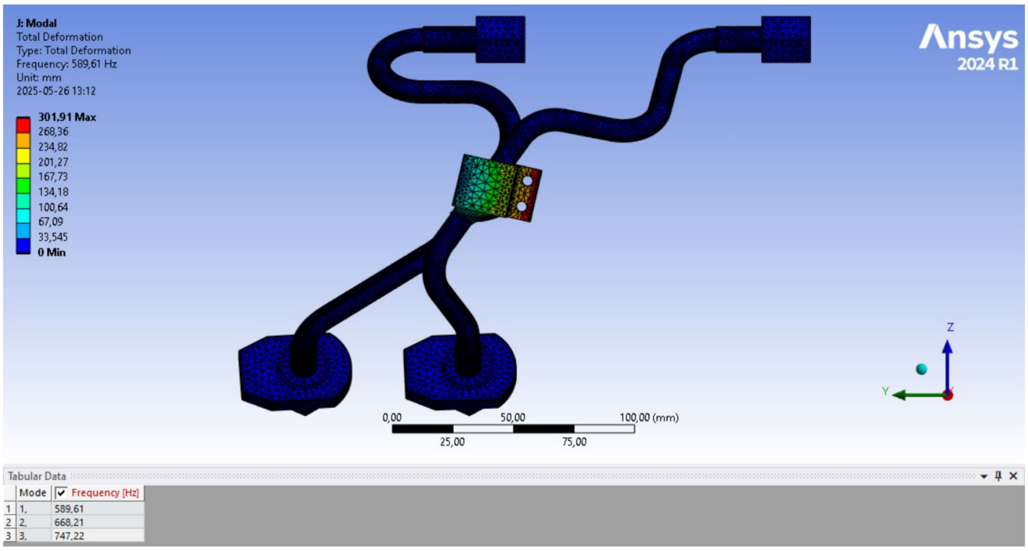
Figure 8.22: Transient structural - Equivalent stress of IN 718

8.5.5 Modal analysis

Modal analysis was performed to find the natural frequency of the pipes and their mode shapes. This analysis helped to assess potential resonance issues under the operational conditions. The same boundary conditions as static structural analysis are used to perform this analysis.

8.5.5.1 Results of modal analysis

Modal analysis started by calculating the natural frequency of the engine with a maximum of 3600 rpm, which is around 60 Hz. The natural frequency of the first 3 modes of the pipes was found to be between 590 and 748 Hz. Since the natural frequency (590 Hz) is significantly higher than the operational frequency (60 Hz), the risk of resonance is low. Resonance typically occurs when the operational frequency approaches or matches the natural frequency of a system. The fuel pipe is also equipped with clamps to minimize vibrations, which further reduces the likelihood of resonance.


J: Modal
Total Deformation
Type: Total Deformation
Frequency: 589,61 Hz
Unit: mm
2025-05-26 13:12

	Mode	☑ Frequency [Hz]
1	1.	589,61
2	2.	668,21
3	3.	747,22

Figure 8.23: Modal analysis of IN 718

9

Design iteration and considerations

This chapter involves reflection, considerations, and design iterations of the proposed design from the start of the concept development to detail design and FEM analysis phase.

9.1 Selection of concept and manufacturing process

During the concept generation phase, extensive work was done to build a concept that achieves key requirements and desires. After exploring multiple design alternatives, the final concept, “PBF of outer pipe in 2 halves” was chosen based on how well it met the key requirements that were identified during the research and expert interviews. These requirements include functionality, manufacturability, assembly, surface finish, and cost.

Additive manufacturing was the go-to manufacturing process to achieve all these requirements. Since pipes have complex bends, making them in a conventional manufacturing process is tedious and more expensive. So, 2 different additive manufacturing processes, the direct energy deposition method and the powder bed fusion method, are planned to be used to manufacture the pipes.

In case of the direct energy deposition method, the outer pipe is supposed to be printed around the inner pipe. So, the inner pipe must be clamped in such a way that it doesn’t move, and it required a special fixture design to clamp the inner pipe. When the outer pipe is printed around the inner pipe, a lot of heat is generated that could weaken the characteristics of the inner pipe. Regarding the cost aspect, it is one of the costliest additive manufacturing processes, and also has a rough surface finish. It was also difficult to find a supplier to manufacture the pipe using this process.

Whereas in the powder bed fusion method, all these parts are printed separately with a good surface finish. The cost of producing these components was cheap when compared to the current traditional manufacturing process. But the pipes were supposed to be soldered along the seam to achieve one of the key requirements, “The system should be a permanent assembly”. Multiple suppliers were considered for producing the pipes using Powder Bed Fusion technology in a cost-efficient manner. By taking cost, surface finish, and potential suppliers in Sweden into consideration, powder bed fusion emerged as the most feasible method.

9.2 Detail design phase

In the detailed design phase, there was a lot of learning regarding the design of outer pipes, specialized sleeve and end connectors. There were many design iterations in these components to achieve the desired performance.

During the early stages of concept development for the selected concept, the outer pipe covered the whole inner pipe and was soldered along the seam. But when it is soldered, it may lead to some burrs around the edges of the pipe and since both the ends of these pipes would have a movable end connector it would need additional post-processing process to remove the chips or burr in the outer pipe. The additional process would also increase the manufacturing cost and lead time. In order to eliminate this, it was decided to add specialized sleeves on both ends of the outer pipe. These specialized sleeves would be soldered along the edges and end connectors would sit in the specialized sleeves. These specialized sleeves on both ends of the outer pipe are of the same size and of circular cross-section to promote standardization.

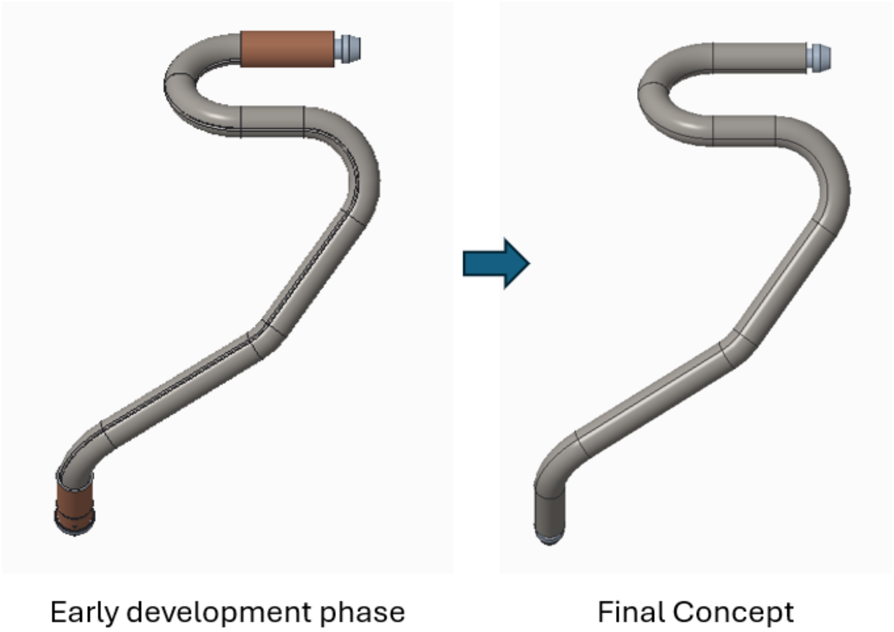


Figure 9.1: Design iterations for outer pipe

In the current fuel injection pipes, the end connectors in the injector side can translate and rotate, whereas the end connectors at the common rail side can only rotate. This leads to the assembly process being a bit difficult to align the flare part of the inner pipe with the mating component. So, it was decided to make the end connectors on both the injector and common rail ends rotate and translate.

Based on principles such as design for manufacturing and design for additive manufacturing, refinements were made to the design of the outer pipe. Initially, the profile of the outer pipe was designed to have a circular cross-section. The profile of the outer pipe was modified to an internally ribbed circular profile with the necessary clearances to increase the strength of the pipe. The final clearance kept was 0.3mm clearance between the inner and outer pipe.

While simulating the print setup in Materialize Magics software, it was found that the modified cross-section 1 as in Figure 9.1 was not self-supported, and hence, it had some support structure between the modified cross-section 1. To remove these support structures, an additional post-processing process is required. To eliminate this, the cross-section was optimized, aiming towards maintaining a lesser overhang angle. This profile is self-supported and doesn't need additional support structures.

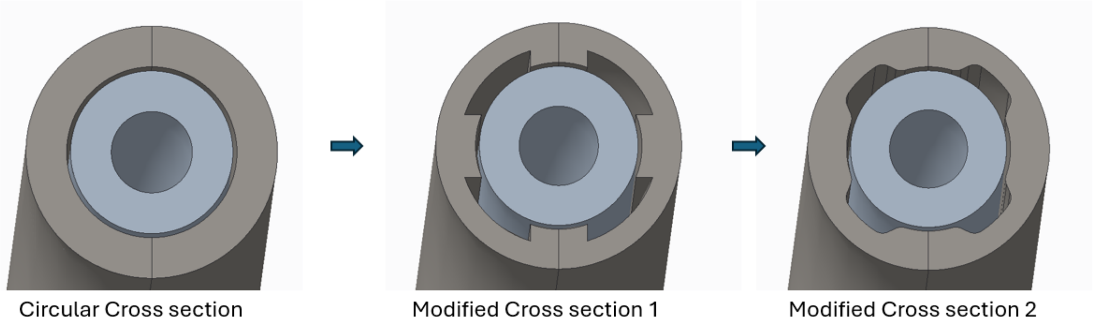


Figure 9.2: Design iterations for cross-section of outer pipe

10

Future recommendation

This chapter discusses a potential concept for future work that can contribute to the success of the product.

10.1 Flexible metallic hoses

Flexible metallic hoses are specialized components that are used in piping to connect two distant points and transport fluid. They are generally used in places where there is relative movement between components and in places where there is a complex arrangement, and also require quick assembly and disassembly [25].

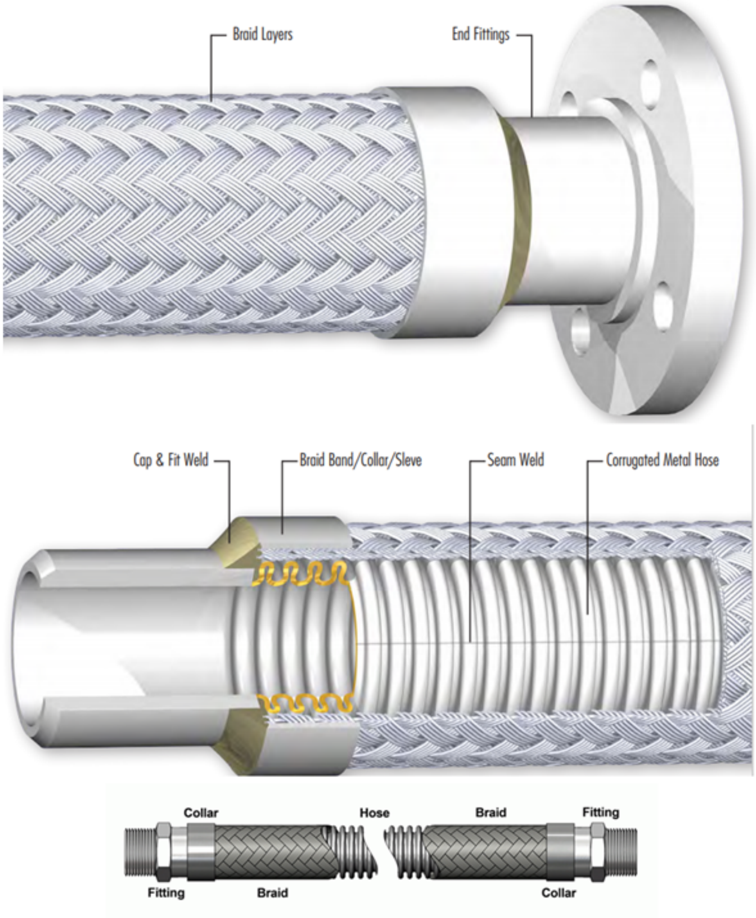


Figure 10.1: Flexible metallic hose construction [25]

These hoses have a complex construction and also can be customized based on the requirements. In general, the flexible metallic hoses consist of a steel braid as the outer layer, a corrugated metal tube as the inner layer, and a customized end fitting as shown in the figure 10.1. The corrugated design of metallic hoses provides flexibility and allows them to absorb vibration and thermal expansion. These hoses are known for their durability and resistance to high temperatures, pressure, and corrosive environments.

10.2 Design details

In this design, the flexible hose is inserted directly over an existing inner pipe with rubber spacers placed at specific locations. Choosing the right hose played an important role in this concept. The major constraint in this design is the bend radius. These corrugated hoses have a specific static and dynamic minimum bending radius that the hose can take without kinking.

In general, the are a lot of guidelines which are followed for flexible metallic hose assembly and usage. As these hoses are planned to be used in an environment where there is no translation movement, only the static bending radius is taken into account, and the assembly guidelines allow for the usage of these hoses in this complex design.

Braided layer	**I.D.**	**O.D.**	**Min. bend radius (mm)**		**WP**	**BP**	**Weight**
	(mm)	(mm)	**Static**	**Dynamic**	(bar)	(bar)	(kg/m)
0	6.35	9.65	15.01	80.01	10.00	—	0.12
1		10.92	24.99	80.01	125.86	503.31	0.13
0	9.53	14.22	18.01	127.99	5.52	—	0.16
1		15.49	38.00	127.99	93.09	372.38	0.30
0	12.70	20.07	22.99	145.51	5.52	—	0.27
1		21.34	51.38	145.51	82.74	331.00	0.40
0	19.05	26.92	32.00	167.99	5.52	—	0.39
1		28.19	70.04	167.99	60.33	241.32	0.40

Table 10.1: Super flexible hose -technical data sheet [26]

For these high-pressure fuel injection pipes, there is a need to find hoses with a bending radius of 18 mm and a minimum pressure resistance of 5 bar. Suppliers are identified that offer hoses meeting these specifications.

According to the data sheet provided by HEBEI QIANLI RUBBER PRODUCTS CO. [26], the product that satisfies the requirements has the dimensions:

- No. of braided layer:0
- Inner diameter: 9.53 mm
- Outer diameter: 14.22 mm
- Static bending radius: 18 mm
- Working pressure: 5.5 bar

These flexible hoses are made of stainless steel 316L and have a working temperature range of -280°C to 420°C.

10.2.1 Spacers

Engines vibrate at very high frequency and constant metal-to-metal interaction between the flexible metallic hoses and inner pipe can cause wear and tear, which can reduce the durability of both the components. To mitigate this, either a Polytetrafluoroethylene(PTFE) or rubber layer can be used as the inner layer of the hoses, but this made sourcing for hoses difficult and to compensate for this rubber spacers as shown in 10.2 are planned can be used.

Figure 10.2: Rubber spacer [27]

These rubber spacers are available in various dimensions, are lightweight and offer exceptional vibration resistance [27]. The profile of these rubber spacers have holes to allow passage of leaked fuel which it more beneficial to be used in the system.

10.2.2 Assembly process

The deciding factor in choosing this concept is the ease of assembly and disassembly. The components used in this design are snap rings, injector and common rail end connectors, clamps, rubber spacers, and flexible metallic hose. The assembly process involved a no. of steps as described below:

- **Step 1:** Take the inner pipe

- **Step 2:** Insert the end connector on the injector side
- **Step 3:** Assemble the snap ring on the injector side
- **Step 4:** Place the rubber spacers and insert the flexible hose over it.
- **Step 5:** Insert the sleeve on the common rail side
- **Step 6:** Insert the fuel leak transfer unit
- **Step 7:** Insert the snap ring and end connector for the common rail side to the assembly.

The assembly process is illustrated in Figure 10.3. The purpose of the sleeve is to enable the nut on the common rail side to move approximately 16 mm. This movement is necessary to facilitate the insertion of the snap ring after the flexible metallic hose has been installed.

Clamps may also need to be used in this system to limit the vibration, which is not illustrated as of now in this design. To make the entire system a permanent assembly, additional post-processing such as welding or the use of sealers is required. This should be done to obtain the approval of the classification societies.

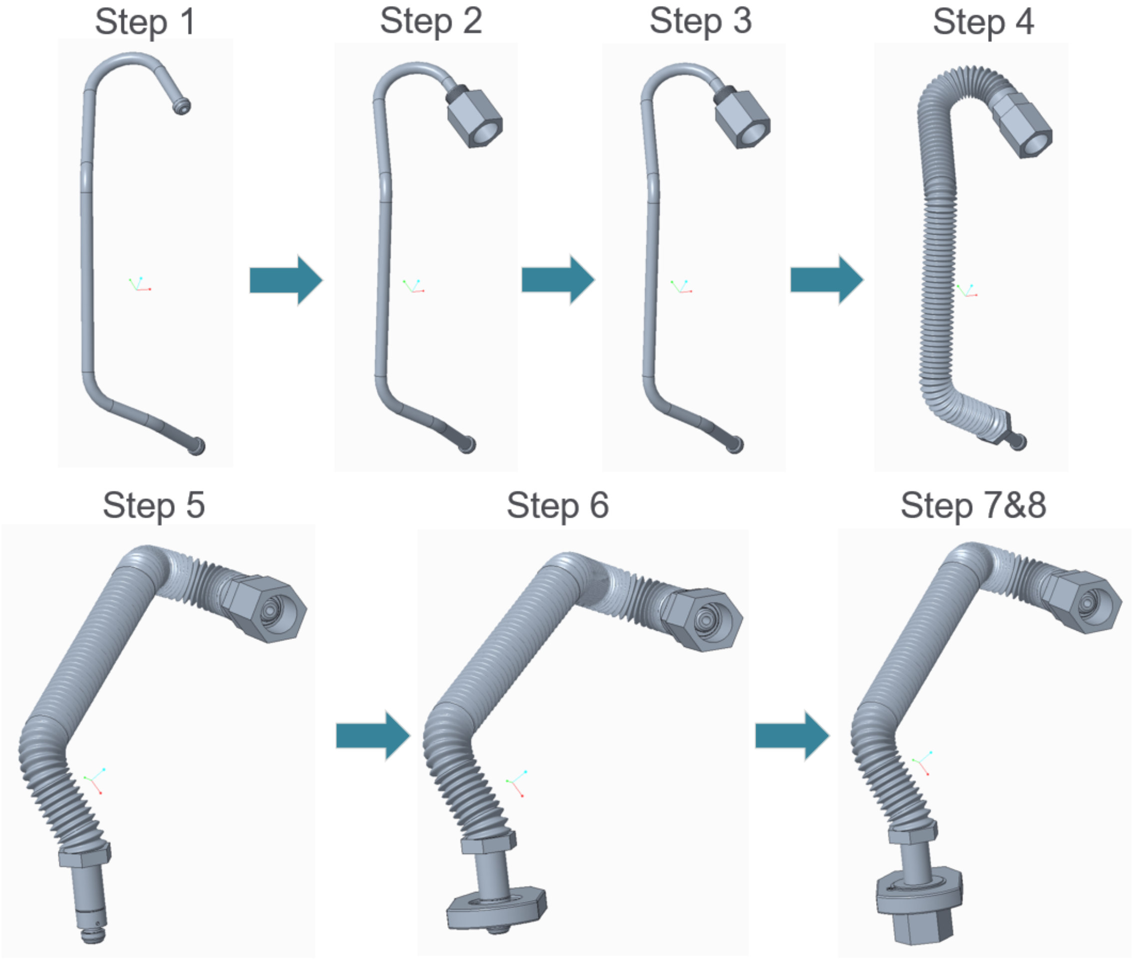


Figure 10.3: Flexible hose assembly process

11

Conclusion

This chapter presents the combined conclusion and discussion of the thesis, and critically reflects on the results.

This thesis investigated and developed an improved design for a double-walled high-pressure fuel-injection pipe for Volvo Penta commercial marine engines, with the goal of making it easier to manufacture and assemble, cheaper to produce, and compliant with regulations.

The current alternative available on market today tend to be expensive and complex to manufacture. Additionally, the traditional extrusion and welding processes make production even harder and more expensive. These issues led to considering advanced manufacturing techniques, especially additive manufacturing (AM), as a possible fix.

The project followed a clear product development path. It started with a detailed review of key classification society rules and moved through requirements, function analysis, and concept brainstorming. From that work, nine distinct designs were sketched, then ranked in a Pugh matrix and scored with the Kesselring method, using criteria such as performance, ease of building, cost, and long-term strength.

Among all the options looked at, the concept named "PBF of outer pipe in 2 halves" - meaning the use of two half shells of the outer pipe around a standard inner pipe came out on top as the most even-handed choice. It satisfied all the main project goals, such as containing leaks, be a permanent assembly, being easy to integrate with existing systems, and keeping costs under control. Direct Energy Deposition being a promising concept, was brushed aside mainly because PBF gives a cleaner surface, more suppliers can handle the work, and it leaves less leftover stress in the material. Although the idea of a flexible metallic hose was tempting because it looked easy to set up and move around, worries about where to buy the hose, how it stands up to flame, and its durability made it a future recommendation for this project.

During the detailed CAD development phase, the selected design was further refined to enhance manufacturability and assembly efficiency. Standardized sleeves were incorporated to minimize manual deburring efforts, and the end connectors were redesigned to improve alignment during fastening operations. These modifications were systematically guided by Design for Additive Manufacturing (DfAM) principles. As a result, the final geometry not only facilitated easier fabrication but also reduced the need for post-processing activities such as rinsing and sanding.

Performing a Finite Element Analysis was useful to validate the design efficiency. The FEM tests covered static, transient, and vibrational analyses to evaluate how the proposed design behaves under pressure, heat, and vibrations. Inconel 718 emerged as the best material choice, delivering strong fatigue and corrosion performance, plus a safety margin of over 2.5. The component met both deformation and fatigue life targets, exceeding 69 million cycles, and modal tests showed its natural frequencies sit well above engine operational frequency, virtually eliminating resonance concerns.

Even with these encouraging findings, a number of caveats remain. Simulations are based on ideal scenarios and fail to account for manufacturing flaws such as porosity, anisotropy, or rough surfaces that often plague additively made parts. Long-term behaviour under real marine conditions and the true costs of post-processing could not be verified experimentally due to the limitations of the project. Though cost modelling suggests AM might ultimately save money compared with conventional approaches, successful deployment still hinges on supplier agreements and careful budget tracking.

In conclusion, this thesis shows that the powder bed fusion of outer pipe using Inconel 718 can meaningfully replace traditional manufacturing of double-walled fuel pipes. The new design is easier to produce, safer to use, and aligns better with current regulations. Physical validation by manufacturing prototypes and running fatigue tests, and qualifying suppliers are important before deploying into service. At the same time, the study suggests looking at flexible metallic hoses, which can make the system more efficient.

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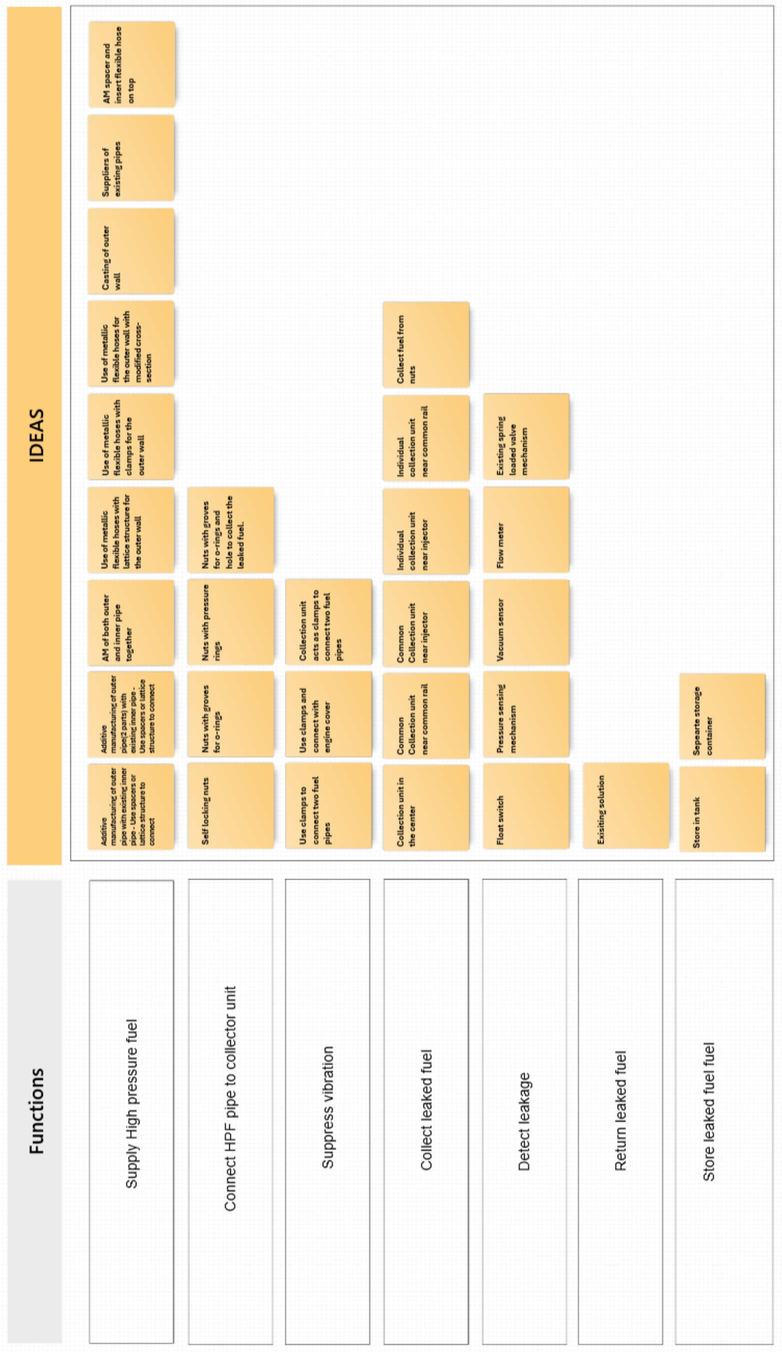
A

Appendix - Morphological matrix



Functions	IDEAS								
Supply High pressure fuel	Additive manufacturing of outer pipe with existing inner pipe - Use spacers or lattice structure to connect	Additive manufacturing of outer pipe(2 parts) with existing inner pipe - Use spacers or lattice structure to connect	AM of both outer and inner pipe together	Use of metallic flexible hoses with lattice structure for the outer wall	Use of metallic flexible hoses with clamps for the outer wall	Use of metallic flexible hoses for the outer wall with modified cross-section	Casting of outer wall	Suppliers of existing pipes	AM spacer and insert flexible hose on top
Connect HPF pipe to collector unit	Self locking nuts	Nuts with groves for o-rings	Nuts with pressure rings	Nuts with groves for o-rings and hole to collect the leaked fuel.					
Suppress vibration	Use clamps to connect two fuel pipes	Use clamps and connect with engine cover	Collection unit acts as clamps to connect two fuel pipes						
Collect leaked fuel	Collection unit in the center	Common Collection unit near common rail	Common Collection unit near injector	Individual collection unit near injector	Individual collection unit near common rail	Collect fuel from nuts			
Detect leakage	Float switch	Pressure sensing mechanism	Vacuum sensor	Flow meter	Existing spring loaded valve mechanism				
Return leaked fuel	Exisiting solution								
Store leaked fuel fuel	Store in tank	Sepearte storage container							

Figure A.1: Morphological matrix

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