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I Abstract

Equinor has initiated a Field Life Extension (FLX) project to prolong the end-life operational capabilities of their installations by innovative methods, including Stafjord A. One of these innovative methods is to implement an on-demand solution for re-supplying the installation with spare parts manufactured through alternative methods, such as additive manufacturing (AM) and rapid casting. However, due to the age of specific components, the documentation for design, material specification, and manufacturing may be missing, i.e., legacy parts.

The main aim of this thesis is to map the path from notification of a potential failure of a legacy part to the installation of a near-identical part. The life extension implies that mechanical equipment, such as valve bodies for the fire deluge systems must maintain their integrity throughout the expanded life cycle. Unfortunately, this component has exceeded its life expectancy by twice. Hence, increased degradation and risk for potential accidents introduce the need for acquiring new valve bodies.

A literature review investigated the challenges and requirements for implementing the on-demand solution for legacy parts. Standards and manufacturing methods have been studied and compared. An Analytical Hierarchy Process was used to analyze the input from experts within AM and rapid casting. Finally, a case review processed the valve body through the Reverse Engineering Process (REP) activities.

A roadmap is proposed based on regulations governing the manufacturing of mechanical components used on the Norwegian Continental Shelf (NCS). Furthermore, requirements for implementing the on-demand solution for legacy parts are described, including a proposition for an explicit criticality assessment for metal AM. A recommendation for operational part-monitoring and identification linked with a digital warehouse of the corresponding part is made to finalize the proposed roadmap for acquiring legacy parts on the NCS.

The Analytical hierarchy process (AHP) reveals that rapid casting outperforms metal AM for valve body manufacturing. In addition, metal AM and rapid casting are benchmarked regarding realistic cost and lead time procurement limitations. The results include the AHP output and indicate that the cost of ordering the valve body favour rapid casting, but the lead time for metal AM is lower than rapid casting. The total cost for metal AM per part is nearly equal to the cost of the initial requested batch of 26 valve bodies produced by rapid casting.

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II Abbreviations

AM - Additive Manufacturing
AI - Artificial Intelligence
AHP - Analytical Hierarchy Process
API - American Petroleum Institute
AMC - Additive manufacturing Class
AMSL - Additive manufacturing Specification Level
ASTME - American Society of Tool and Manufacturing Engineers
AMSE - The American Society of Mechanical Engineers
BJT - Binder Jetting
CAD - Computer Aided Design
CAE Computer Aided Engineering
CNC - Computer Numerical Controls
DNV - Det Norske Veritas
DW - Digital Warehouse
DE - Digital Ecosystem
DED - Direct Energy Deposition
FE - Finite Element
HBM - Hybrid Manufacturing
ISO - International Organisation of Standardization
IoT - Internet of Things
IP - Intellectual Property
JIP - Joint Industry Project
MCDA - Multi Criteria Decision Analysis
MF - Main Function
NORSOK - Norsk Sokkels Konkurranseposisjon
NCS - Norwegian Continental Shelf
OEMs - Original Equipment Manufacturers
O&G - Oil & Gas
PCM - Pairwise Comparison Matrix
PED - Pressure Equipment Directive
PBF-LB - Powder Bed Fusion Laser Beam
REP - Reverse Engineering Process
ReEP - Reengineering Process
RFID - Radio Frequency Identification
RE - Reverse Engineering
SF - Sub-Function
STL - Standard Triangle Language
SM - Subtractive Manufacturing
TQ - Thesis Question
WAAM - Wire Arch Additive Manufacturing
WIPO - World Intellectual Organization
3DSC - Three Dimensional Sand Casting

III Preface

This thesis is the concluding requirement for fulfilling the *Master of Science degree* program within *Construction, Material, and Mechanical systems* at the University of Stavanger (UiS), Norway.

My background as a mechanical engineer and practical background within the offshore industry has contributed to completing this thesis. However, a significant part of the subjects has been unknown to me, and the learning curve has been high from day one. This thesis strives to guide readers that have an equal background as me. Nonetheless, an individual with a general technical background should be able to interpret concept proposals and the results.

Thanks to everyone who has contributed to the content of this thesis. Particular consideration to my supervisors at UiS and Moreld Capnor:

- **Prof. R.M Chandima Ratnayake - University of Stavanger:** His passion for the topic and guidance through my studies have been invaluable. Without his support, the outcome of the thesis would most probably have been different.
- **Jorgen Gronsund - Moreld Capnor:** The contacts and industrial insight would not have been possible without his aid. He has included me in critical discussions with industry experts that have strengthened the content of this thesis considerably.

Last but not least, thanks to my dear family, who have supported me throughout these years of challenging studies, setbacks, and success. You are the best!

1 Introduction

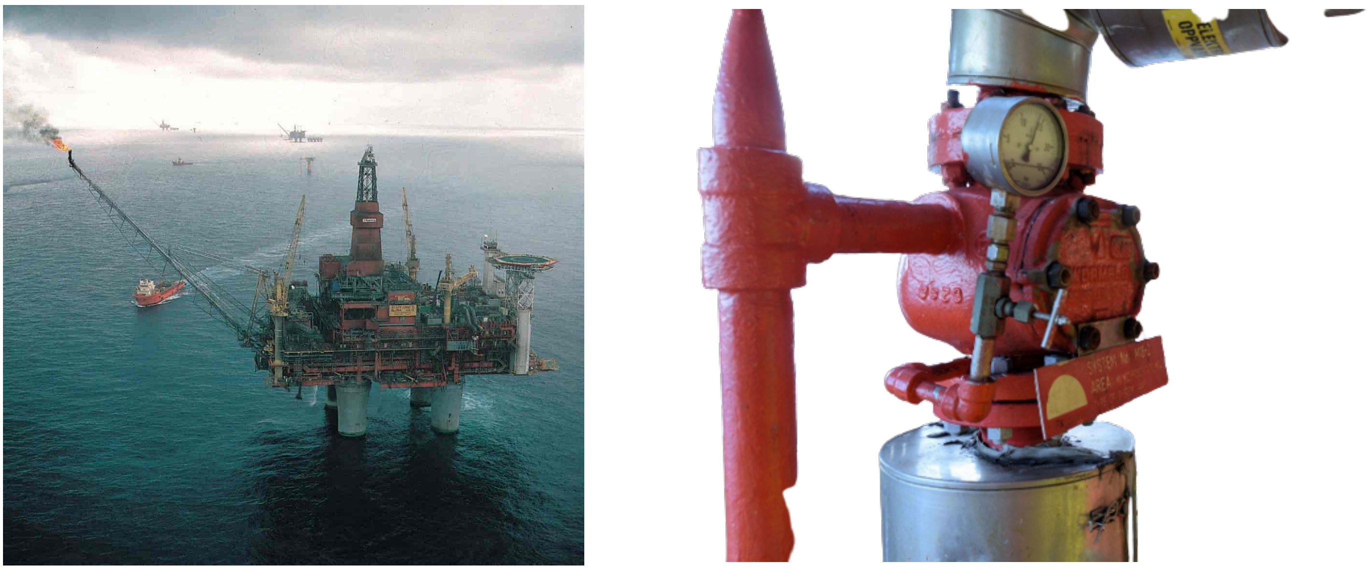
The introduction provides the background and problem description of the thesis. Then, research goals and limitations are defined.

1.1 Moreld Capnor

Moreld Capnor is part of the Moreld group owned by the equity investor Hitecvision since 2019 [1], [2]. The company was established in 1998 as part of Apply Capnor. Introduced in 2002, Capnor was the first professional provider of laser scanning and now has close to 80 people working at different locations. Business sectors cover oil & gas (O&G), marine, pulp & paper, and other generic industries. They are one of the largest domestic providers of laser scanning solutions with ∼50% of the Norwegian market. In addition, they provide design engineering, dimensional control, additive engineering, and manufacturing consulting. Two central locations currently distribute their work; Sandnes, Norway, and Krakow, Poland.

1.2 Background & Early Dialogue

Statfjord is an offshore installation cluster operated by Equinor. It is located northwest of Bergen and is one of the oldest producing oil and gas fields on the Norwegian continental shelf. Figure 1a displays the three main topside structures referred to as Statfjord A, B, and C [3]. The harsh offshore environment imposes detrimental effects on exposed structures and equipment. Further, the ageing structures and components are part of a broad maintenance program that continuously evaluates modifications, repairs, and replacements. A critical part of all installations is the deluge system which provides seawater as a fire barrier. Therefore, the valve body, sensors, gauges, and other equipment connected to this system shall be active and in acceptable condition. Equinor has been



(a) Stafjord C, B, and A

(b) Swing check valve configuration

Figure 1: The offshore installation cluster and the valve

in dialogue with Moreld Capnor regarding valve body replacement. As a result, a reverse engineering case of the valve body was introduced together with an opportunity to utilize a pilot version of a digital warehouse which is part of the on-demand solution. In addition to collaborating with Moreld Capnor, industrial and educational contributions have aided in thesis progress and final results. Table 1 and figure 2 presents these organizations.

Table 1: Organizations and thesis contributors

Organization versus contributions	
Organization	**Contribution**
Equinor	Project owner
Moreld Capnor	Project provider and project research
University of Stavanger	Project research
Karlebo	Casting and additive manufacturing consultation
Molstad	Casting and additive manufacturing consultation
Velo3D	Additive manufacturing consultation
Nordic Additive Manufacturing	Additive manufacturing consultation
Wilhelmsen	Digital ecosystem consultation
Castolin Trio	Company visit and consultation
Mechantronics Innovation Lab	Standard consultation
Frekhaug Stål	Casting provider

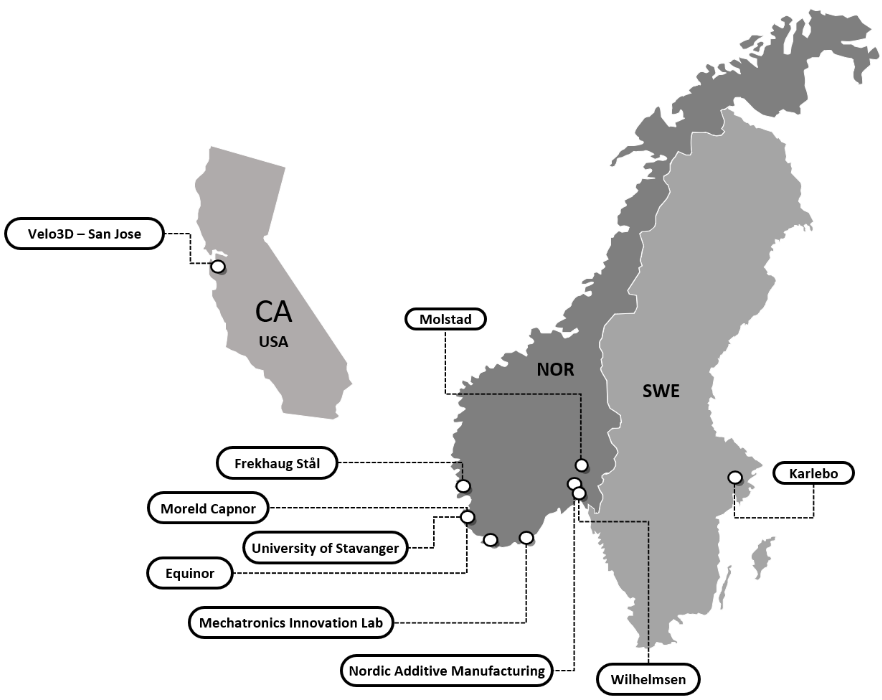


Figure 2: Map of thesis contributors

1.3 Dialogue

A dialogue with Equinors' field life extension unit is given, which provides a basic understanding of the challenge related the thesis.

- **Methods that detect part problems:** *The deluge system is upgraded with other valve types (some exceptions exist). The most common valve damages are detected from inspection and operator checks. Fault indicator has mostly been related to threaded connections, on rare occasions also, failures.*

- **The path from notification to installation today:** *The mechanic can sometimes make a temporary repair, managed by the technical department. However, one-to-one replacements are impossible when we lack spare parts or complete valves. Then onshore department must be involved. Available technical documents are not either available and must be projected each time. The reason is that measurements related to upstream and downstream will differ due to modifications. Also, the replacement becomes a multidisciplinary issue when old alarm functions must be replaced with a new option. Due to the cost and general scope, the project responsible aspires to bundle similar operational tasks in a single activity. This action usually leads to project delays. A tedious part of the supply chain is that one-to-one replacement is non-existing, and different installation teams have difficulty agreeing on what should be done to apply an alternative solution. Also, maintenance and modification suppliers have challenges with capacity and lead times.*

- **The most optimal scenario:** *A complete one-to-one replacement in a material which complies with the demands and challenges of galvanic corrosion (Super duplex, titanium, 6Mo)*

- **The safety stock of valve body spare parts** *The current aim is to upgrade one installation, which will release valves for overhaul and spare parts for the other installations. In generic terms, a wish for two stocked and completed spare parts is set at all times. The reason is to have the ability to share parts with three installations. For this solution, there have been no spare parts available for the original solution for 4-5 years, and separate facilities have implemented a new solution.*

- **Cost and system variations** *A rough estimate of 500,000 to 1,000,000 NOK per unit is expected due to upstream and downstream modifications. There are three different setups where upstream and downstream piping must be modified. These will be different in all situations. It will probably be possible to do everything except the alarm function. If the original alarm function is used, more parts are required than the valve body. Everything can be consolidated to reduce components that build less (as for the original design). If a flow switch is implemented (as in the original design), this must be provided in the new design.*

- **Part consolidation of the homemade system** *Parts displayed in the provided documentation provide the original function of the original valve, including the alarm function. Everything can be compressed/consolidated to reduce components that build less (as for the original design).* Flow and piping diagrams are displayed in Appendix A.

1.4 Problem Description

Figure 3: The original valve manufactured by PADDE, Wormald in 1983 [4]

During a routine inspection of Stafjord A, leakage was detected in the deluge valve body. In addition, the body inspection determined that the degradation of threaded connections reduced the capability of maintaining a complete pressure seal. Other inspections confirmed 26 other cases of a similar problem.

The thesis will focus on the body for the non-return valve, illustrated in figure 3 above. This component has been operating for over 30 years, and exploration for replacement alternatives is under investigation. Early discussions with Equinor provided three solutions for replacement with a focus on cost, lead time, and functionality. However, the complex decision-making of these alternatives has delayed the project, and the need for system implementation is growing. A description of the proposed solutions is given below.

1. **Homemade solution:** This solution originates from internal investigations of their current system. Installing a few of these systems would release valve bodies that could be used as spare parts to other installations like Statfjord B and C. Other components from the old system could then be reused in the new system together

with off-the-shelf parts. This solution requires up and downstream modifications, implying a dedicated project and increased maintenance relative to a one-to-one replacement. The total cost of this system is not fully known. However, rough estimations have indicated a price range of 500,000-700,000 NOK per system. Appendix A demonstrates the piping and instrumentation drawings for the current system and the homemade solution.

2. **New system:** In addition to the increased activities and complexity of the homemade solution, a new system has a higher risk of becoming even more expensive due to outsourcing, inquiry of new components, and increased modification of upstream and downstream areas. A price range of 500,000 to 1,000,000 NOK per system has been predicted.

3. **Reverse engineering:** To make a one-to-one replacement, reproducing the valve body in nearly identical or better conditions requires an investigation of the design, material identification, and manufacturing evaluation. If considered feasible, the one-to-one replacement would be a strong option for replacing the valve bodies without modifications to the current system. Figure 4 displays a rendered version of the scanned valve body used on the offshore installations.

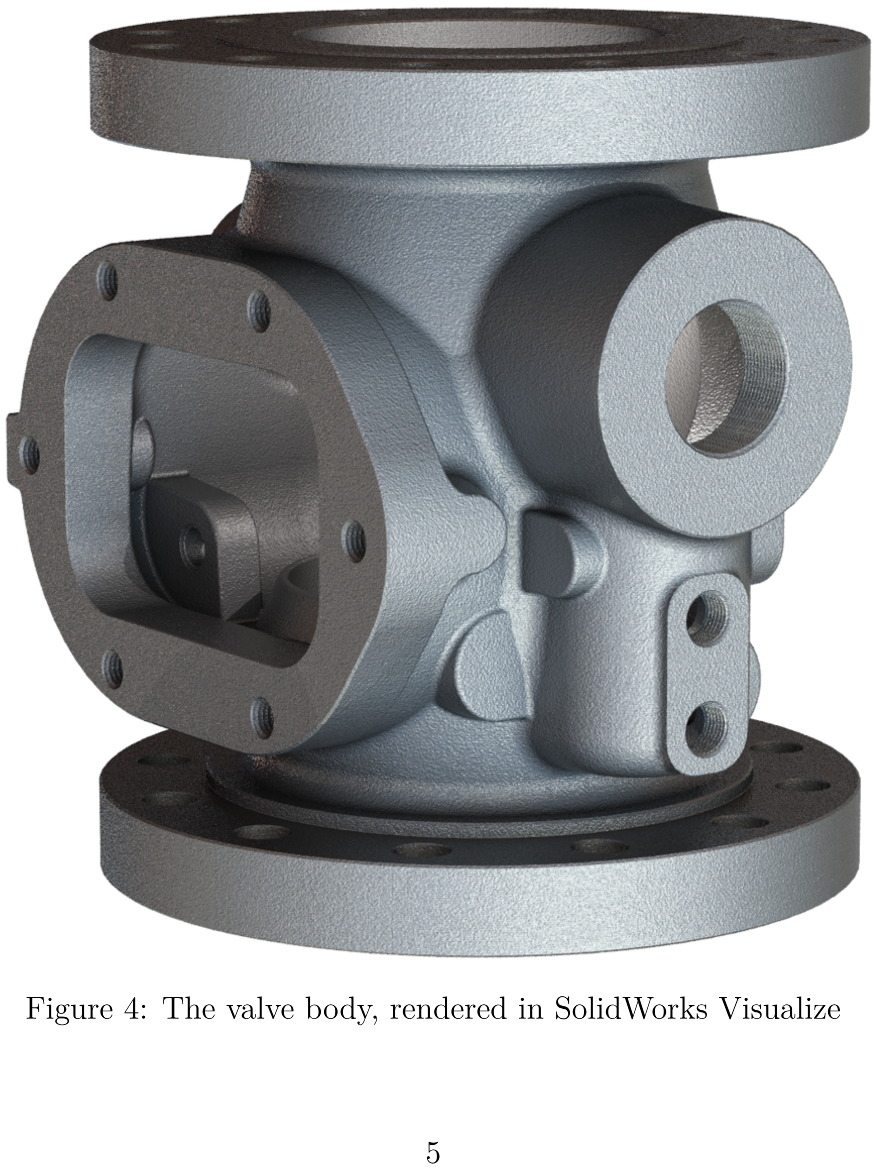


Figure 4: The valve body, rendered in SolidWorks Visualize

Table 2 presents a comparison of attributes versus the above options of solutions. Some of these valve attributes are unclear; for example, the system's modifications may need extensive maintenance depending on the number of parts, i.e., complexity. The lead time and cost of these options are also not fully defined. Therefore, a one-to-one replacement of the valve body could become optimal based on the provided information.

Table 2: Attributes and options for valve replacements

Attributes versus alternatives			
Attribute	**Homemade**	**Reverse engineering**	**New system**
Number of parts	High	Low	Medium
Complexity	High	Low	High
Cost	High	Uncertain	High
Lead time	High	Uncertain	High
Increased maintenance	Yes	No	Yes
Physical storage	Yes	No	Yes
Increased Inspection	Yes	No	Yes

1.4.1 Thesis Challenges

The valve is a legacy spare part, i.e., it partially lacks documentation of the design, material or manufacturing processes. Therefore, a Reverse Engineering Process (REP) is applied. The REP investigates geometry, materials, qualifications, optimization choices, and manufacturing alternatives. However, within the O&G industry on the Norwegian Continental Shelf (NCS), the activities and requirements for reproducing legacy parts by an alternative method such as AM and rapid casting, also known as Three-Dimensional Sand Casting (3DSC), are not adequately studied. Thus, creating an opportunity for exploration.

The valve body has been studied by Equinor once before. However, it was not feasible to proceed with the project at the time. Regardless, evaluation with the REP is analyzed by comparing AM with 3DSC. Most importantly, the investigation will look at the possibility of finding a manufacturing method that may have a realistic possibility of applying a one-to-one replacement of the valve body while producing an essential component to the roadmap of activities and requirements

1.4.2 The Consequence of Topic Neglect

The main problem of disregarding the thesis topic is the risk of bottlenecking the use of alternative manufacturing technologies within the O&G industry on the NCS. The process activities on their own are well documented, yet, the existing path for critical legacy parts is not. Therefore, investigating an option for path consolidation is suiting. However, *topic neglect* could also risk further development within academia and restrict personnel from seeing the holistic perspective of the activities and the requirement for investing their business in on-demand services and legacy spare part acquisition.

1.5 Research Goal & Thesis Question

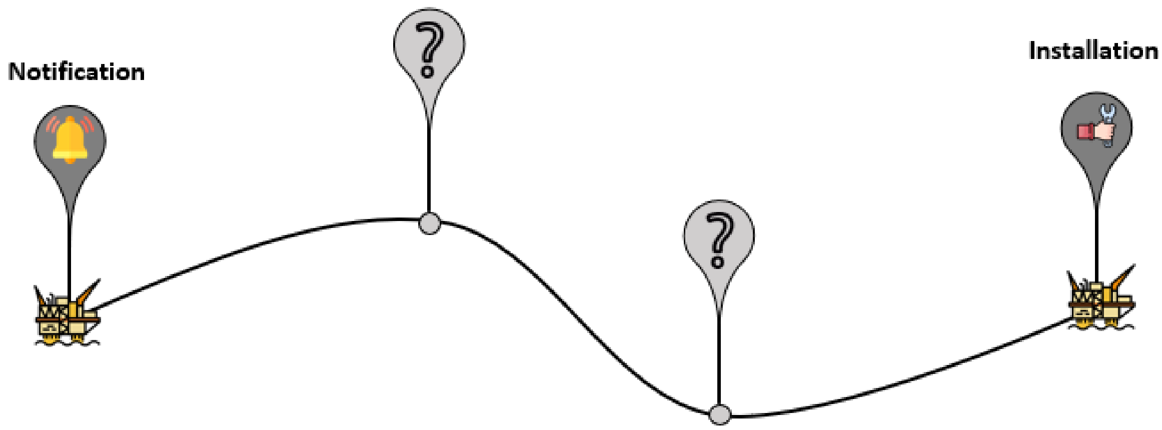


Figure 5: Legacy spare part mapping

This research explores methods of acquiring legacy spare parts by the on-demand solution and current alternative technology, which help define a roadmap based on the REP, see figure 5. Furthermore, the valve body provided by Equinor is used as a benchmark for testing the regulations and standardizations for manufacturing. Therefore, a thesis question (TQ) has been formulated to guide the investigation.

> **TQ:** *How can the path from notification to installation of legacy spare parts be mapped in the O&G industry on the NCS?*

This question carries an important underlining subject related to how the application and the environment affect the part and the manufacturing decision of reproduced parts. Furthermore, the TQ ensures a focus on the essential topics throughout the thesis.

1.6 Limitations

This thesis connects multiple subjects of studies where limitations are set to maintain the general scope of its content. However, within the O&G industry, acquiring legacy spare parts by alternative manufacturing methods is a relatively new topic. Therefore, the literature and case reviews explore realistic approaches and adaptions from other industries. The definite constraint is to relate the scope and approaches to the valve body, but with the subliminal understanding that it may be applied to other similar legacy parts. Therefore, the valve body will be used as the reference component throughout the thesis if not stated otherwise.

2 Methodology

The methodology provides a synopsis of the thesis layout, project time estimations and how the research method is applied to the literature review and case review.

2.1 Work Break Down Structure & Project Timeline

The research is based on a qualitative theory approach used by Creswell [5]. Together with literature, the research has accumulated information from experts in education and relevant industrial positions. Figure 6 display the thesis Work Breakdown Structure (WBS), where the sections are linked to their respective main topic and their source of investigations method.

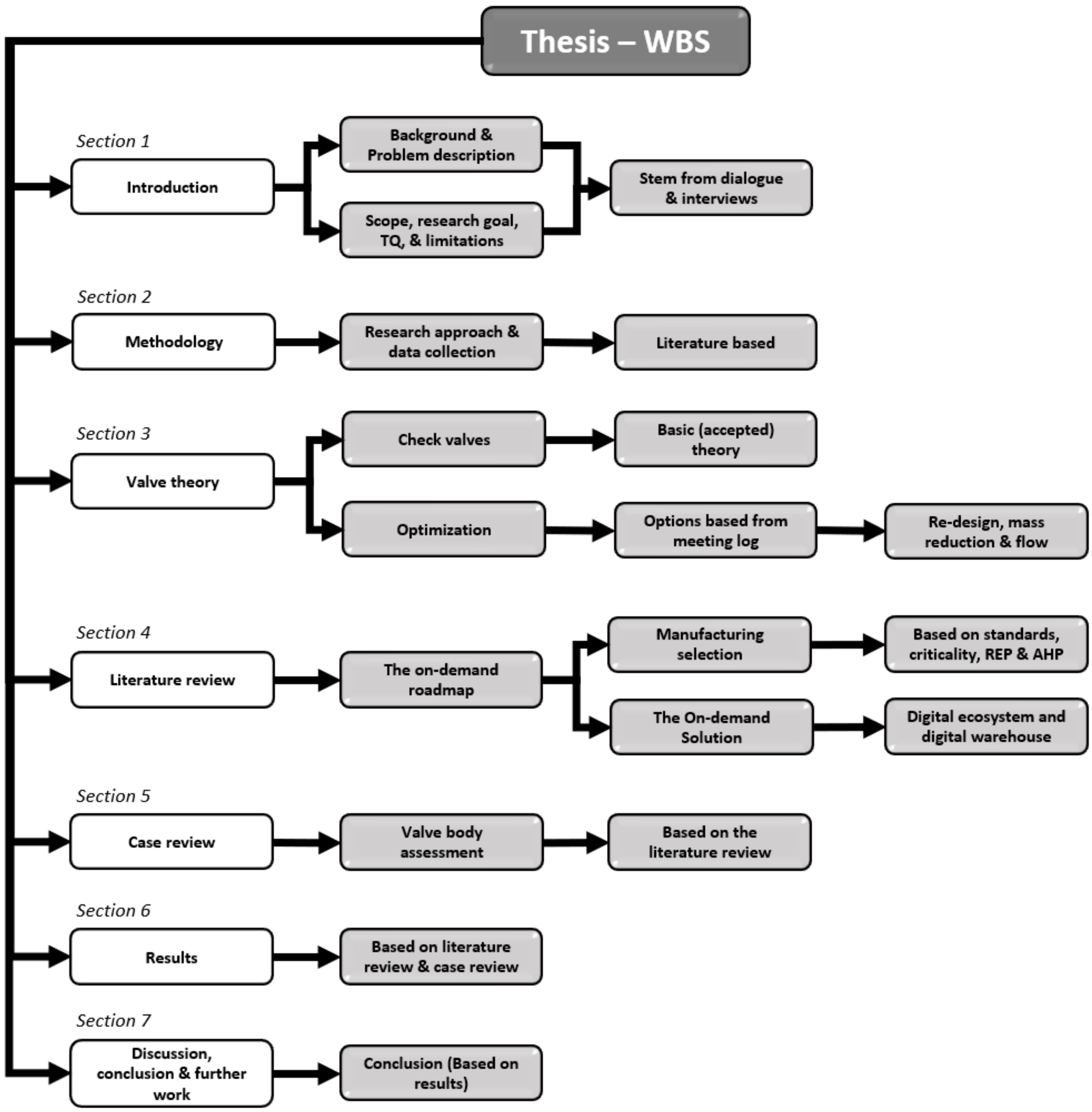


Figure 6: Thesis Work breakdown structure

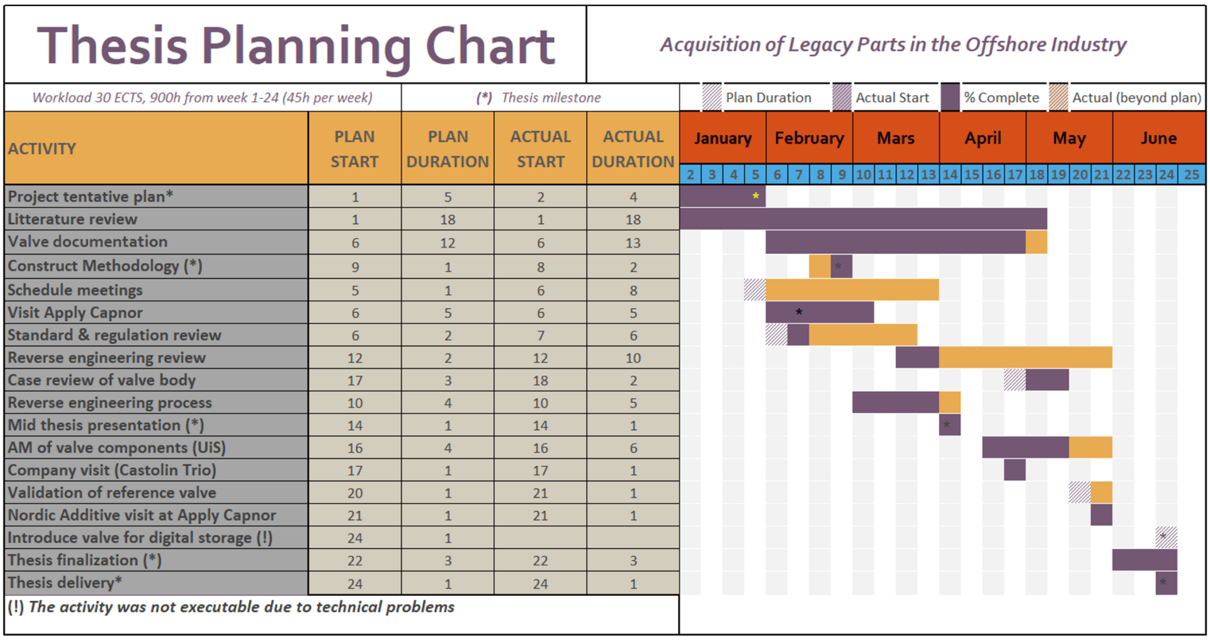


Figure 7: Time estimation

Figure 7 above displays the time estimations concerning the main activities essential for constructing the framework around the main goal and thesis question. Adjustments related to the activities have been made where specific optimization of the valve body was changed only to be included in a holistic view. Also, introducing the valve to the digital storage (warehouse) was not doable due to site update and maintenance.

2.2 Data Collection

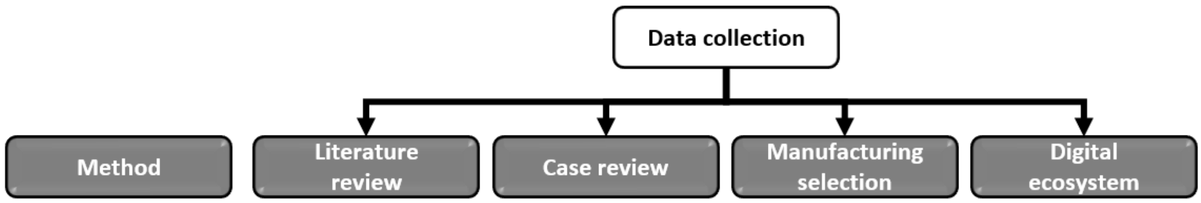
Three primary methods have been used for collecting data; literature review, interviews and questionnaire, and a case review

- **Literature Review:** Literature from space, aviation, and marine industries is used due to their practice of manufacturing legacy parts with alternative methods and their high level of the critical application. An exploration and comparison of standards within AM and 3DSC are given in addition to input from interviews with Moreld Capnor, Molstad Model & Form, and Karlebo. A specific comparison between two specific AM standards provides information for assessing the valve for manufacturing. Also, a proposition of evaluating the part criticality to the consequence of the failure by adapting aviation literature.

- **Interviews and Questionnaire:** Input from interviews with organizations and companies from table 1 is used in the AHP. This method uses the questionnaire's qualitative inputs based on Thomas L. Saaty's decision-making analysis [6]. This tool is an excellent option for further guidance in selecting an alternative manufacturing method for legacy spare parts. The criteria used for building the hierarchy are obtained by analyzing the accumulated interviews and case comparisons of previous manufacturing samples within casting and AM.

- **Case review:** By analyzing the valve body from aspects of environment and application, the REP outlined in the literature review becomes substantiated by applying the valve body to this process. Technical activities for obtaining the valve geometries were performed at the office of Moreld Capnor in Forus, Sandnes. In addition, a full-scale 3D-printed version of the valve body was printed in an industrial plastic material at UiS. Additional parts used for making a functional valve were manufactured at UiS. The valve replica provides geometrical verification such as dimensional accuracy and gives a tangible output concerning functionality.

Figure 8 describe the sources for data related to the main thesis sections. Literature, interviews and discussions between industrial experts within maintenance, manufacturing (AM, casting, machining), and thesis supervisors are general for all sections. The case review includes hands-on activities with scanning and digital analysis as examples. Manufacturing selection applies all three methods, including a questionnaire for obtaining quantitative results from the AHP. The Digital Ecosystem relies on literature and interviews with industry personnel.



Method	Literature review	Case review	Manufacturing selection	Digital ecosystem
Literature	x	x	x	x
Interviews	x	x	x	x
Questionnaire			x	
Hands-on		x	x	x

Figure 8: Section and sources

3 Valve Theory

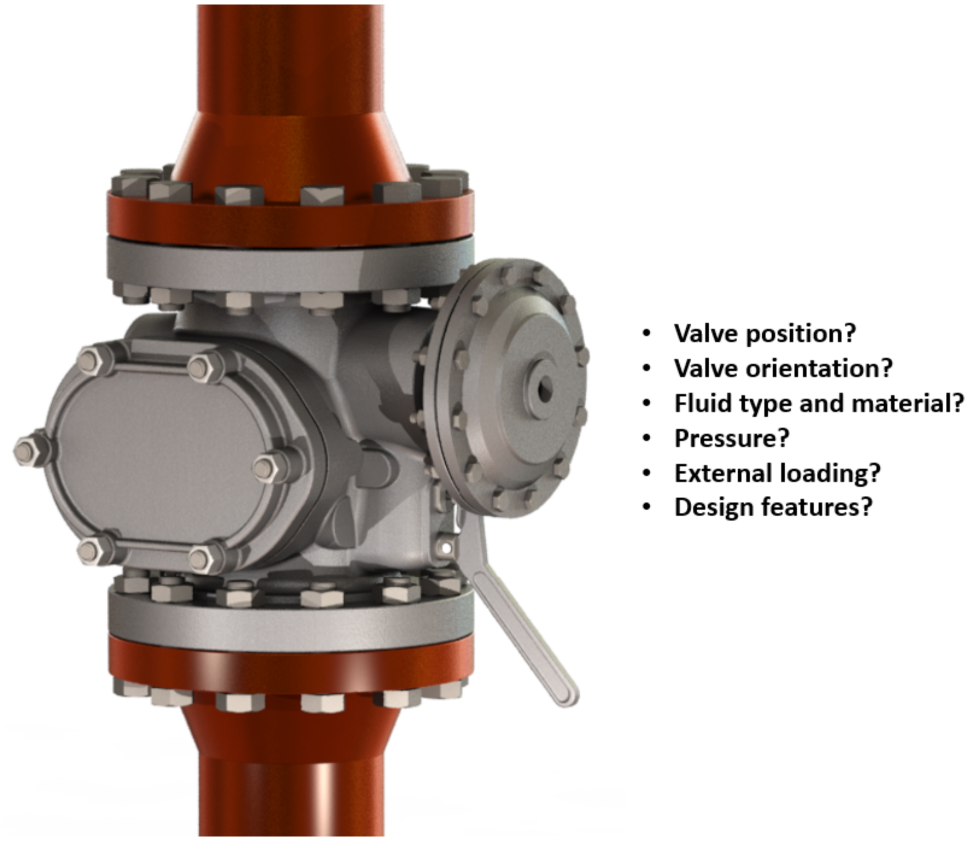


Figure 9: Six-inch valve body in vertical orientation with a mounted restrictor

Check valves are a common type of non-return valves. They are relatively cheap and can be assembled with few parts, making them easy to maintain and replace. The valve body is a raise-faced flanged swing check valve with a manual release and an alarm for activation [7]. Figure 9 displays the valve body and initial considerations that are important for understanding the operation of the valve.

- **Valve position:** The position of the valve body can describe the environmental effects that may act on the valve body. Due to the corrosive atmosphere (mostly in outside positions of the installation), the degradation process can be catalyzed due to aggressive mediums (oil, exhaust, seawater). Discussion with Equinor revealed that the valves are positioned inside and outside the facility.

- **Valve orientation:** The orientation for swing check valves varies between the intermediates of horizontal and vertical positions. Figures provided by Equinor have indicated that most of the valves are in a vertical orientation.

- **Fluid type and valve body material:** Seawater is used as a medium, and the system is classified as a wet system, i.e., the system is pressurized and always contains fluid. Initial discussions with Equinor indicated a nickel-resist material identified as 6Mo (UNS S31254) by original drawings provided by MRC Global.

- **Pressure and external loading:** The internal pressure and external loading can affect the integrity of the valve body. Stress corrosion cracking is a threat due to the combination of the corrosive fluid and the internal pressure, roughly 22 MPa. External loading such as vibrations may also contribute to fatigue-related issues.

- **Design features:** Depending on the type of valve, features related to geometrical design can influence the flow performance and the differential pressure drop through the valve.

There are different configurations of the six-inch valve and its sub-components. Nevertheless, the valve bodies are, in general identical. For example, figure 10 presents internal components of a configuration where a restrictor is used for locking the release block and the disc in a vertical orientation. In addition, the disc (clack) and the rubber seal mounted into the disc body prevent back-flow and protect other downstream equipment such as pumps and turbines from damage. For this specific valve, the release mechanisms or sub-functions (restrictor, manual release, and manual release block) are essential for allowing the water to flow.

Maintaining a flow rate that keeps the valve fully open is important for mitigating disc (clack) oscillations and preventing premature and secondary downstream failures. However, reducing the flow rate will also reduce the friction and shear stress of the fluid while minimizing the pressure drop. For example, suppose the pressure becomes too low,

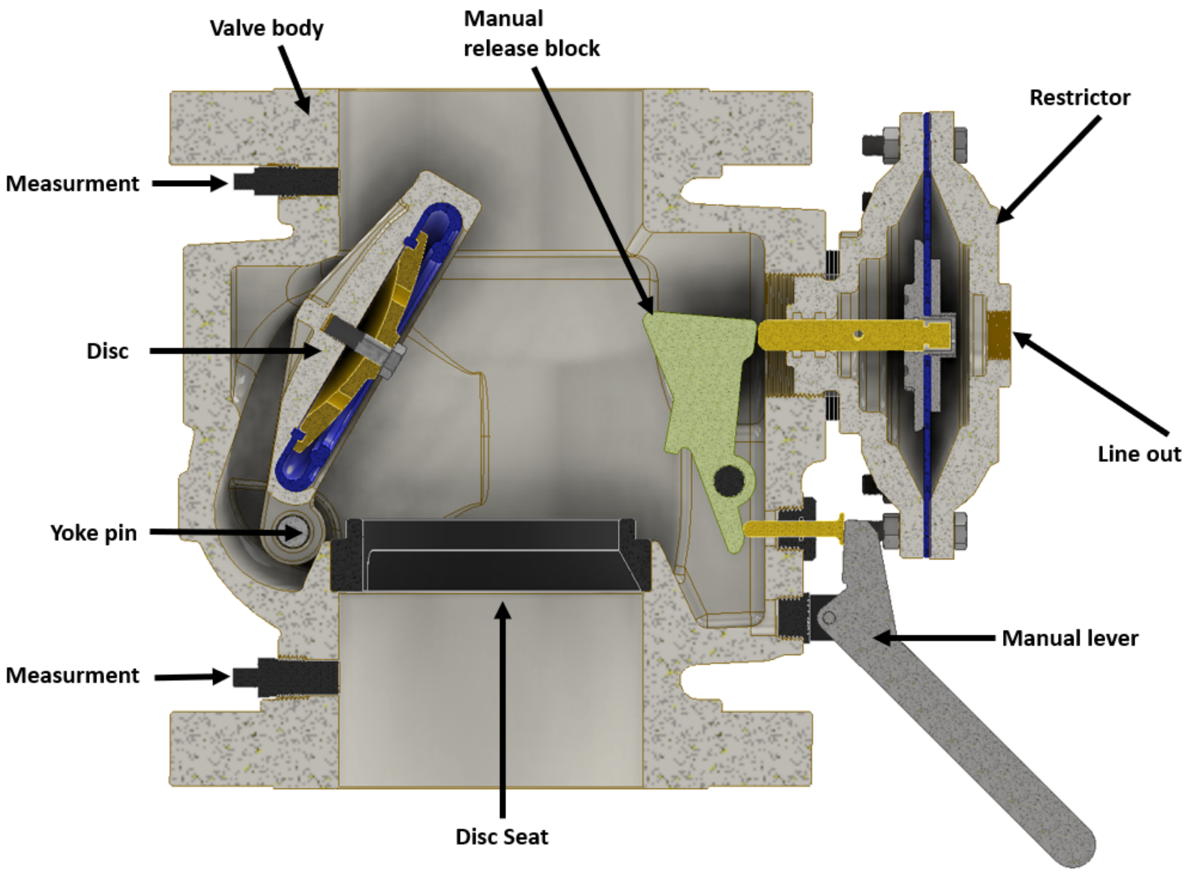


Figure 10: Internal components

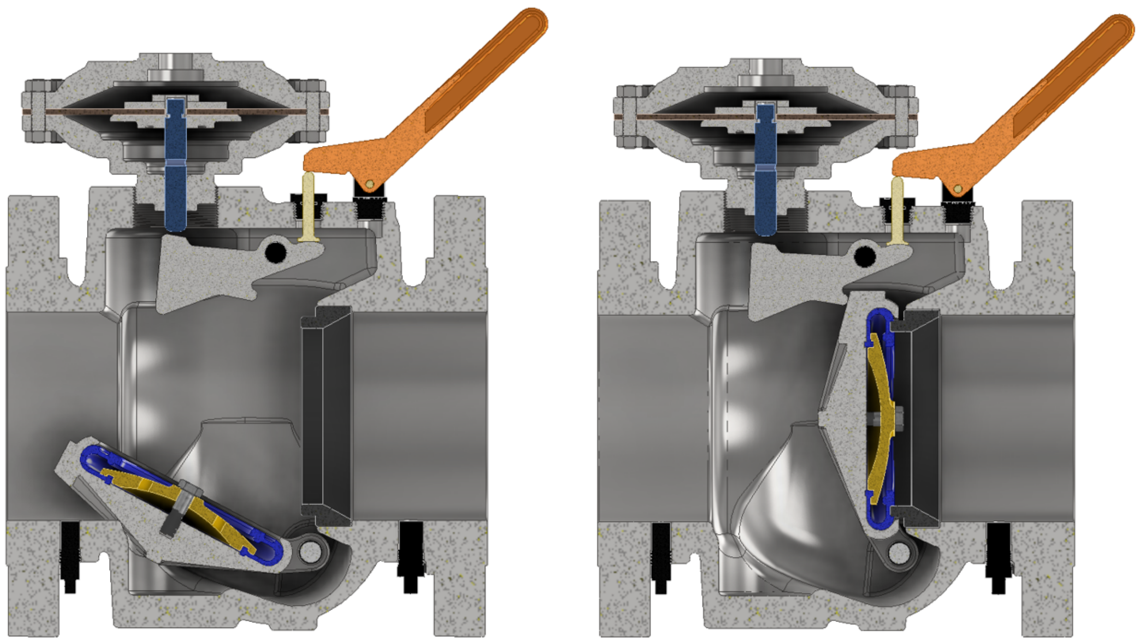
erosive wearing due to the cracking pressure imbalance (opening and closing force) may appear. This valve's imbalance is not an issue due to the release lock. On the other hand, high pressures can create vibrations and increase the pressure drop due to friction. While re-designing a valve body, the flow rate (Q) can be calculated for maximum, regular, and minimum flow conditions. Therefore, it can be used to understand the amount of flow that promotes issues such as disc oscillation or hammering due to reverse flow when the valve is closed.

The pressure drop (ΔP) through the valve can be found by comparing the design against the fluid flow efficiency. It is related to the flow coefficient C_v given in equation 1, where G is the fluid's specific gravity. Rearranging the equation gives the pressure drop (pressure differential) over the valve, which can be used for design optimization and mitigating areas where turbulent flow may occur [7, p. 35].

$$C_v = Q\sqrt{\frac{G}{\Delta P}} \quad \longrightarrow \quad \Delta P = Q\sqrt{\frac{G}{C_v}} \tag{1}$$

Another significant concern when designing or re-designing a valve body is to mitigate the cavitation formed in regions with low pressures due to high fluid velocities and sharp geometry cut-offs. The cavitation represents changes from the state of liquid to vapour where tiny bubbles induce degradation in the form of erosion, reducing efficiency. Equation 2 can be utilized to predict the pressure drop where ΔP_v is the pressure differential where damage from cavitation begins. K_c is the cavitation index from determining ΔP_c, P_1 and P_v are the inlet pressure and liquid vapour pressure at the inlet, respectively.

$$\Delta P_c = K_c(P_1 - P_v) \tag{2}$$



Fully open

Fully closed

Figure 11: Disc positions, open and closed

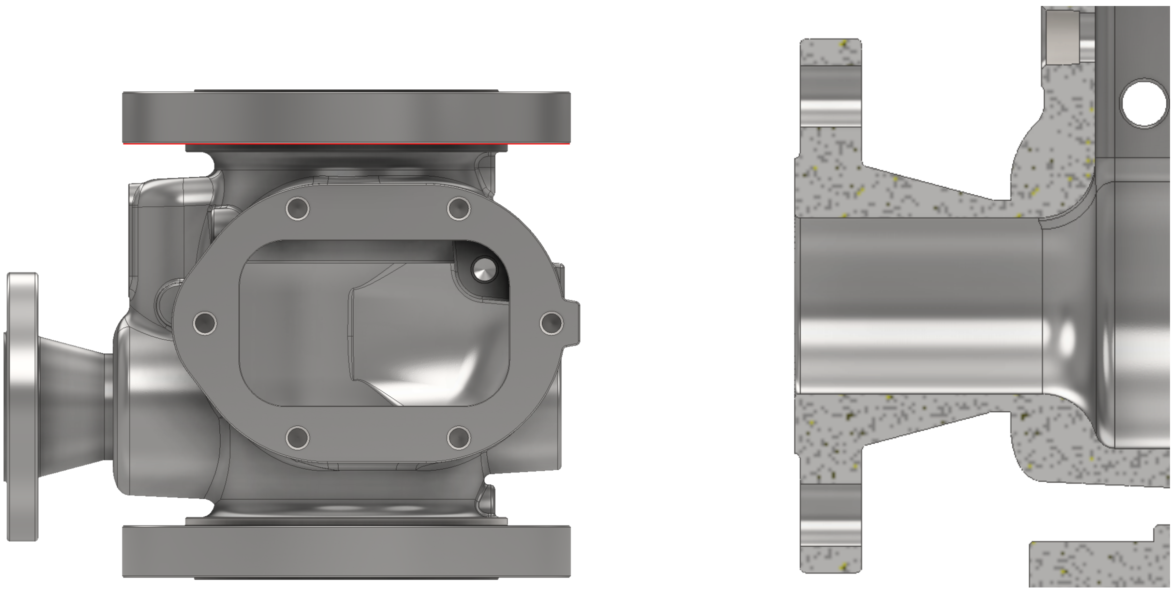
3.1 Options for Optimization

Except for part evaluation, the REP's technical activities can use optimization due to regulations or customer requests. Part optimization strives to improve the performance and functionality of the valve body where a specific or a combination of engineering subjects is applied. Some of the options for valve body optimization discussed with supervisors at Moreld Capnor and UiS are pointed out below, together with explanatory consideration associated with the valve.

- Re-design
- Generative design (mass reduction)
- Flow pattern and pressure drop

3.1.1 Re-design

The degradation of the threaded connections of the valve body influenced the suggestion made by Equinor that a re-design could replace some of these connections [8, p. 3] Appendix D. The proposition was discussed with Moreld Capnor and their engineering branch in Krakow, Poland. As a result, a design engineer proposed a solution where the restrictor outlet merges into the valve's body. Figure 12a and figure 12b presents this modification. The restrictor connection was re-designed in Inventor from proposition according to ASME B16.5-2009. The critical issue of this design concerns the increasing geometrical complexity. It may narrow the options of manufacturing methods able to produce the part.



(a) Flange (b) Flange cross section

Figure 12: Re-design of threaded connection

3.1.2 Generative Design

The activity was performed in a CAD software called Fusion 360 (F360) [9], an optional add-on for iterative design studies. The add-on is focused on Generative Design (GD) based on cloud processing, artificial intelligence, and machine learning. The aim is to reduce the design process while increasing options called ”outcomes” used for design evaluations. There are four phases for GD in F360.

1. **Design simplification:** The internal and external geometry of the valve is complex. Numerous features, such as chamfers, fillets, and, edges could cause problems in the GD study where the success of the converging solution increase with fully defined surfaces. However, due to the internal static pressure of the valve, the internal constraints are more important than external surface constraints. Figure 13 displays the internal features from the scanning process. Figure 14 presents the simplified version of the internal surfaces. F360 was used to perform this simplification before creating a generative design study.

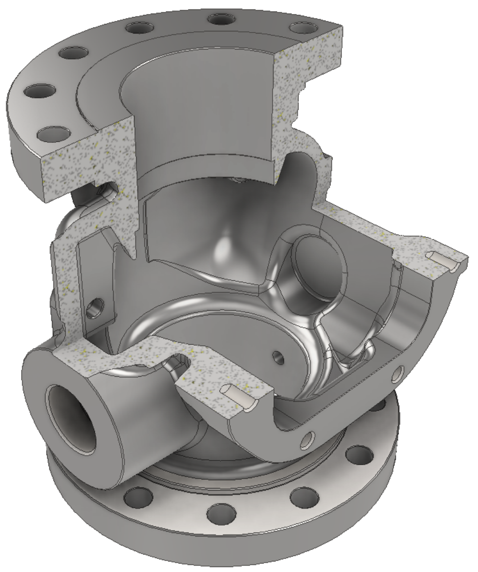


Figure 13: Valve body with original internal scan features

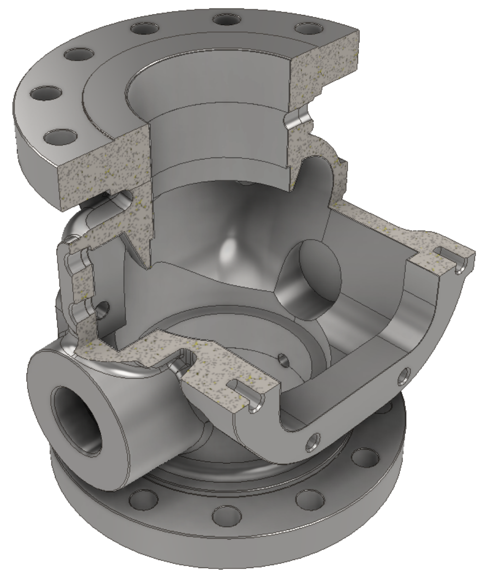


Figure 14: Valve body with simplified internal features

2. **Defining constraints, goals, and material:** A generative design study aimed at ”*structural components*” is specified after the face simplification. Finally, figure 15 presents the finished prepared valve before starting the solver. Four main options for constraints must be chosen before running the solver. It includes the geometry domain, conditions, criteria, and material of the valve design.

    - **The design space** defines obstacles geometry, preserving geometry, and starting geometries. The obstacle geometry describes a space where the solver is prohibited from building material. For example, the flanges in figure 15 have obstacles designed around and through the bolt holes. Preserving geometry (green) is geometries that will be incorporated into the final design. It applies to the valve body’s internal geometry, flanges, and the 2-inch connection.

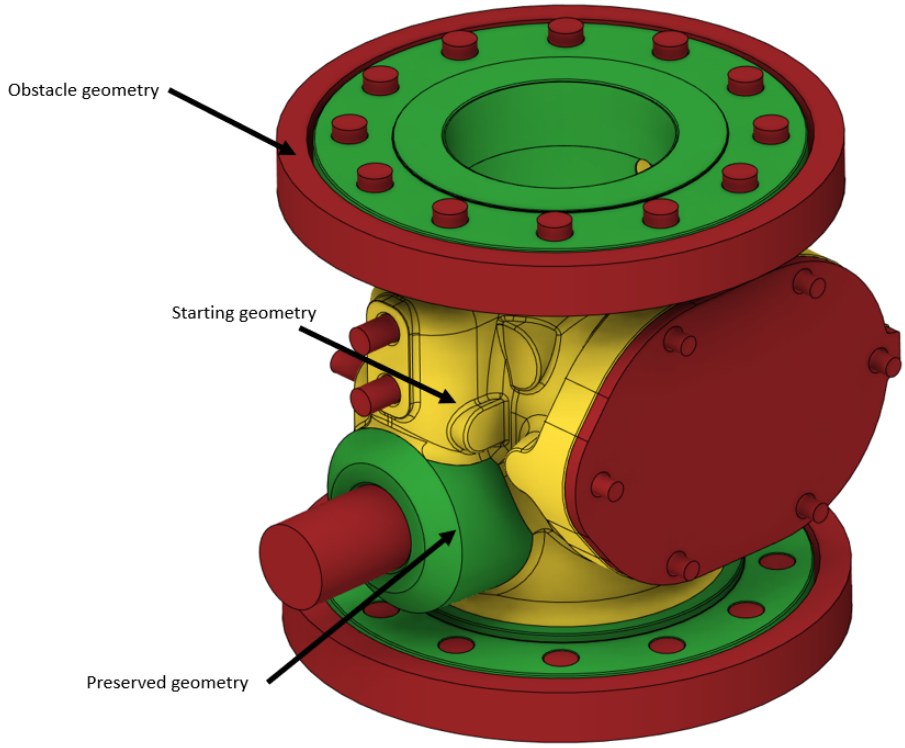


Figure 15: Design space constraints

- **Design conditions** specify structural constraints regarding fixed axes in x,y, and z directions. Also, the valve body is experiencing a uniform pressure of 22 MPa on the internal walls of the valve body.
- **Design criteria** determine the objectives and the manufacturing options. The objective for this case is to reduce the mass while keeping the integrity of the valve. I.e., maintaining the mechanical properties during operation. A safety factor of $\sigma_{yield} \times 1.2$ was applied as an example. The manufacturing options specify cost estimation and four manufacturing options. AM, milling, 2-axis cutting and die casting. Outcome generation only specifies AM and die-casting as manufacturing options.
- **Materials** specify various options that can correlate with cost and manufacturing selections. Therefore, Ti-6AL-4V is chosen for generating outcomes based on the software's available materials and the discussed material options for the valve body (6Mo, super-duplex and titanium).

3. **The selection of outcomes:** When the solver has converged to a solution, multiple part outcomes are produced. These outcomes can be used for comparing manufacturing methods versus the cost of manufacturing, stress versus strains, manufacturing methods versus safety factors, etc.

4. **Post-processing:** The outcomes can take different directions depending on the purpose of the analysis. For example, figure 16 takes outcome 8, which has been converged aimed at casting. The other seven outcomes were converged as suggestions based on AM. The outcome is improved by cleaning the geometry from edges and protruding features that the GD solver produced. Further steps can be

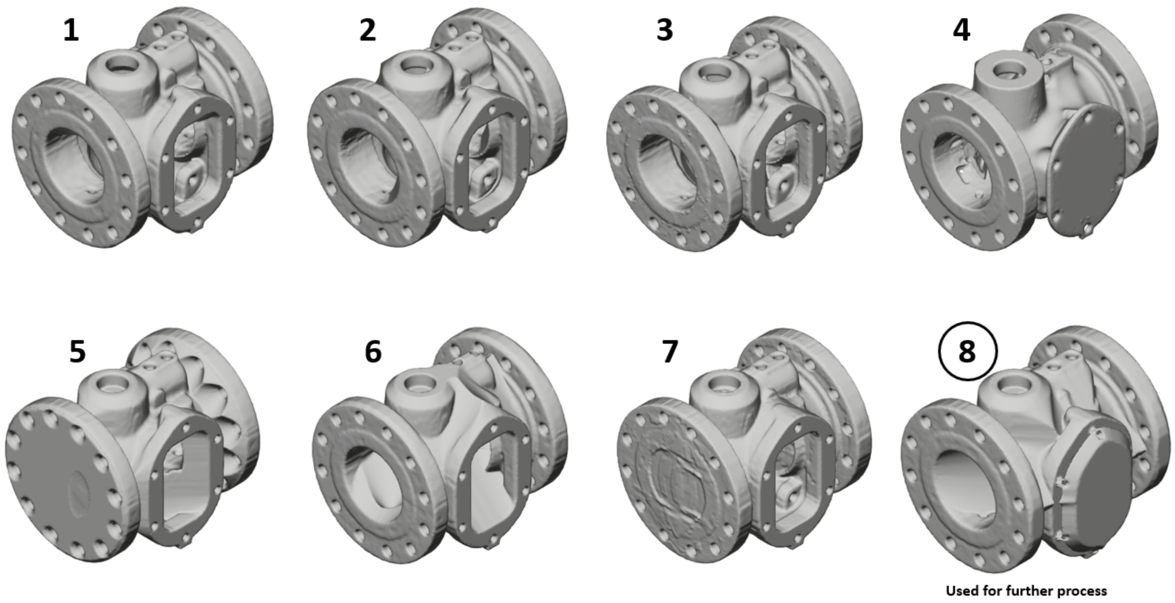


Figure 16: Selection of generative outcomes

applied where finite element tools can assess the part numerically. However, a cautious approach to FE (Finite Element) for AM parts should be considered where non-uniform stresses are formed. No further analysis based on generative design is performed in this thesis.

Figure 17 display the geometrically processed version of outcome 8. The re-shaping of the external features is visible; it is where the algorithm has minimized mass related to maximizing the material stiffness. For reference, the generative design outcome provided around a 12% reduction in mass. *This method should be used cautiously and is provided to demonstrate a new optimization tool that can be used in the REP.*

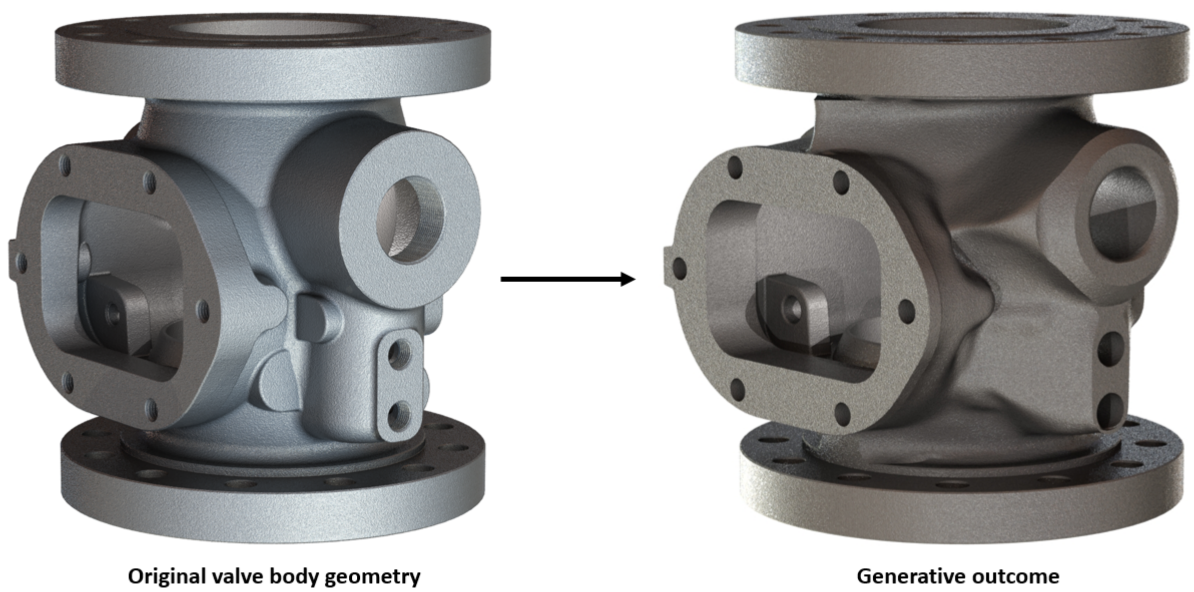


Figure 17: Selected outcome from the generative design study

3.1.3 Flow Pattern

The third option for optimization is related to mitigating fluid turbulence and pressure drop. Many internal components will contribute to determining the fluid pattern through the valve, hence, the pressure drop over the inlet and outlet. In addition to the basic equations for determining pressure drop and flow rate, differential analysis can study flow properties such as pressure and velocity points inside a defined control volume.

The theoretical details will not be defined, but an example of the output from a Computational Fluid Dynamic (CFD) simulation is given. The simulation can approximate the pressure and velocity fields while visualizing turbulent areas that can be used further for calculating cavitation and driving any design changes. Figure 18 represents an example of velocity vectors caused by flow, friction, and geometry created in SolidWorks Flow Simulation [10]. ANSYS, OpenFOAM, or any other numerical software tool can also be used.

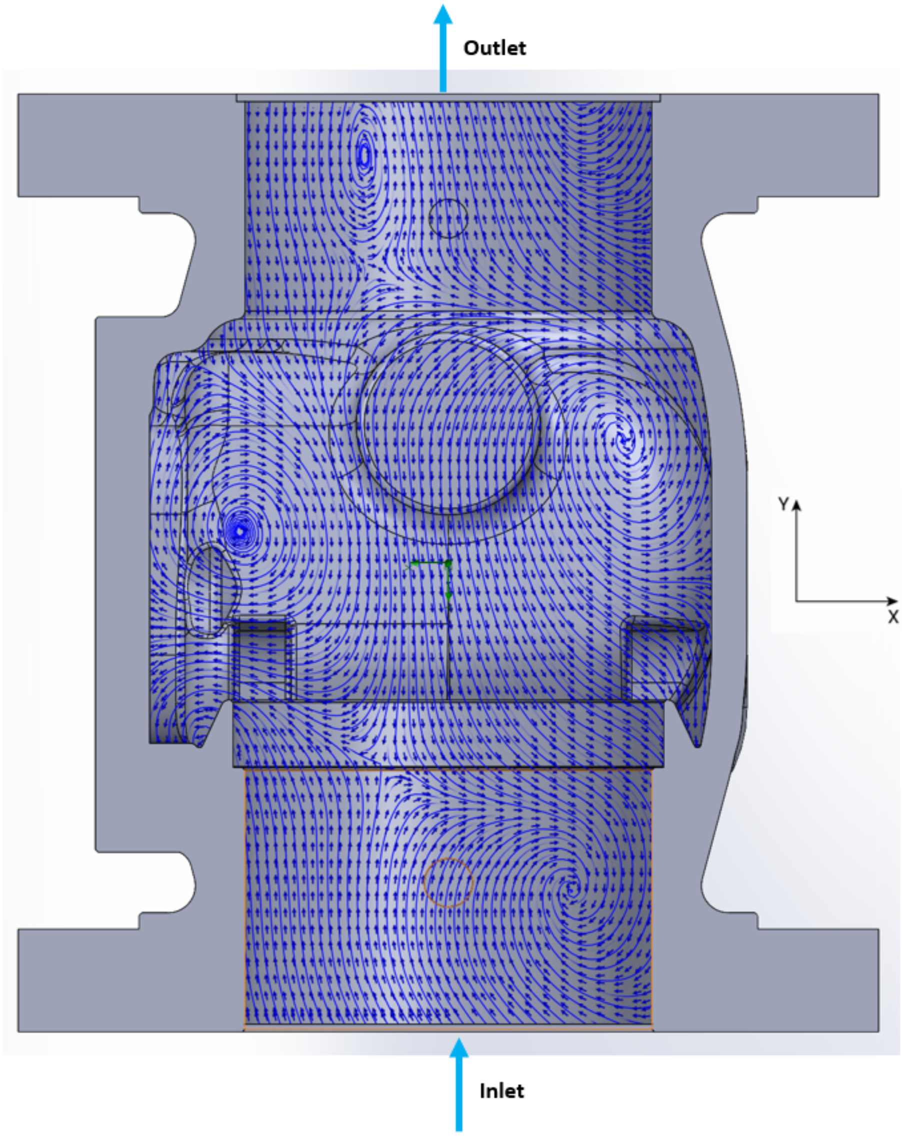


Figure 18: Vector velocity plot without internal components

4 Literature Review

According to experts from the marine industry and an extensive market research report from March 2021 provided by Jabil, the use of AM for legacy and part production is quickly expanding [8], [11]. From a historical perspective, this increase is a mixture of OEMs that have gone out of business, i.e., lost documentation and tooling—also an increased maturity within manufacturing technologies and materials science. In addition, it enables stakeholders to invest in AM and rapid casting equipment that serves many stakeholders in the supply chain, such as; AMs, foundries, machine shop services, feedstock providers, and qualification entities. Further discussions with personnel within the O&G industry imply that the ageing of offshore installations will increase the need for businesses to invest in on-demand solutions to supply the industry with new and obsolete parts.

4.1 Supply Chains

The conventional (physical) path for spare parts in the O&G industry has not changed dramatically since the early adaptions of digitalization. This implementation correlates offshore maintenance programs with stock levels, procurement, and logistics [12]. A representation of the current spare part path is displayed in figure 19, and a specific explanation of path activities related to the valve is described below [13].

The valve has been operating for more than twice the life expectancy. Therefore, any degradation such as wear and tear of threaded connections is not surprising. It can even be that visual input from an inspection assesses the degradation to a level that is not harmful at the time and, until further notice, is maintained under observation. Nevertheless, the valve is noted as a potential issue, and the offshore technical department discusses options for action. Increased inspection revealed that 26 identical valves had similar degradation. Due to the accumulation of notifications of potential problems, the three options for replacement methods (homemade, new system, or reverse engineering) were formed. Discussions between technical personnel offshore and the onshore engineering team made it clear that a replacement option must perform equally or better in terms of reliability, maintainability, and functionality. A new system or parts for a homemade solution can be ordered directly from the supplier or an existing physical warehouse. Components are then shipped from the supplier or the centralized warehouse to the installation.

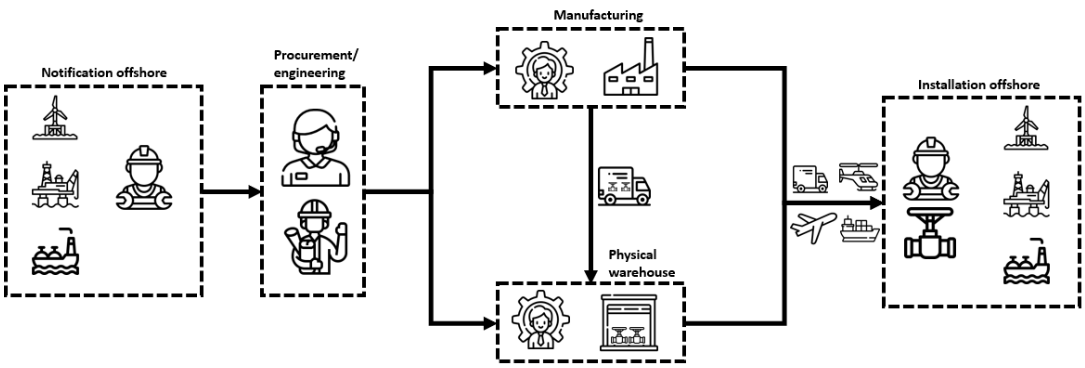


Figure 19: Conventional supply chain route

4.1.1 On-demand Supply Chain

All marine vessels and offshore installations have limited space for critical spare parts. In a failure event, spare part replacement of a critical component is available and ready to be installed. Additional spare parts for safety level stock must then be transported offshore by boat or helicopter. Going to port may be the most logical action for marine vessels, but fixed offshore installations (O&G, wind) do not have that option. However, in all cases, the aim is to reduce operational downtime. Figure 20 presents the route for spare part acquisition in an on-demand condition where the part is purchased through a digital repository (warehouse).

The digital warehouse enables a customer to place an order for a part that has been created by conventional machine design or by request (reverse-engineered). The dominant obstruction is maintaining an established relationship with the supply chain constraints, including the suppliers, data management, warehouse and inventory management, capacity management, and information systems [8, p. 3]. Figure 21 presents an alternative option for future AM on-demand acquisition of spare parts. By moving the manufacturing to the installation, only consumables such as gas and feedstock would be required to be shipped offshore. The decision-makers must consider that all parts may and will not be an option for on-site on-demand manufacturing but could remove a great amount of physical storage space and decrease the logistics of that amount to almost zero.

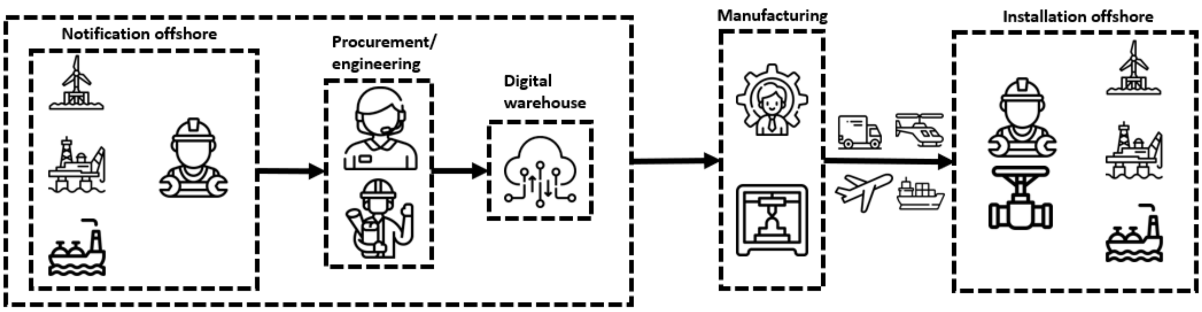


Figure 20: On-demand supply chain route

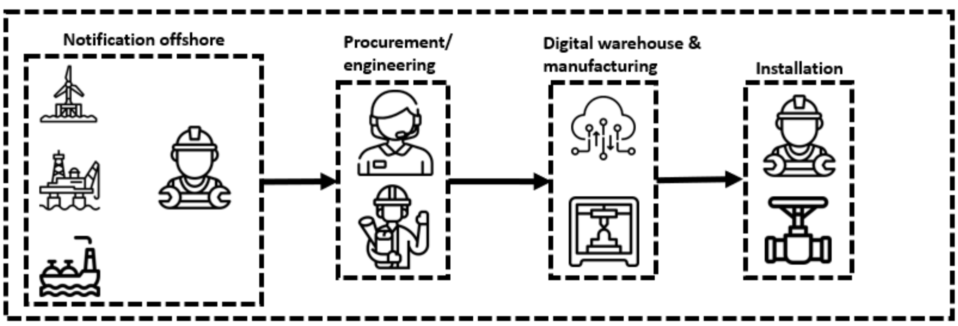


Figure 21: On-demand on-site supply chain route, future route

4.2 Standards & Regulations

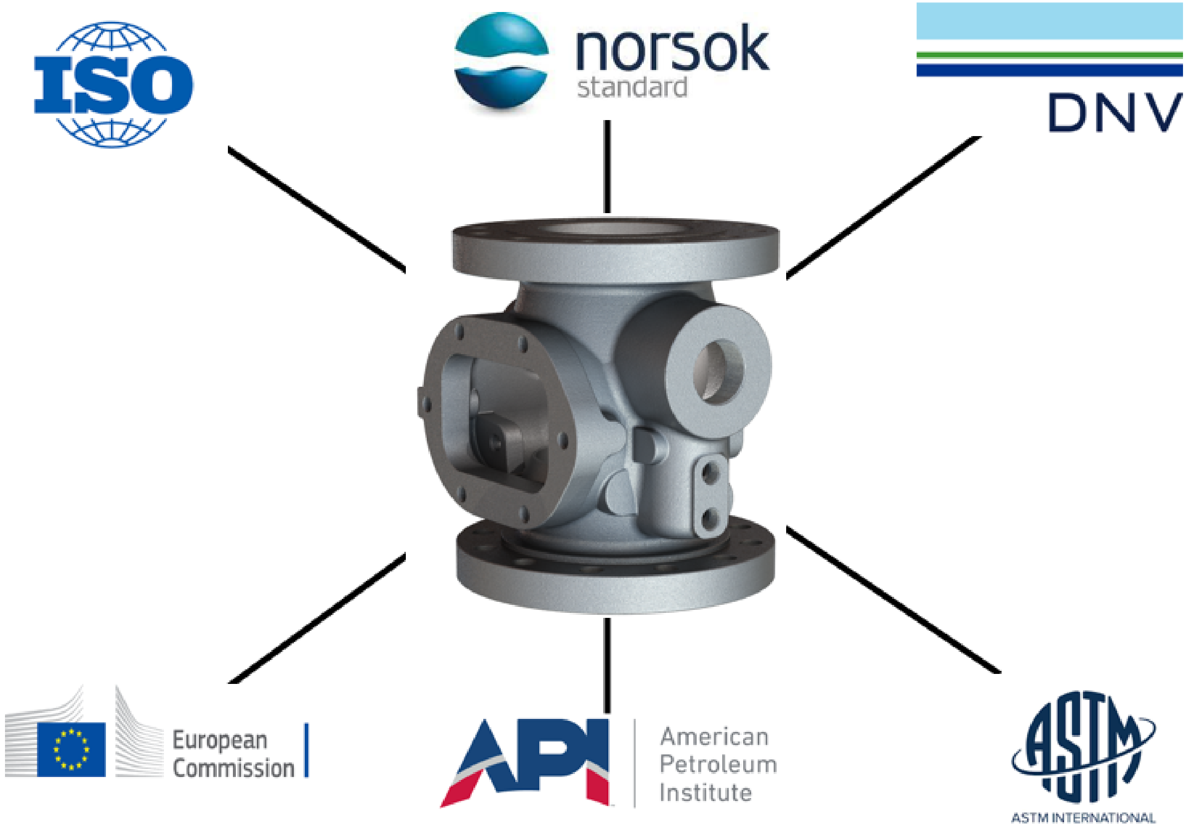


Figure 22: Regulatory organization, association, and classification entities

Mechanical spare parts within the O&G industry have a variety of regulations that apply to different sections of the supply chain. Purchasing, material, design, manufacturing, and testing may be considered. This section will briefly describe five regulatory organization and their importance to valve body re-production. Then, a selection of critical normative standards for AM is revised, followed by a path comparison for the qualification of parts manufactured by metal AM. Finally, an overview of essential reference standards for a rapid casting process is described. Figure 22 display five individual organization that have importance for valve body qualification, i.e., leading to part conformance and ensuring operational safety.

European Union (EU): The EU-pressure directive sector, is one of eighteen sectors that control goods, materials, foods, drinks, and other equipment and services sold within the EU (also within and between countries assigned under the European economic zone). The pressure equipment directive 2014/68/EU(PED) article-1 states that; it *"applies to the design, manufacture, and conformity assessment of stationary pressure equipment with a maximum allowable pressure greater than 0,5 bar"* [14]. The PED shall provide safety while guaranteeing unrestricted product movement within the EU. The directive states that new pressure equipment, second-hand (used), or imported third part equipment outside the EU shall conform to the PED. The document implies that a reversed engineered part such as the cloned valve body also is required to conform to the PED. Articles 3, 4, and 6 refer to putting the part into the manufacturer's service, technical requirements, and obligations. In addition to the general statement of conformance of new or used equipment, article 6, paragraph 1 declare the following important remarks [14]:

"When placing their pressure equipment or assemblies referred to in Article 4(1) and 4(2) on the market ***or using them for their own purposes****, manufacturers shall ensure that they have been designed and manufactured in accordance with the essential safety requirements set out in Annex I."*

"When placing their pressure equipment or assemblies referred to in Article 4(3) on the market ***or using them for their own purposes****, manufacturers shall ensure that they have been designed and manufactured in accordance with the sound engineering practice of a Member State".*

DNV-Det Norske Veritas: Is an independent classification society that provides certification, testing, and technical advisories [15]. They offer their services to seven sectors where O&G greatly contributes to their business. A selection of key documents developed for AM is briefly described below.

- **DNVGL-ST-B203** - *Additive manufacturing of metallic parts*
  This standard (ST) was produced in a joint industry project with other companies and organizations. It guides the qualification of metal parts such as the valve for use in the O&G industry.
- **DNVGL-CG-0197** - *Additive manufacturing, qualification, and certification process for materials and components*
  This class guideline (CG) establishes a qualification system for approval and certification of components, materials, and products created by AM.
- **DNVGL-CP-0291** - *Additive manufacturing feedstock*
  Class program (CP) document related to feedstock approval. It is also related to DNVGL-CP-0267, which specifies the approval of AMs.

NORSOK-Norsk Sokkels Konkurranseposisjon: Translated to English, "the Norwegian shelf's competitive position" is a collection of standards initially developed by the Norwegian petroleum industry to serve as an industrial benchmark for manufacturing of equipment to the domestic O&G sector. Today NORSOK is globally acknowledged and is used and accepted by many end-users worldwide. A selection of essential standards linked to the valve body is listed below [16].

- **NORSOK-M001** - *Materials selection*
  Specifies requirements and guidance for selecting material and protection against corrosion within production of hydrocarbons and processing facilities, support, and supply systems such as fire deluge systems where the valve body is integrated.
- **NORSOK-M630** - *Material data sheets and element data sheets for piping*
  Provides requirements for material and material data sheets (MDS) directed at piping systems; the MDS can also be applied for pressure vessels such as the valve body.

- **NORSOK-M650** - *Qualification of manufacturers of special materials*
  This standard provides specific requirements and specifications for receiving manufacturing approval and is essential for foundries and casting manufacturers.

- **NORSOK-Z008** - *Criticality analysis for maintenance purposes*
  This standard aims at the maintenance optimization and preparations for installation systems such as topside, sub-sea, and O&G terminals. It provides criticality classification of components which includes valves.

API-American Petroleum Institute: is an organization dedicated to the O&G industry. API provides industrial conformity, which increases the industry's safety, efficiency, and sustainability. In addition to NORSOK, API specifications are usually applied or referenced within drilling and well operations but also provide a vital design standard that can be used for guidance in design optimization [17].

- **API20S** - *Additively manufactured metallic components for use in the petroleum and natural gas industries*
  In October 2021, API released its first standard dedicated to AM of metallic parts. This standard is comparable to DNVGL-ST-B203 in the qualification path but has some distinct differences explained in section 4.

- **API6D** -*Specification for pipeline and piping valves*
  This design standard can be used for design changes, testing, and documentation. It follows the American Society of Mechanical Engineers (ASME) class 2500 (32.6 MPa) rating, which denotes that the valve body can be modified according to the API6D and interface with ASME-VII division 2 when the pressure limit is greater than 20.6 MPa [18].

ISO & ASTM-International Organisation of Standardisation) & American Society of Tools and Manufacturing Engineers:. ISO is an international organization, whereas ASTM is a national association part of ISO. ISO/ASTM has created international cooperation in sectors such as AM. DNV, API, and NORSOK standards often reference ISO and ASTM standards for testing, testing methods, process activities, calibrations, print orientations, etc [19], [20].

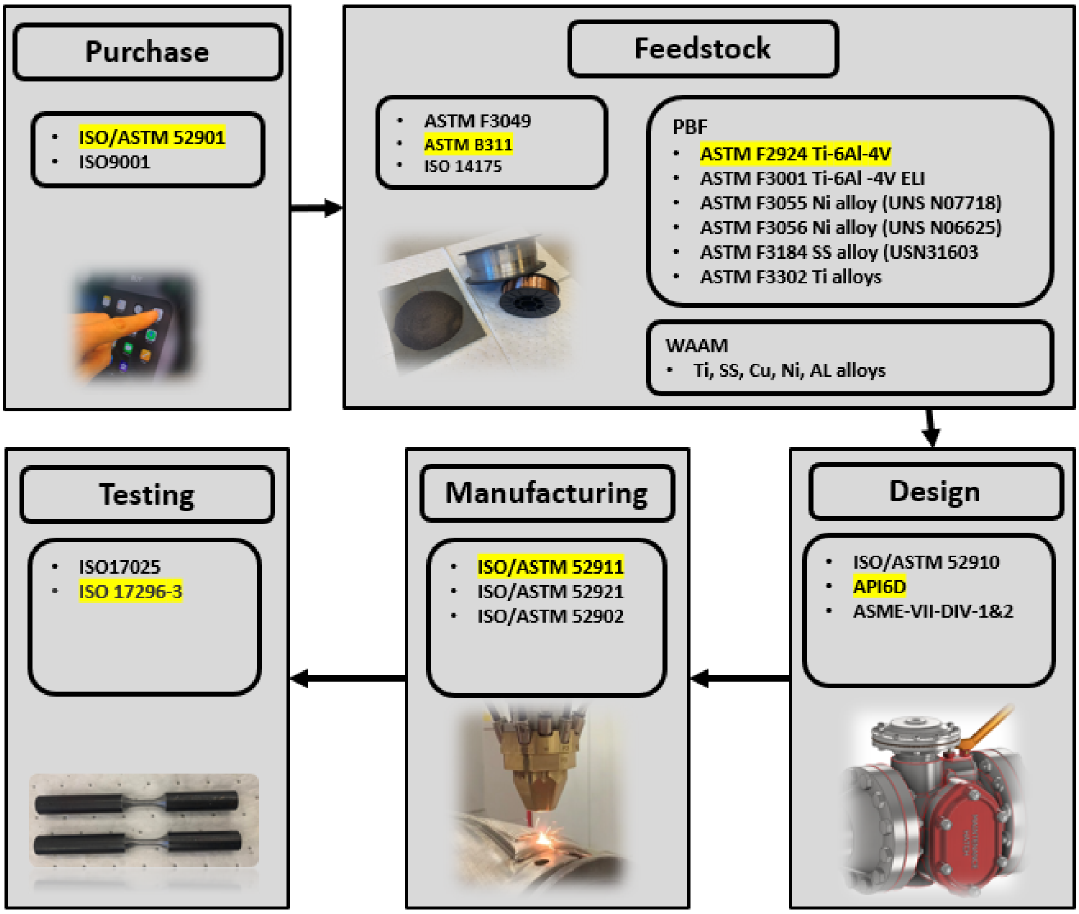
- **ISO-9001** - *Quality management systems:* Provides a certification with a set of standards needed for manufacturers that are offering their services.

- **ISO-17296-3** - *Additive Manufacturing General Principles part 3*:Provides important requirements for part testing of AM-produced processes and specifies the selection criterion.

- **ISO/ASTM-52901** - *Requirements for purchased AM parts:* States requirements for purchasing which is used in DNV-GL-STB203 and API20S.

- **ASTM-F2924** - *Standard specification for additive manufacturing Ti-6 Al-4 with PBF-LB:* This standard is an option for valve body cloning material for AM by powder bed fusion (PBF) process.

4.2.1 Metallic Additive Manufacturing - Standard Overview



Purchase
ISO 9001 – Quality management systems
ISO/ASTM 52901 - Additive manufacturing — General principles — Requirements for purchased AM parts

Feedstock
- ASTM F2924 - Ti-6Al-4V
- ASTM F3049 - Standard Guide for Characterizing Properties of Metal Powders Used for AM Processes
- ASTM B311 - Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
- ISO 14175 - Welding consumables - Gases and gas mixtures for fusion welding and allied processes

Design
- ISO/ASTM 52910 – AM - Design - Requirements, guidelines and recommendations
- API6D – Specification for Pipeline and Piping Valves
- ASME-VII-DIV-1&2 – Boiler & pressure vessel code

Manufacturing
- ISO/ASTM 52911 - AM - Design - Part 1: Laser-based powder bed fusion of metals
- ISO/ASTM 52921 - Coordinate systems and test methodologies (will be changed to ISO/ASTM DIS 52921)
- ISO/ASTM 52902 – AM - Test artifacts - Geometric capability assessment of additive manufacturing systems

Testning
- ISO 17025 - General requirements for the competence of testing and calibration laboratories
- ISO 17296-3 - AM— General principles — Part 3: Main characteristics and corresponding test methods

NOTE: Highlighted text are case specific for the valve body and PBF, this is provided as an example

Figure 23: Mapping of normative and informative standards, DNVGL-ST-B203

Figure 23 above, specifies some essential normative and informational standards from DNVGL-ST-B203 *"additive manufacturing of metallic parts"*. The presented overview is established such that a relatively quick assessment of the needs concerning AM can be made as the focus is to get a simplistic overview of key documents related to the roadmap. There are normative and informational standards for design, manufacturing, and testing included in DNVGL-ST-B203. However, many of them are not mentioned but are presented in figure 23. The reason is that they are either overlapping each other or are in close subject relation.

- **Purchase:** ISO/ASTM 52901 defines the order of documents to be used to exchange documents between part distributor and customer. I.e., feedstock (powder, wire) requirements, order information, part definition data, inspection methods, part properties, etc.

- **Feedstock:** Available and approved feedstocks for Powder Bed Fusion-Laser Beam (PBF-LB) within the DNVGL-ST-B203 standards is provided. Ti-6Al-4V is an adequate candidate for building the valve body. Several options exist for other feedstock types, such as super duplex and experimental high molybdenum concentration. However, these materials have not yet been approved for use by this standard. Material specifics can be found at SANDVIK, and HOGANS, to name a few [21], [22].

- **Design:** In addition to API6D, which specifies the design, manufacturing, and testing for valves, ISO/ASTM 52911 provides design consideration for the manufacturing method of PBF.

- **Manufacturing:** ISO/ASTM 52911 provides overall guidance for manufacturing AM components with PBF-LB. The document also refers to other standards and reference documentation concerning part file handling, design, quality assurance, and dissertation papers.

- **Testing:** Several standards define specific testing and testing requirements. However, ISO-17296-3 (which will be replaced by ISO/ASTM DIS 52927) is specifically aimed at manufacturers, parts users, and customers. It provides the requirements of part testing, quality, and test procedures for AM processes.

Figure 24 presents a Quality Control Requirement (QCR) matrix that was constructed to support essential standards depending on the Additive Manufacturing Class (AMC). This matrix compares specific part testing activities versus AMC levels for Direct Energy Deposition (DED) and PBF processes. The three QCRs control steps used for manufacturing compliance, secure process qualification through build part qualification testing (BPQT), Part Qualification Testing (PQT), and Product Testing (PT), respectively.

Quality Control Requirement Matrix		WAAM									PBF-LB								
		AMC-1			AMC-2			AMC-3			AMC-1			AMC-2			AMC-3		
Testing	**Standard(s)**	BPQT	PQT	PT	BPQT	PQT	PT	BPQT	PQT	PT	BPQT	PQT	PT	BPQT	PQT	PT	BPQT	PQT	PT
Bending	ASTM E384 ISO 7438 (WAAM)	*			*			*											
Porosity	ASTM B311	*			*			*			x			x			x	x	x
Chemical	ASTM A751	*			*			*			x			x			x		
Tensile	ISO 6892-1 ASTM E8/E8M	*			*	*	*	*	*	*	x			x		x	x	x	x
Impact	ISO 148-1 ASTM E23	*			*	*	*	*	*	*	x			x		x	x	x	x
Hardness	ISO 6507-1 ASTM E290 ASTM E384	*			*	*	*	*	*	*	x			x			x	x	x
Microstructure	ASTM E3 ASTM E407	*			*	*	*	*	*	*	x			x			x	x	x
Visual	NS-EN 13018					*	*		*	*						x		x	x
Surface (NDT)	ISO 3452 ISO15549 ISO 9934 ISO 17296-3					*	*		*	*						x		x	x
Volumetric (NDT)	ISO5579 ISO15708-B ISO 16810	*			*	*	*	*	*	*						x		x	x
Dimensions	By agreement					*	*		*	*						x		x	x

Abbreviations

- **AMC -** Additive Manufacturing Category
- **WAAM (*) -** Wire Arc Additive Manufacturing
- **BPF-LB (x) -** Powder Bed Fusion Laser Beam
- **NDT -** Non destructive testing

- **A = BPQT -** Build Part Qualification Testing
- **B = PQT -** Part Qualification Testing
- **C = PT -** Part Testing

Description

WAAM
- BPQT is equal in all AMCs (blue)
- PQT and PT for AMC-2 and AMC-3 are equal (green)

BPF-LB
- BPQT is equal in all AMCs (yellow)
- No PQT or PT for AMC-1
- No PQT for AMC-2

Figure 24: Testing requirement versus AMC level according to DNVGL-ST-B203

The amount of extracted test specimens depends on the AMC and AM manufacturing processes. The complete overview is found in DNVGL-ST-B203. Nonetheless, the example above is based on the complex geometry of the valve body and the assumption that industry input defined the AMC and available materials. For example, if an AMC-3 option is selected, cost and time would increase significantly due to qualification requirements.

For comparison, the API20S was released in October 2021, aiming at the *"Petroleum and Natural Gas Industries"* [23]. This standard is almost identical to DNVGL-ST-B203 regarding the purchase, criticality levels, design, manufacturing, and pre- and post-processing activities. However, the distinctive difference in API20S is that it offers specifications for DED, PBF, and Binder Jetting (BJT). In addition, there are stricter feedstock requirements for virgin feedstock but a smoother use of the qualification path than DNVGL-ST-B203.

Interpreting the above matrix can be done by taking the valve body as an example and using figure 25 as a reference, where the PBF-Laser Beam (LB) method is used as the preferred AM process.

1. First, an AM method (WAAM or PBF) is selected. Here, PBF-LB is used.
2. Secondly, the AMC level is chosen. AMC-2 is selected.
3. Finally, select the vertical needs (X) with the horizontal requirements.

Quality Control Requirement Matrix		PBF-LB AMC-2		
Testing	**Standard(s)**	**BPQT**	**PQT**	**PT**
Bending	ASTM E384 ISO 7438 (WAAM)			
Porosity	ASTM B311	X		
Chemical	ASTM A751	X		
Tensile	ISO 6892-1 ASTM E8/E8M	X		X
Impact	ISO 148-1 ASTM E23	X		X
Hardness	ISO 6507-1 ASTM E290 ASTM E384	X		
Microstructure	ASTM E3 ASTM E407	X		
Visual	NS-EN 13018			X
Surface (NDT)	ISO 3452 ISO15549 ISO 9934 ISO 17296-3			X
Volumetric (NDT)	ISO5579 ISO15708-B ISO 16810			X
Dimensions	By agreement			X

Needed for part qualification

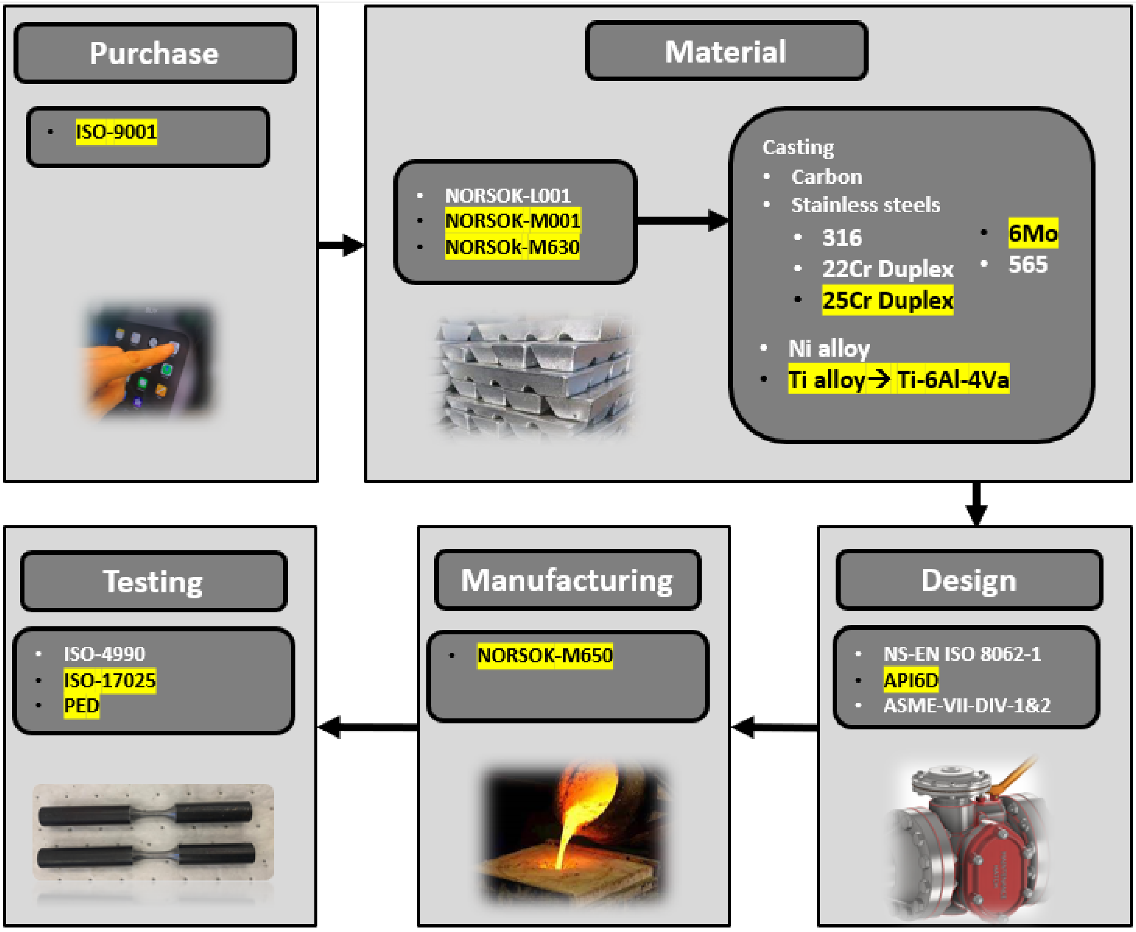
BPQR [X]
- Porosity
- Chemical
- Tensile
- Impact
- Hardness
- Microstructure

PQT [X]
- None

PT [X]
- Tensile
- Impact
- Visual
- Surface (NDT)
- Volumetric (NDT)
- Dimensions

Figure 25: Quality requirements for an AMC-2 part manufactured by PBF-LB

4.2.2 Steel & Metal Casting - Standard Overview



Purchase
- ISO9001 – Quality management systems

Material
- NORSOK-L001 – Piping and valves
- NORSOK-M001 – Materials selection
- NORSOK-M630 – Material data sheets and element data sheets for manufacturing

Design
- NS-EN ISO 8062-1 – Geometrical product specifications (GPS)
- API6D – Specification for Pipeline and Piping Valves
- ASME-VII-DIV-1&2 – Boiler & pressure vessel code

Manufacturing
- NORSOK-M650 – Qualification of manufakturers os special materials

Testning
- ISO 4990 - Steel castings — General technical delivery requirements
- ISO-17025 - General requirements for the competence of testing and calibration laboratories
- PED – Pressure Equipment Directive

NOTE: Highlighted text are case specific for the valve body and PBF, this is provided as an example

Figure 26: Guidance standards and documentation for casting qualification

The casting process is a well-recognized and proven manufacturing method where the qualification requirements are not as extensive as for AM processes. Figure 26 above provides an overview of standards and documents that can be used for guidance when applying a path for material, design, manufacturing, and testing for casting. A more in depth explanation of important documents is provided below:

- **Material:** NORSOK-M001 specifies requirements and guidance for selecting material based on the system, type of medium, and minimum of 20 years of design life. NORSOK-M630 defines the material requirements and provides a selection of Material Data Sheets (MDS), which can be chosen depending on the demands of the spare part component. NORSOK-M001 reference to standard ISO 21457 for material selection within production systems seen in figure 27. It mentions the "Firefighting-fighting systems - Deluge system", which determines the type of material that should be considered for valve body manufacturing. Due to galvanic corrosion considerations, three preferred materials have been discussed with the customer, 6Mo, Titanium, and super duplex. Appendix B supplies examples of the MDS. Also, an example of manufacturers' qualifications regarding sand casting and productions with super duplex is given.

Table 6 – Materials for utility use

Service	Equipment	Materials	Notes
Fire-fighting systems	Dry CO_2 systems	Carbon steel, CRA	
	Deluge system	See table 4	
	AFFF piping	Type 316 SS, type 22Cr duplex SS, FRP/GRP	

Table 4 – Materials for seawater systems

Systems/equipment	Materials	Notes
Vessels	Titanium, FRP/GRP, type 25Cr duplex SS	
Piping valves and inline instruments	Type 25Cr duplex SS, FRP/GRP, type 6Mo SS, titanium, carbon steel with polymeric lining.	1
Valves in GRP systems	FRP/GRP, Carbon steel with polymeric lining, NiAl bronze, titanium, type 25Cr duplex SS.	
Normally drained systems	Type 25Cr duplex SS, titanium.	
Pumps	Type 25Cr duplex SS	

Notes
1. For inline instruments alloy 625, alloy C276 and alloy C22 may be used in addition to materials listed

Figure 27: Material guidance for utility systems, NORSOK-M001

- **Design:** Documents used for guidance to design and re-design are the same as for AM, API6D, and ASME-VII. However, ISO-8062 (GPS)- *"General dimensional and geometrical tolerances and machining allowances for castings."* This standard may contribute to changes in the casting process due to specific criteria regarding the geometrical tolerances.

- **Manufacturing:** NORSOK-M630 references NORSOK-M650 for the qualification of the manufacturer regarding the sand casting process and the material used for casting. Similarly, Appendix B provides an attachment of manufacturers' Qualifications Test Record (TQR) for sand casting and production with super duplex.

- **Testing:** NORSOK-M630 also considers the PED, where they state [24, p. 5]:

  "The provision of the NORSOK standards are intended to comply with the requirements of the EC "Pressure Equipment Directive" and the Norwegian implementation regulation "Forskrift for trykkpåkjent utstyr" issued 9 June 1999"

  The previous introduction to PED supports the requirements for PED conformance of the valve body. In addition to the testing requirements given in NORSOK, ISO-4990-steel castings provide an overview of normative testing about casting.

4.2.3 Standards Summary

Regulatory aspects must be considered when a reproduction of the valve body or any other components is prepared. Figure 28 is a compressed version of previous documentation that needs to be investigated during valve body reproduction. The **X** indicates the dominant documentation to which other reference standards can be located. An example is the DNVGL-ST-B203 which provides requirements for the manufacturing process and refers to testing standards such as tensile testing.

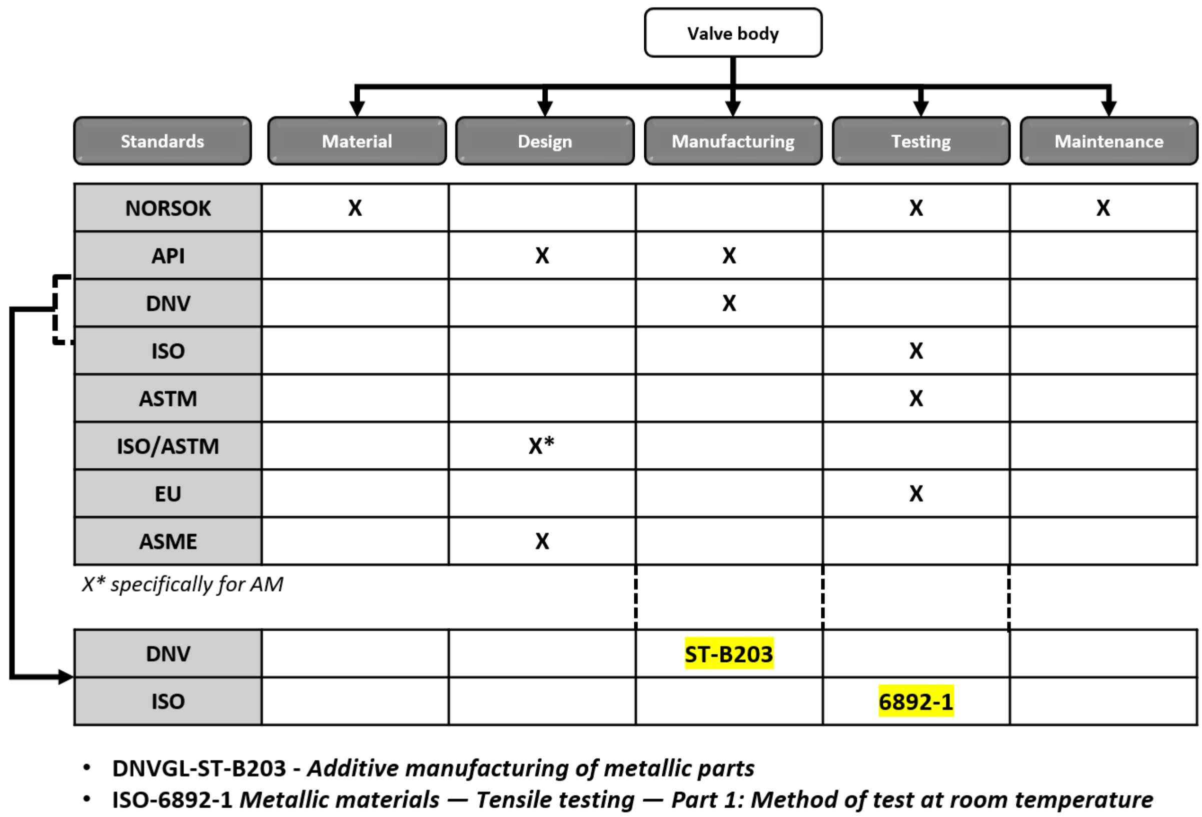


Figure 28: Leading regulatory documentation

4.3 Methods of Manufacturing

Identifying realistic manufacturing options is essential for evaluating the feasibility of part production and replication. The technical abilities for alternative manufacturing methods such as metal AM, rapid casting, and hybrid manufacturing are available. However, different cost and qualification routes challenge the implementation of these methods. Therefore, this section explores pre-determined manufacturing methods suitable for valve body reproduction. Figure 29 presents a consolidated overview of the discussed manufacturing options and processes.

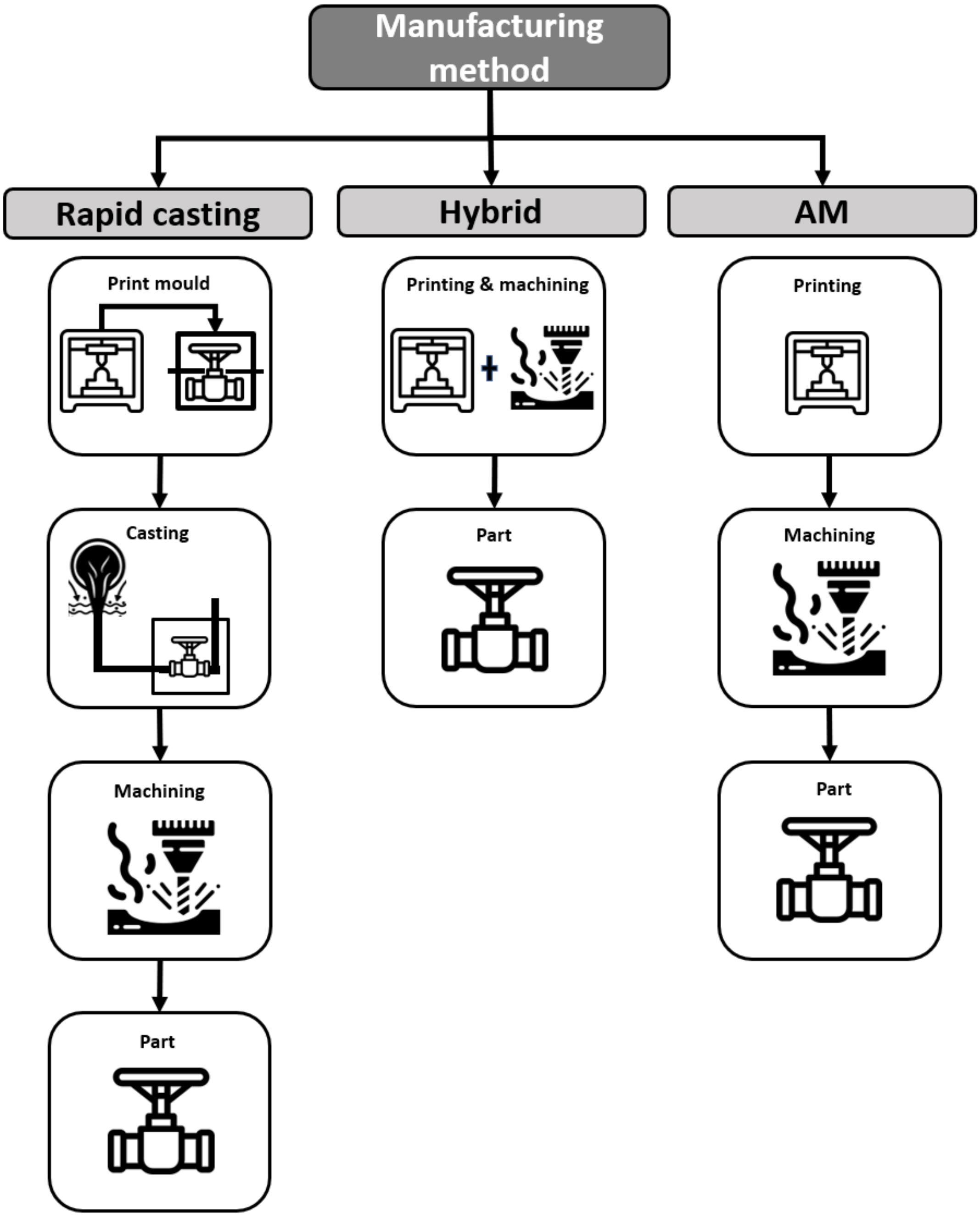


Figure 29: Manufacturing methods

4.3.1 Additive Manufacturing

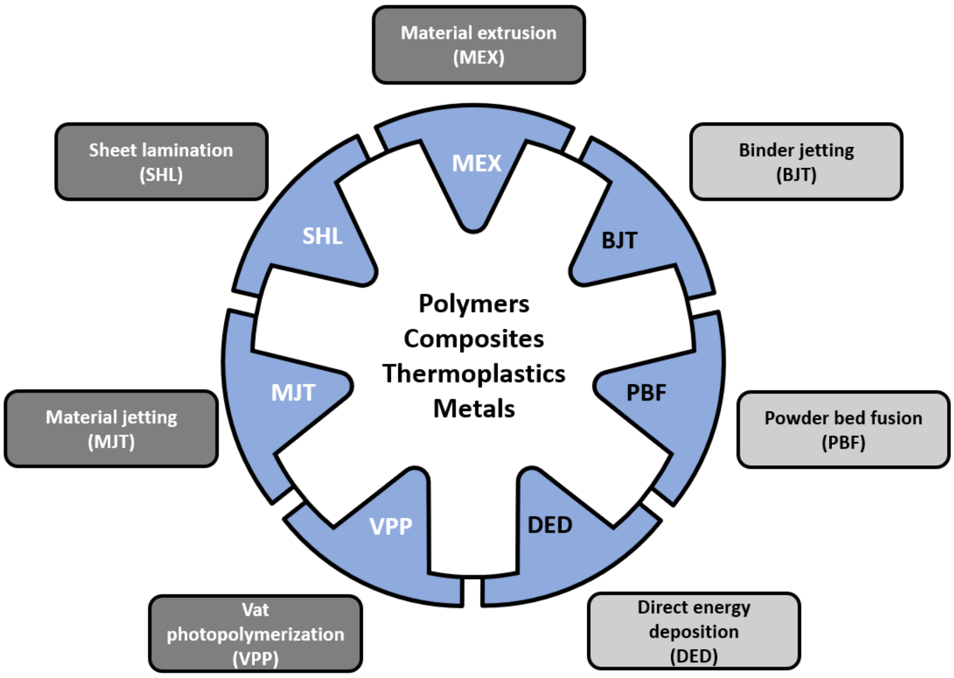


Figure 30: Material categories and AM processes

Additive layer manufacturing (ALM) is a method that uses the two-dimensional plane and extrudes it into three dimensions (3D) by adding material layer-by-layer. The technology has been used for over 30 years but has seen increased technological advances in quality, speed, materials, process and part qualification in the past ten years [25]. Figure 30 above presented seven AM manufacturing processes that have been defined according to ISO/ASTM 52900. Four main material categories accompany the ALM processes where Polymers, composites, thermoplastics, and metals are used.

Sections will refer to the *metal AM process* within Binder Jetting (BJT), PBF, and DED. The general process for producing a part through the above-mentioned processes is described in figure 31. The process includes scanning and part design related to the reverse engineering process (REP) and conventional machine design mentioned in the coming sections.

- The process begins with a part design or a scan that generates point cloud data (localized geo-reference locations of the part).
- The design or cloud data is formatted to a mesh, and if needed or requested, part optimization and simulation can be performed. Adjusting STL resolution (quality) is also optional before STL export.
- The STL is imported to a printer slicer software that provides part printing control, such as density and infill patterns, with printer parameters, speed, nozzle and printer bed temperature, etc.
- Post-processing such as print support removal, heat treatment, machining, and testing are standard methods used before the part is finished.

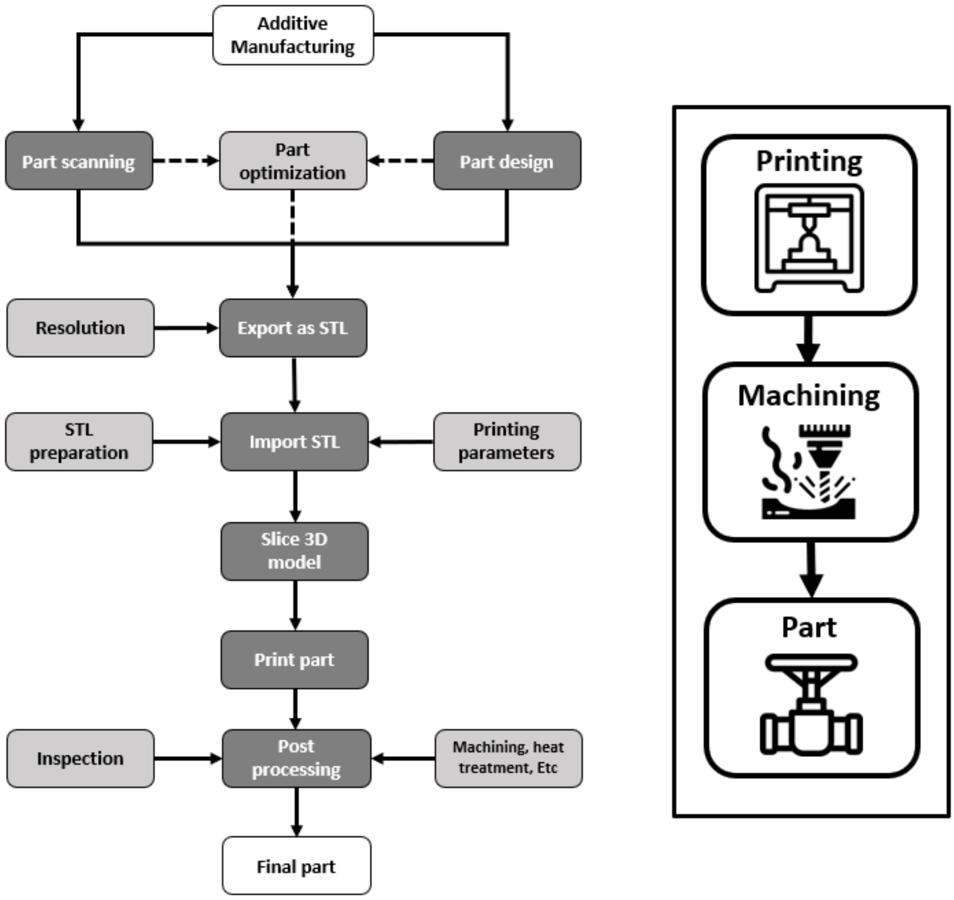


Figure 31: Activities for additive manufacturing

Figure 32 provides a full-scale 3D printed version of the valve body. The Fortus 450mc industrial 3D printer at UiS produced the part in a material called Acrylonitrile Butadiene Styrene (ABS) (plastic). The part is used in the case review section but will not include the specific production process activities.

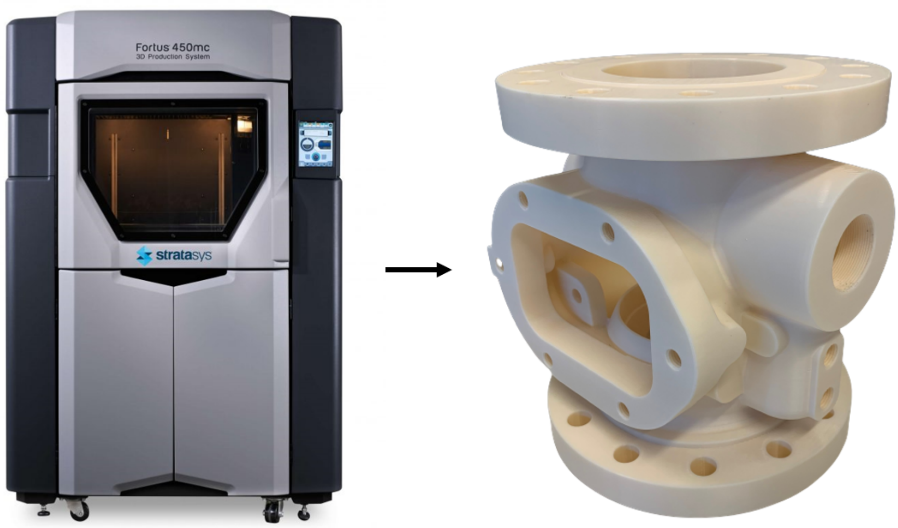


Figure 32: Fortus 450mc industrial 3D printer and the printed reference valve body

4.3.2 Casting

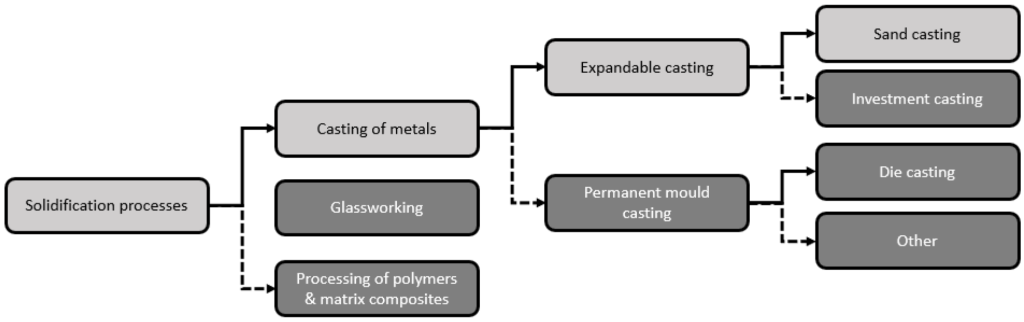


Figure 33: Solidificaiton processes, [26]

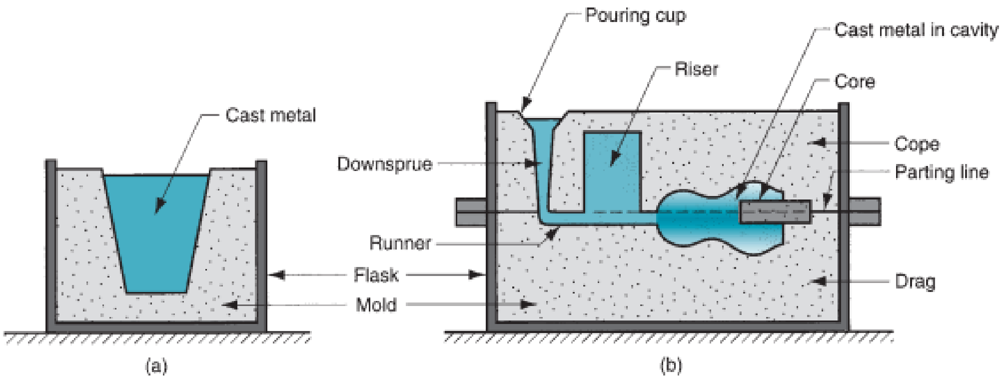


Figure 34: Sand casting, [26]

Casting produces components and structures in various sizes and shapes through pre-fabricated moulds. Figure 33 above describes the main solidification processes and the relevant category (solid line) used for this thesis. There are two main groups of casting, expendable mould and permanent mould. The expandable mould can only be used once and is common for sand-casted and investment casting methods. Permanent moulds are used until they become worn or damaged. Figure 34 describes the components in a sand casting operation [26]. A description of process activities referenced to figure 35 is given below.

- The process begins with the part design for the parting line (mould split). Then, proper feed and gate design allow the molten metal to be poured into the mould quickly while mitigating turbulence, gaps and contraptions. The casting pattern can then be created.
- The mould is prepared where the flask (container box) surrounds the cope and drag used for the upper and lower section of the mould.
- If internal surfaces are needed, a core is made and assembled with the rest of the components before pouring.

- Various types of sand are used when casting; a common type is silica $Si0_2$. The primary purpose of the sand is to maintain form, function, and control heat dissipation while cooling. Also, sand grain size and grain size distribution affect the casted part's surface roughness and the mould's permeability and strength.
- The mould is filled with metal from a casting ladle (container). The metal will continuously cool down during the pour and become solidified after a specific time.
- A shakeout and fettling (un-moulding) remove the excess material and parting lines of excessive material and recover the solidified casted part.
- The post-process activities can differ depending on the part application and the material. However, typical procedures such as heat treatment, inspection and testing are expected.

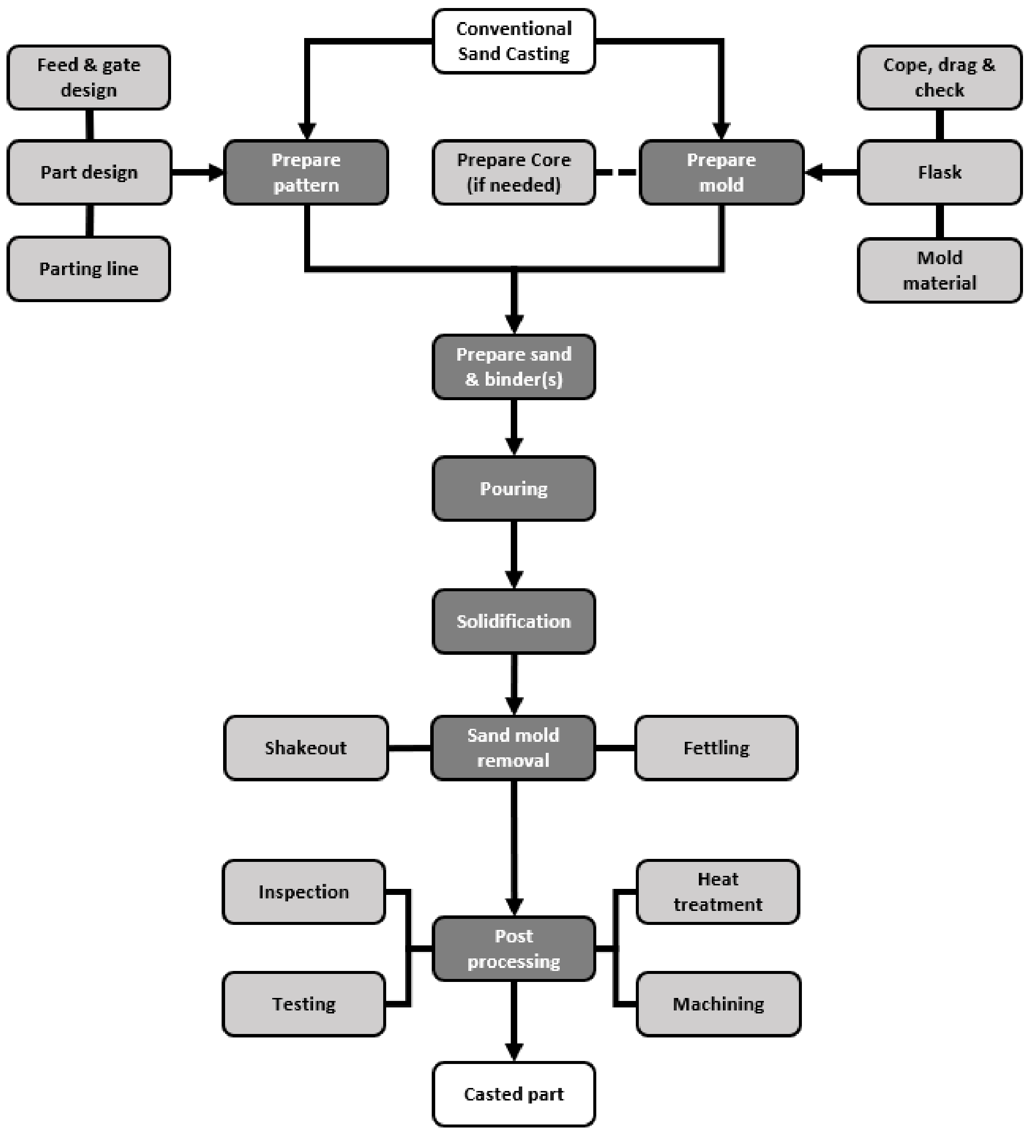


Figure 35: Main activities for sand casting

4.3.3 Rapid Casting - 3D Sand Casting

Rapid casting or Three-Dimensional Sand Casting (3DSC), has expanded the possibilities for complex geometry while reducing the total lead time for making cores. This technology has excellent economic benefits for part acquisition where a low or medium batch production is needed. The process is separated into three main activities; printing, casting and machining. The mould is 3D sand printed with Binder Jetting technology (BJT) before elements of the casting process are applied. Finally, post-processing activities may be applied. Figure 37 demonstrates the activities within a 3DSC process.

- The valve is designed to create a part file or scan, which results in point cloud data (described in detail in the case study review).
- The digital file can be optimized due to regulatory demands or customer requests. Riser and gate design can also be optimized to increase pouring velocity, reduce turbulence inflow, or control heat transfer during solidification.
- Before sending the digital file to the printer, the cloud data or CAD file converts to Standard Tessellation Language (STL) format or the specific format for the dedicated printer.
- Feedstock and binder materials must be supplied to the machine to provide continuous production.
- Figure 36 displays the BJT method, which builds the mould layer-by-layer. The feedstock adheres to a binder material which continuously builds the part (mould). The printed part (or parts) are cleaned and, if necessary, assembled before casting. The completed cast follows the post-processing activities from the casting process 35.

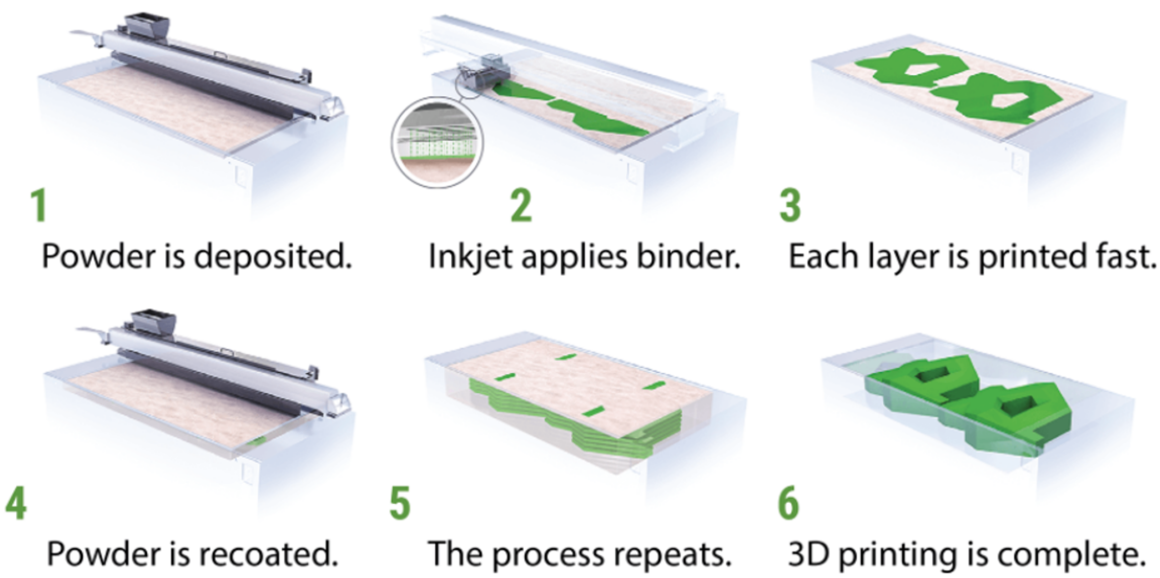


Figure 36: Process activities for 3D-Sand printing [27]

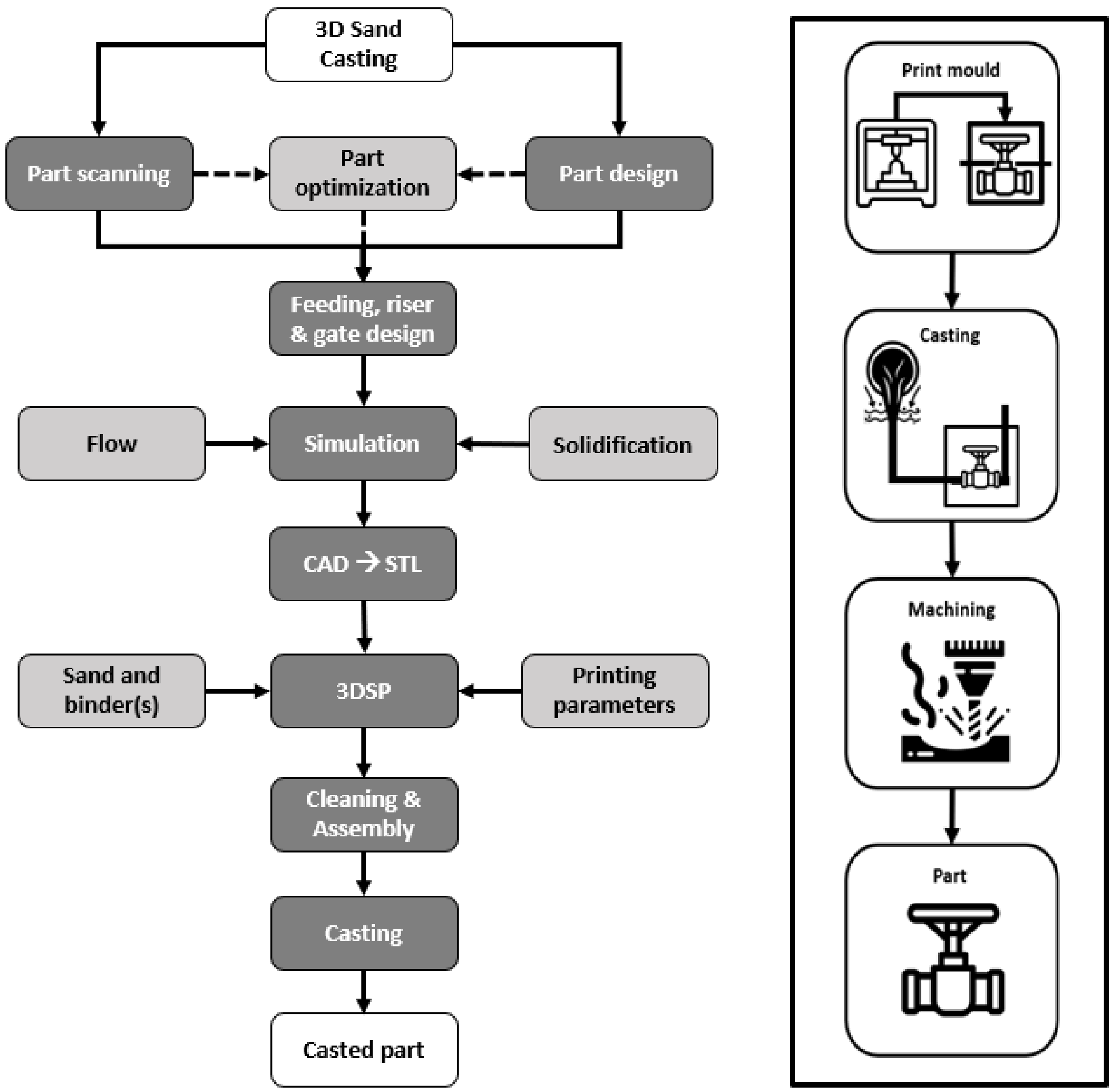


Figure 37: Process activities for 3D-Sand Casting

A few important equations governing flow velocity (v), the time to fill of the mould cavity (T_{MF}), and solidification time (T_{TS}) can be described by equations 3, 4, and 5 respectively. C_m is the mould constant, V represent the casting volume, A is the surface area of the casting in cm^2 for $n = 2$, Q is the volumetric flow rate, g gravitational acceleration, and h height of the designed casting sprue.

$$v = \sqrt{2gh} \tag{3}$$

$$T_{MF} = \frac{V}{Q} \tag{4}$$

$$T_{TS} = C_m \times (\frac{V}{A})^n \tag{5}$$

4.3.4 Subtractive Manufacturing

The subtractive manufacturing (SM) industry has been the backbone of modern manufacturing, especially with the early introduction of computer numerical controlled (CNC) machining. The modern foundation of the SM industry started during the second world war and was rapidly developed to support industries needing increased precision and repeatability [28]. This method produces high-quality parts with an excellent surface finish and features with high repeatability and accuracy. SM have several categories, described in figure 38. The valve body has e complex geometry which makes SM unfit for production. Initial discussions with CNC operators confirmed that the relevant machining operations for this thesis consider the conventional category, where standardized surface tolerances for flanges, bolt holes, threading, and chamfering would be used.

Figure 39 presents the 3D printed reference valve body fixed in the MAZAK machine at the mechanical workshop at UiS. Discussion with the machine operator confirmed that the machine could produce the required operations for holes, threads, and flange surfacing of the authentic valve body.

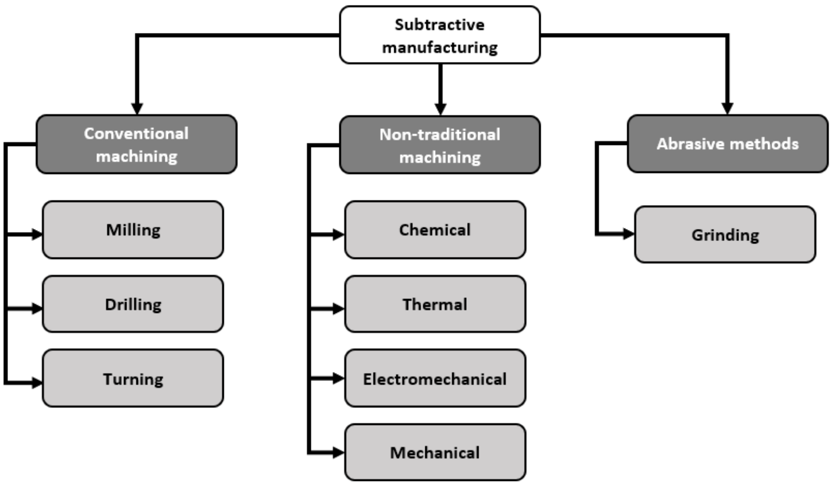


Figure 38: Subtractive categories

Figure 39: 3D printed reference valve body mounted in the MAZAK CNC machine

4.3.5 Hybrid Manufacturing

Hybrid manufacturing (HBM) within AM and subtractive manufacturing started to develop in the early 2000s. The most advanced machines can perform DED and machining (CNC) operations in one build, including multi-materials for highly customized applications. Integrating the benefits of the CNC process with AM expands the possibilities for reducing the dedicated machining activity and the total lead time of parts. [29] The constant maturity of this technology has enabled these machines to become part of options related to manufacturing selection.

A virtual test of this technology could have been performed at Mechatronics Innovation Lab (MIL) in Grimstad, Norway. However, time and funding restricted this activity. Instead, a discussion was conducted with the laboratory responsible regarding the possibilities of applying this technology. Producing the valve body on their Lasertec 65 3D hybrid machine was not deemed impossible; the material specification is currently a limitation since only a handful of materials are available. The activities for an HBM operation are displayed in figure 40. It resembles the path of the regular AM process. However, a practical reason for applying this method is related to the inclusion of machining operations during the part build. The printing process would simultaneously construct the part with the machining process until the part is finished, hence, minimizing post-processing.

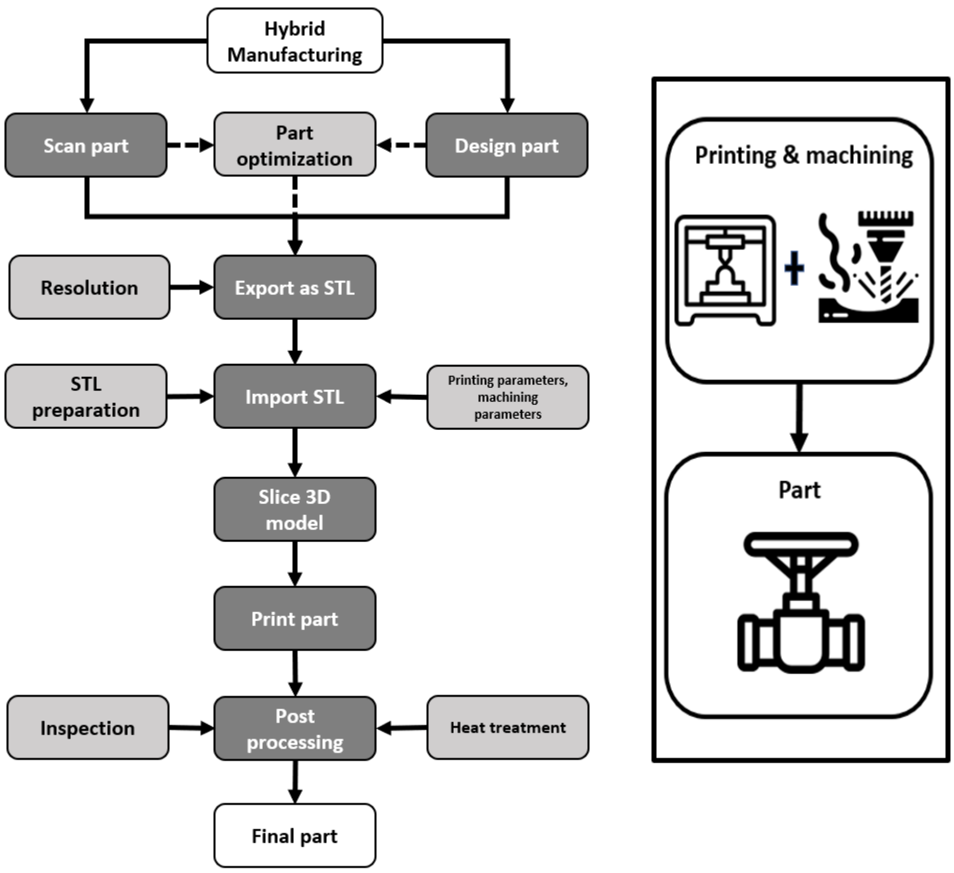


Figure 40: Process of hybrid manufacturing

4.4 Reverse Engineering

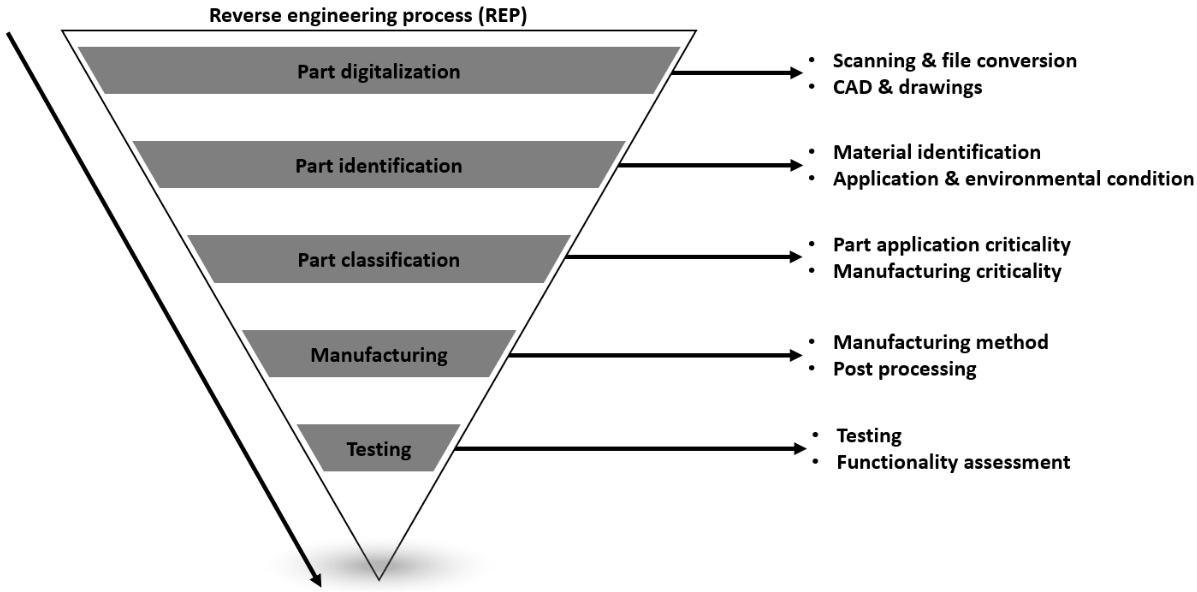


Figure 41: Reverse engineering process

The following subsection will look at the aim and challenges regarding the Reverse Engineering Process (REP). Then, define the valve's main and sub-functions and relate them to the consequence of failure. Finally, a look into the aviation industry aids in establishing a proposition for a concise evaluation of manufacturing criticality levels for metal AM in the O&G on NCS. Figure 41 displays the top-down approach of the REP for reconstructing legacy spare parts. The top-down approach is used as a reference.

4.4.1 Aim & Challenges

Two primary REP alterations can be performed on a one-to-one replacement legacy component such as the valve body [30].

1. **Material revision:** The reproduced valve body must perform equally or with increased performance relative to the original valve body.

2. **Manufacturing processes:** Alternative manufacturing methods such as AM or 3DSC are explored and must be able to be qualified with the selected material from the material revision.

The main goal of the REP is to reproduce the original valve body to conform to the original performance, current regulations, and customer specifications. Therefore, the term *part cloning* will be used for defining a legacy part that is reverse engineered. However, the challenges of part cloning start with digitalization, where the resolution of a handheld scanner such as the EinScan HX delivers a 0.05mm resolution [31]. Therefore, it hints that precise surface recognition is not achievable. I.e., constructing an exact valve body clone is not possible. Another example is the nickel resist material of the original valve body. The initial composition of the raw material used for the casting ingot may differ from the final material characteristic of the cloned part. The reason is the different evaporation temperatures of dissimilar metals [30]. Despite the challenges, digitalization and identification involve engaging the stakeholders (customers, manufacturers, and qualifying entities.) Follow-up meetings where REP activities and decisions are confirmed or re-evaluated are not uncommon.

4.4.2 Valve Data & System Hierarchy

The REP depends on accumulated data, establishing part classification where the criticality of its Main Functions (MFs) and related Sub-Functions (SFs) is mapped. The evaluation is often discussed with the customer and defines the basis for a manufacturing method and associated post-manufacturing activities. Figure 42 specifies the extent of the known data and its source. The starting point provides information regarding original material and valve manufacturing process specifications. Valve application and environmental conditions affecting the valve body are prioritized. This is also mentioned in a meeting with Wilhelmsen and is quoted from the meeting log in Appendix D.

"It is vital for any reverse engineering project to understand how the part is affected by the environment and vice versa. Also, it is critical to understand the main function and sub-function related to the part. It gives a holistic view of the part and its purpose".

It insinuates that at least one of the 26 requested valve body clones is exposed to aggressive environments (wind, oil, acid solutions). Therefore, the RE for the most exposed part should be evaluated. NORSOK-Z008 -*Risk-based maintenance and consequence classification* can aid by displaying a brief outline of the MFs and SFs of the system. The standards provide maintenance program guidelines for static mechanical components used on the NCS, which can be implemented in the design or re-design phase of the valve body [32]. Figure 43, obtained from NORSOK-Z008, presents the equipment hierarchy used to provide a practical resource distribution for maintenance. Here, the MF is the valve which is separated into SFs for valve body (containment), control functions (release valve, drain), and monitoring (pressure, flow, alarm). The SFs are attached to a tag number used for tracking the parts to the asset (valve) and the system.

Valve body data	Non	Limited	Full	Source
Dimensions			x	Scan
Geometry			x	Scan
Tolerances		x		Standards
Material		x		Customer & standards
Application			x	Customer
Environment			x	Customer
Manufacturing method		x		Customer
Qualification requirements		x		Customer & standards

Figure 42: Valve body data accumulation

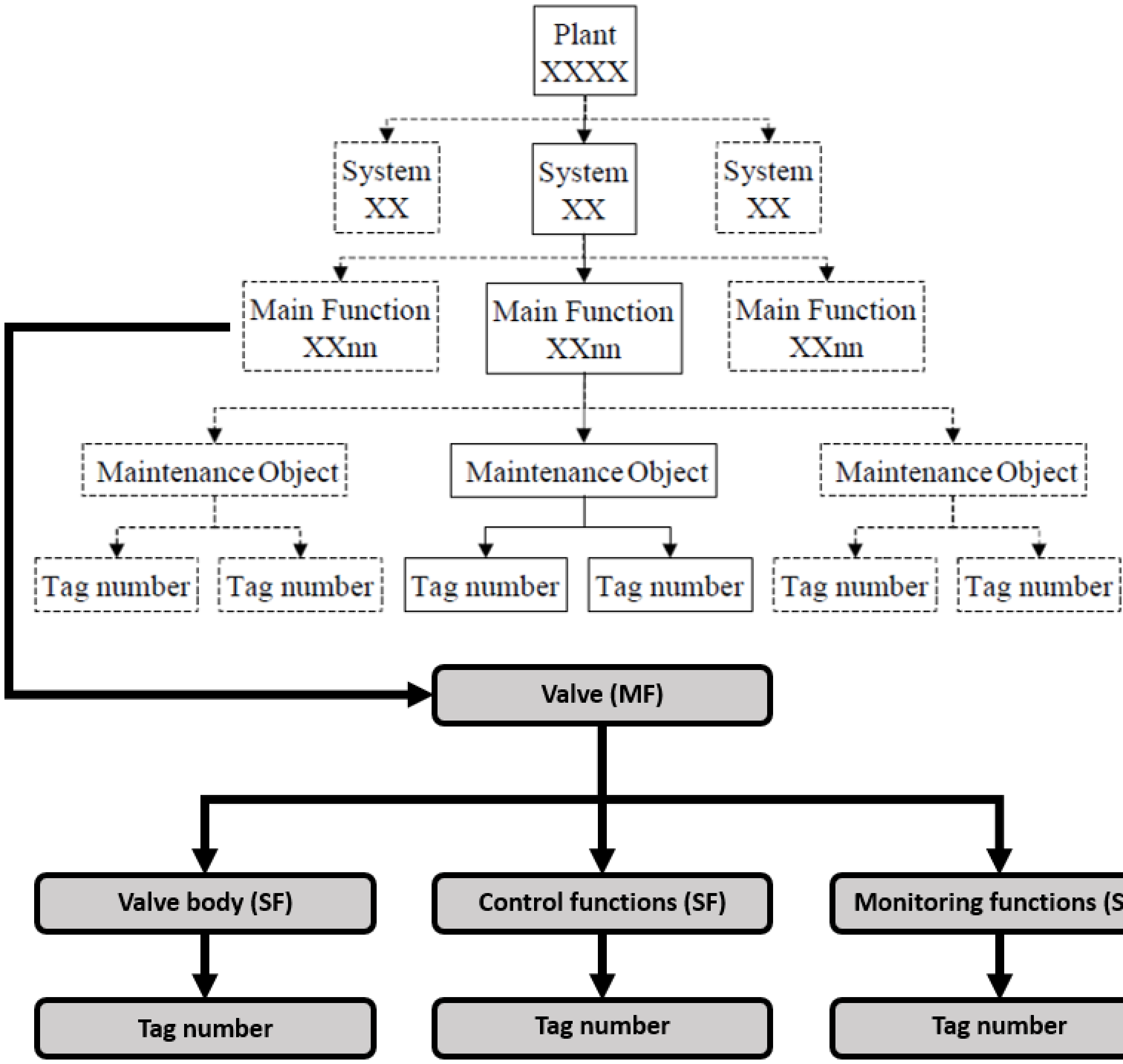


Figure 43: Adoption of NORSOK-Z008 MFs and SFs (system) hierarchy

A look at the maintenance requirements and logistics of the valve system significantly contribute to the criticality due to incidents that lead to delays within the informational flow and supply chain (availability, tool suppliers, lack of personnel). It can contribute to unworthy conditions where the fire barrier system is deemed unfit, leading to a production stop and revenue loss [33]. The initial dialogue revealed that no current spare parts are available and have not been in stock for four years. The aim is to maintain two one-to-one spares at all times.

4.4.3 Consequence of Failure

The assessment of qualification requirements and criticality level of part application and manufacturing should begin as soon as possible. If an early investigation is applied, estimation of cost and lead time can be provided earlier, which minimizes process pitfalls [34]. The criticality also controls the extent of the RE project, starting with a question related to part failure.

What would the consequences be if the component would fail?.

Table 1 - General consequence classification

Class	Health, safety and environment (HSE)	Production	Cost (exclusive production loss)
High	Potential for serious personnel injuries. Render safety critical systems inoperable. Potential for fire in classified areas. Potential for large pollution.	Stop in production/significant reduced rate of production exceeding X hours (specify duration) within a defined period of time.	Substantial cost - exceeding Y NOK (specify cost limit)
Med.	Potential for injuries requiring medical treatment. Limited effect on safety systems. No potential for fire in classified areas. Potential for moderate pollution.	Brief stop in production/reduced rate of production lasting less than X hours (specify duration) within a defined period of time.	Moderate cost between Z – Y NOK (specify cost limits)
Low	No potential for injuries. No potential for fire or effect on safety systems. No potential for pollution (specify limit)	No effect on production within a defined period of time.	Insignificant cost less than Z NOK (specify cost limit)

Figure 44: Consequence classification matrix obtained from NORSOK-Z008

This question is related to safety and economic impacts if the valve body fails or SFs fail due to valve body defects, causing a chain reaction. Therefore, the valve body is a barrier that mitigates the risk of unwanted accidents. Consequently, the criticality of the valve is deemed relatively high, and evaluation related to the consequence of failure in the valve body, threaded connections, moving parts, and flange connections should be considered. Figure 44 presents a general consequence classification matrix taken from NORSOK-Z008. Comparing the table against the valve body's importance would indicate that a failure's consequences could lead to serious injuries and spreading fires if no redundancy systems are in place.

An assessment of reliability is not included in this thesis but is mentioned due to the presence of the two leading failure mode drivers, mechanical and corrosion. The topic of reliability engineering concerns the in-depth analysis of equipment reliability assessments; the aim is to mitigate and identify failures with high probability and study their cause. It can be applied to the valve body, where the cause and effect of failures may be quantified. The assessment can lead to design improvements and may also enhance the operation and maintenance of the valve assembly [35].

4.4.4 Part Criticality in the Aviation Industry

Components used in the aeronautics and space industry operate in extreme environments. Severe mechanical vibrations, high loads, and temperature fluctuations put the aircraft and load-bearing parts under static and dynamic stress. *A study in space industry* by Christo Dordlofva [34] investigates aspects of qualification related to design for additive manufacturing. This investigation is based on a bottom-up approach for product development seen in figure 45 [36].

A considerable amount of rocket engine failure can be traced to oscillations related to the combustion process where the chemical reaction produces high mechanical stresses on the motor [37]. A failure can result in immense costs, extending to loss of life and significant financial impacts. To mitigate the risk, criticality assessment of components categorized as mission-critical (i.e., components that fail lead to mission failure) is a primary ac-

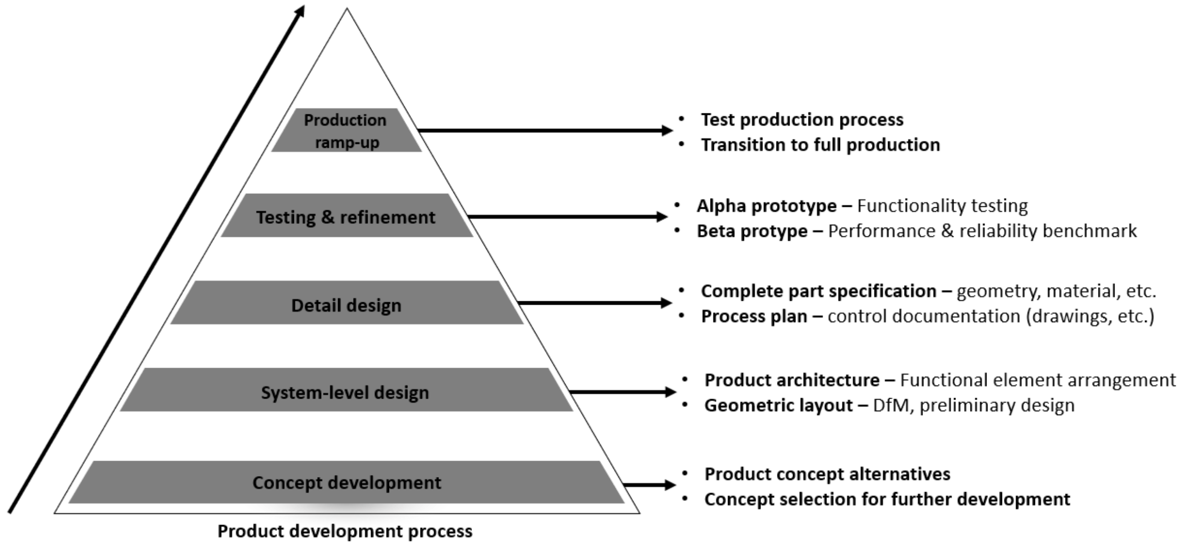


Figure 45: Product development process

tivity within the product development process of parts. Accordingly, the committee of ASTM F42 research and implements technology through AM standards, whereas ASTM F42.07.01 is a sub-committee focusing on aviation [38]. They have proposed four levels of criticality where the consequences of failure relate to the level of testing and qualification requirements. More importantly, they define the critically by the *load bearing components* which can be compared to the severity levels for the consequences [39].

From a product development point of view, assessing the outcome of part failure is essential for obtaining part dependability. Therefore, using the classification levels could aid in selecting the part criticality and should be verified in collaboration with the customer and AM before further development.

The severity categories for space parts can be seen in figure 46a, where four categories define the consequence of part failure. Level 1-4 relates to required activities in the product development process where fracture control is implemented in catastrophic and critical categories. Fracture control provides a methodical practice for inhibiting failure of a part during the part service life of undetected cracks and defects. Figure 46b is an example from a more extensive proposal of a classification matrix constructed by John Schmelzle-F42.07 committee.

		Type of consequence	
Category	Level	Dependability	Safety (examples)
Catastrophic	1	- Failure propagation	- Loss of human life - Loss of system
Critical	2	- Loss of mission	- Severe injury (not life threatening) - Major damage to an interfacing flight system
Major	3	- Major mission degradation	-
Minor/Negligible	4	- Minor mission degradation - Other effects	-

(a) Severity categories adapted from the space industry [34, p. 25]

F42	Part level description
Class 1	• Part contributes to critical support of ground and flight loads • Part is critical in maintaining the integrity of the craft • Part failure may lead to critical or an catastrophic outcome • Loss of life, severe damage to the craft and an unacceptable risk of injuries
Class 2	• Part failure may lead to reducing the integrity of the craft • Part failure pose an operational risk due to reduction in functional capabilities. • Part failure may lead to injuries, increasing the workload for flight crew
Class 3	• Part contribution for support of ground and flight loads are partly significant • Part failure does not affect operational capabilities but may increase flight crew workload
Class 4	• Part failure has negligible or no effect on operational capabilities

(b) Severity classes adapted from F42 [39]

Figure 46: Consequence categories and severity classes adapted from F42

4.4.5 Part Criticality in the O&G Industry

The O&G industry applies many of the principles for risk mitigation as the aviation industry. Regarding consequences, part failure could lead to a chain of events resulting in significant environmental damages, such as the 2010, Deepwater Horizon accident. It resulted in years of repercussions and repair for marine life and local fishing industries [40]. The product development process for parts within the O&G industry must demonstrate their integrity in terms of mechanical performance and life expectancy to conform to its intended application. A sound engineering practice should also include a safety factor according to governing standards.

The joint industry projects from the standards section involves companies challenging the verification requirements, qualification needs, and the maturity of the AM technology. While manufacturing standards such as DNVGL-ST-B203 and API20S are an essential cornerstone for AM of metallic parts within marine and O&G, the criticality levels for parts are strict regarding the amount of testing. As a result, the same industries have hesitated to implement AM due to the increased cost of criticality, especially for high critical parts.

Figure 47 and figure 48 compares DNVGL-ST-B203 and API20S levels of qualification routes for DED (WAAM) and PFB-LB methods. The layout is formatted using the proposed path from DNVs standard and adapted to API20S for easy comparison [41].

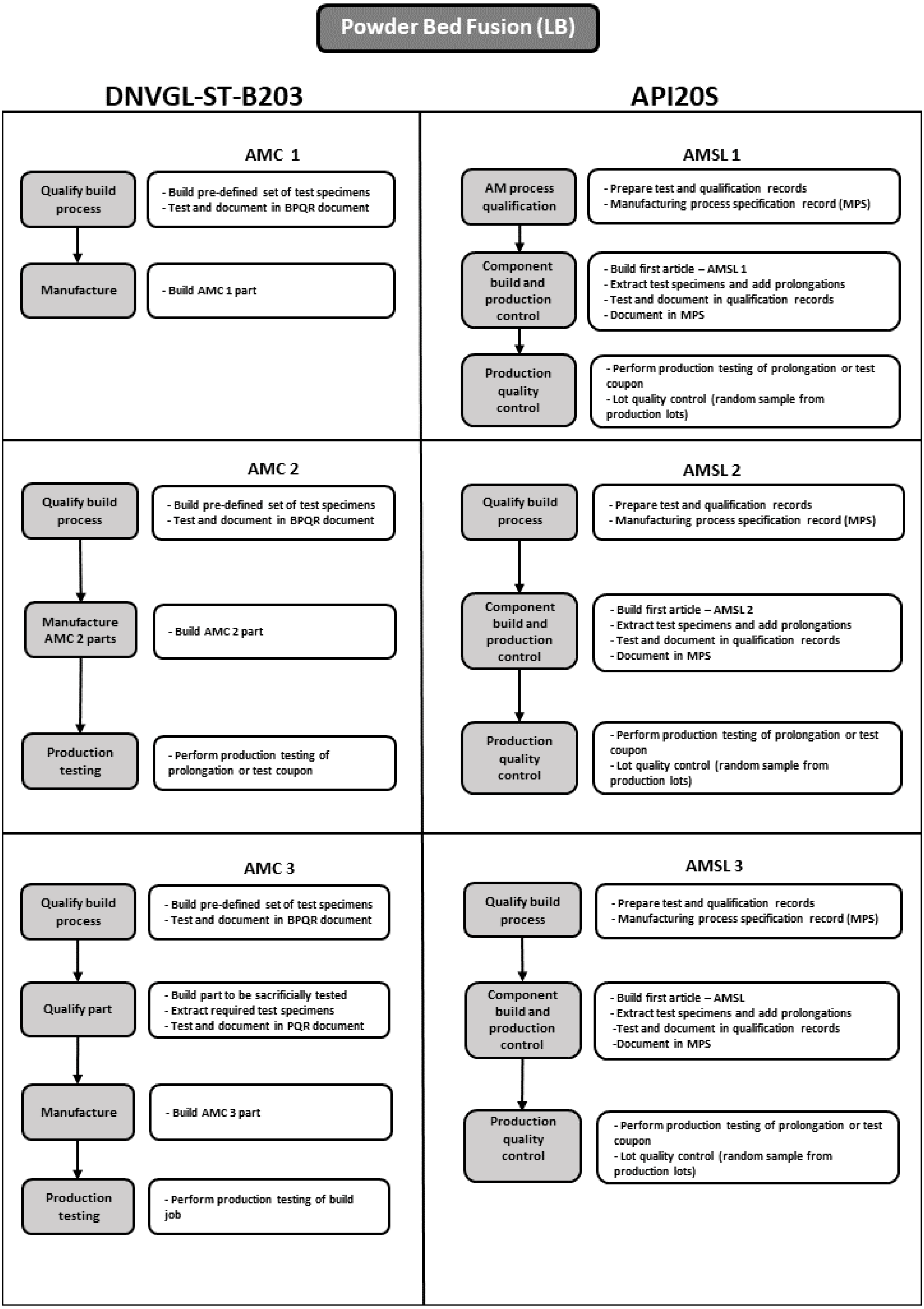


Figure 47: PBF (Laser Beam) qualification pathway, DNV versus API

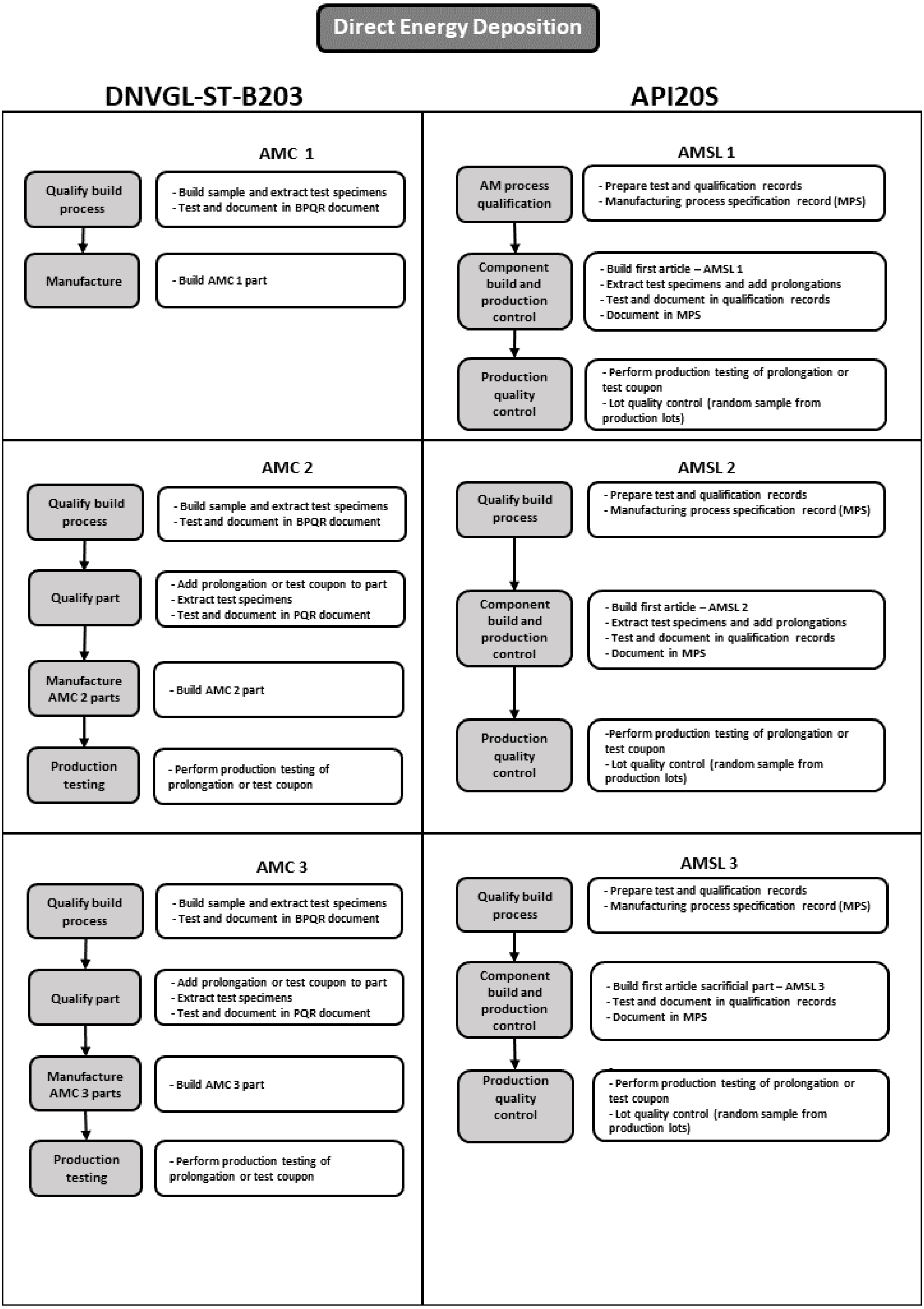


Figure 48: DED (WAAM) qualification pathway, DNV versus API

There is not a significant difference between these qualification paths. However, the API20S is stricter regarding the use and reuse of feedstock. Also, the amount of test specimens extracted from the qualification print is more substantial. A new revision of DNVGL-ST-B203 is currently being developed where BJT is included. The new revision aims to improve user-friendliness and include in-situ measurements, further developing process qualification rather than individual part qualification.

4.4.6 Class Adaption

The aviation industry has been proposing to correlate the consequence of failure to load-bearing components and is beginning to introduce it to the criticality levels for AM. It aids the categorization of spare part applications and may reduce the need for customer input by setting specific parameters related to the part. By doing so, defining the AM criticality may become more straightforward.

As deciding the part criticality within the O&G is still very dependent on the customer input, the proposition above may apply to the O&G industry but includes pressurized vessels where the valve body is used as an example. Figure 49 is a representation of

AM adaption	Pressurized systems	Load bearing systems	Applications
Class 4 **AMC-3, AMSL-3**	**Part that contain or transport** • High pressurized gas • Large amount of flammable fluids • Aggressive corrosive mediums **Consequence of failure may be** • Loss of life • Large Structural damages • Large economical losses • Large Environmental damages	**Part that transfer** • High dynamical loads • Large amount of vibrations/impulses • High static loads in aggressive environments **Consequence of failure may be** • Loss of life • Large Structural damages • Large economical losses • Large Environmental damages	➢ **Safety valves (hydrocarbon) with high pressure** • Turbine fan blade • Specific fasteners • …
Class 3 **AMC-2, AMSL-2**	**Part the contain or transport** • Medium pressurized gas • Limited amount of flammable fluids • Corrosive mediums **Consequence of failure may be** • Local shutdown • Injuries • Local structural damages • Limited economical losses • Local environmental spills • Increased workload	**Part the transfer** • Medium dynamical loads • Medium amount of vibrations/impulses **Consequence of failure** • Local shutdown • Injuries • Local structural damages • Limited economical losses • Local environmental spills • Increased workload	➢ **Deluge valves with medium pressure** • Gear • Impeller • …
Class 2 **AMC-1-2, AMSL-1-2**	**Part the contain or transport** • Low pressure fluids or inert gas • Non-corrosive mediums **Consequence of failure** These parts may affect daily routines but does not inflict class 3 or class 4 consequences	**Part that transport** • Low dynamical loads • minimal vibrations **Consequence of failure** These parts may affect daily routines but does not inflict class 3 or class 4 consequences	➢ ***Fresh water valve with low pressure*** • Pipe support • Bolts and nuts • …
Class 1 **AMC-1, AMSL-1**	Part that does not have any effects on daily operations nor safety for personnel or installation.	*Part that does not have any effects on daily operations nor safety for personnel or installation.*	• Tooling • Accessories (spacers, levers, etc) • …

Figure 49: Proposition of a class adaption of criticality levels

the classes related to F42.07 proposition [39]. This version is adapted to the AMC and AMSL levels for additive manufacturing, where load-bearing and pressurized systems have been chosen for application comparison. The figure specifies four classes where AMC-3 and AMSL-3 assimilate class 4 from F42, figure 46b. An example is provided where the highlighted points under *applications* describe a selection of components which could correspond to the class level.

- **Class 4:** This class would apply to a highly pressurized (pressure class ASME-2500) safety valve filled with hydrocarbons operating in an aggressive environment with vibrations and dynamical loading. The qualification requirements would entice AMC 3 and AMSL 3 due to the consequences of the described conditions; this would most probably be confirmed with the consequence classification matrix in NORSOK-Z008.
- **Class 3:** The rated class is dedicated to the valve body where the worst-case conditions are applied with the defined system pressure of 22 MPa. The compression ratio is negligible relative to a pressurized gaseous system as seawater is used. The system with gas will be more prone to secondary accidents due to the significant gas expansion ratio. AMC-2 and AMSL-2 could be a fitting level for qualification based on the conditions and application of the valve.
- **Class 2:** This class consider a valve with a low pressurized fluid of freshwater. Depending on the specific application, the criticality may be reduced to the lowest criticality, AMC-1 and AMSL-1.
- **Class 1:** May apply to accessories of the valve body such as the lever or marking (identification) tools.

In discussion with Moreld Capnor, comparative evaluations have previously been discussed and documented within an organization and used as a benchmark for other parts evaluated for AM [8]. The aim of providing a comparative classification example is to increase tangible comparisons for evaluating and cataloguing parts based on their criticality for application and manufacturing.

5 Manufacturing Selection Method

The original valve is a casted product. Nonetheless, the literature review has discussed factors that challenge the manufacturing method of the valve body. The maturity of technology drives the possibility of reducing manufacturing activities that may mitigate lead times and increase the batch quantity. Also, new metallurgical advances broaden opportunities within the material selection, application, and material properties. Technological maturity and metallurgical advancements may also aid the ecological aspects of manufacturing by reducing pollution of the environment. An initial investigation of manufacturing options can strengthen the awareness for deciding on an approach based on a Multi-Criteria Decision Analysis (MCDA) method such as the Analytical Hierarchy Process (AHP).

5.1 Hierarchical Structure

The AHP can be applied as a tool for problems that conventionally would be decided between people in an organization [42]. These problems often have multiple criteria, making comparisons of manufacturing alternatives increasingly tricky. The AHP has excellent benefits regarding the qualitative and quantitative data processing capabilities. The data can be processed simultaneously, converting answers into numerical values.

The layout of a generic hierarchical model adapted to valve body manufacturing selection is presented in figure 50. There are two alternatives for the selection of manufacturing, A_1 and A_2 (AM and 3DSC) that are prioritized concerning four primary criteria, B_1 to B_1 and eleven sub-criteria C_1 to C_4. Experts' judgements are used to weigh criteria. The weighting originates from the scale of relative importance presented in figure 51.

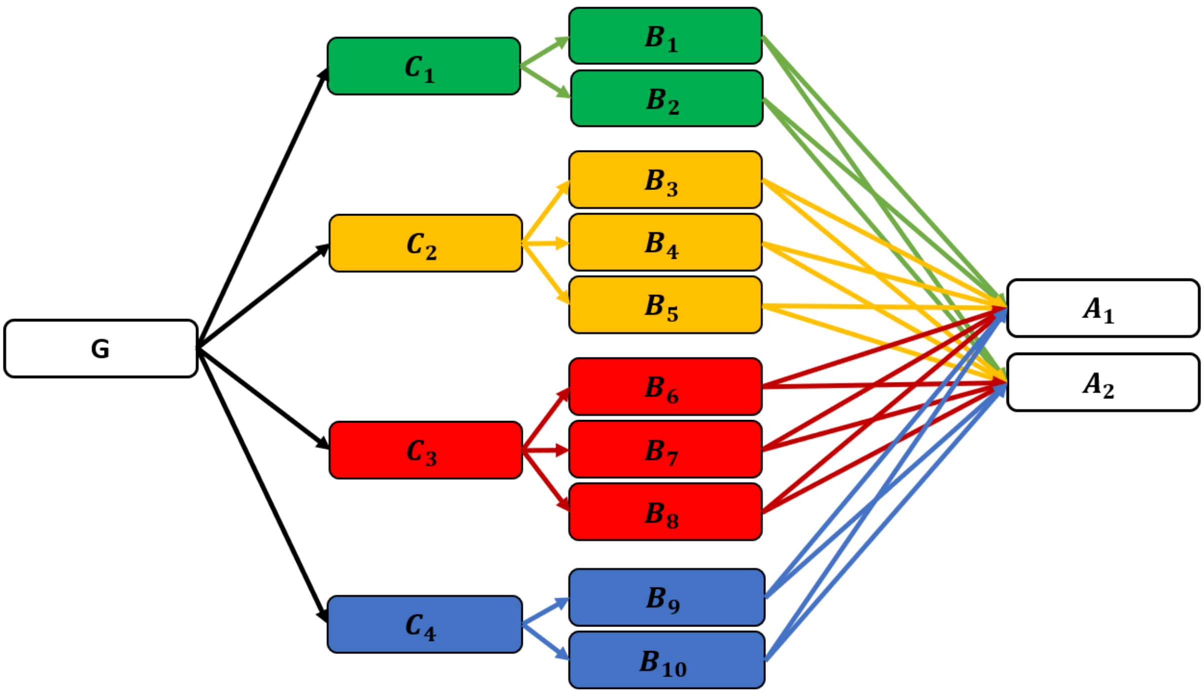


Figure 50: Hierarchical model

Scale of relative importance

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contributes equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible affirmation order
2, 4, 6, 8	Compromise of adjacent intermediate values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it

Figure 51: Weighting scale used by experts to evaluate pairwise comparisons

5.2 Pairwise Comparison - Example

The pairwise comparison evaluates the hierarchy's driving elements (criteria), where each criterion (node) is compared based on the predecessor node. For example, comparison of C_7 relative to C_8 based on C_3. Then C_7, C_9 and C_8 and C_9 are compared between each other based on C_3. Figure 52 display this specific comparison. The pairwise comparison is equal for all nodes. However, comparing the alternatives depends on the predecessors in reverse order. For example, the comparison of A_1 and A_2 is concerning B_1. Evaluation performed over several levels of the hierarchy may induce a non-consensus for multiple expert judgments (weight). Therefore, the geometric mean on equation 6 is used to average these weights [43].

$$\bar{w} = \left(\prod_{i=1}^{n} w_i\right)^{1/n} \tag{6}$$

5.3 Hierarchy Calculations

The example from figure 52 forms a Pairwise Comparison Matrix (PCM) based on their weighing of values. By applying the scale of relative importance, if the comparison is advantageous, the value will be a whole number. However, the value will be a fraction if the comparison is less advantageous. PCMs will be created on each level concerning the predecessor's node and can be calculated by defining the PCM matrix $\underline{A}$ for **n** nodes.

$$\underline{A} = [a_{ij}] \quad where \quad a_{ji} = [\frac{1}{a_{ij}}], \quad a_{ii} = 1, \quad (1 \leq i \leq n) \text{ and } (1 \leq j \leq n) \tag{7}$$

The PCM from the example in figure 52 can be described by table 3 where the individual values contribute to matrix weighting and the corresponding matrix equation 8.

Table 3: Pairwise comparison of costs

	manufacturing	qualification	transportation
manufacturing	1	3	9
qualification	1/3	1	3
transportation	1/9	1/3	1

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the spare part cost?																
valve manufacturing costs									Valve testing & qualification costs							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
						x										

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the spare part cost?																
valve manufacturing costs									Valve transportation route costs							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
x																

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the spare part cost?																
Valve testing & qualification costs									Valve transportation route costs							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
						x										

Figure 52: Pairwise comparison of spare part cost

$$\underline{A} = \begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 \\ w_2/w_1 & w_2/w_2 & w_2/w_3 \\ w_3/w_1 & w_3/w_2 & w_3/w_3 \end{bmatrix} = \begin{bmatrix} 1 & 3/1 & 9/1 \\ 1/3 & 1 & 3/1 \\ 1/9 & 1/3 & 1 \end{bmatrix} \tag{8}$$

The eigenvector then becomes

$$\underline{w} = [w_1 \quad w_2 \quad w_3] = [9 \quad 3 \quad 1]$$

If a hierarchy becomes complex, i.e., a large number of nodes, the non-trivial solutions of $\underline{w}$ are calculated using equation 9 below. The equation is further abbreviated where it becomes an eigenvalue problem for a non-trivial solution.

$$\underline{A} \times \underline{w} = \begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 \cdots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 \cdots & w_3/w_n \\ \vdots & \vdots & \vdots \quad \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & w_n/w_n \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ nw_2 \\ nw_3 \\ \vdots \\ n \times w_n \end{bmatrix} = n \times \underline{w}$$

$$\underline{A} \times \underline{w} = n \times \underline{w} \tag{9}$$

The experts' judgements contributing to filling the matrix may not be entirely consistent. However, if the AHP has high values of inconsistency, the criteria must be revised. Samarakoon and Ratnayake explain the details of consistency analysis [43].

"*As the matrix A has a particular form (i.e. each row is a constant multiple of the first row), the rank of the matrix is one, and except for one eigenvalue, all the other eigenvalues of the matrix A are zero. However, the sum of the eigenvalues of a positive matrix is equal* *to the trace of the matrix, and the nonzero eigenvalue has a value of n (i.e. the size of the matrix), referred to as* λ_{max} *and used for consistency analysis*".

Performing a consistency analysis may is used to validate the weighting made by the experts. For example, in an inconsistent case where the eigenvalue problem is described by equation 10, the discord from expert judgment may insinuate that if $\underline{w}$ is unknown, the estimates of $a_{ij's}$ in matrix $\underline{A}$ are known. It indicates the existence of errors and poor consistency of expert weighting.

$$\underline{A} \times \underline{w} = \lambda_{max}\underline{w} \quad \text{where} \quad \lambda_{max} \geq n \quad and \quad \lambda \backsim 0 \tag{10}$$

For obtaining tangible output from the matrices, The activity weight estimation is calculated by normalizing the largest eigenvector in equation 10. Equation 11 describes the procedure of normalization.

$$a' = [a_{ij}'] \quad where \quad a_{ij}' = \frac{a_{ij}}{\sum_{k=1}^{n} a_{ik}} \quad for \quad (1 \leq i \leq n), (1 \leq j \leq n) \tag{11}$$

Now the relative weights (eigenvectors) can be obtained by using equation 12.

$$\underline{W} = [w_k] \quad where \quad w_k = \sum_{i=1}^{n} \frac{a_{ij}'}{n} \quad for \quad (1 \leq i \leq n), (1 \leq j \leq n), (1 \leq k \leq n) \tag{12}$$

Observations show that the consistency of judgement increases if λ_{max} approaches the value of n. Therefore, the inconsistency can be measured by $\lambda_{max} - n$. So if $\lambda max = n$, the hierarchy is fully consistent. The average of the remaining eigenvalues is calculated by implementing the consistency index (CI) in equation 13 [43].

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{13}$$

The output of the CI must be reasonable. Therefore, randomized pairwise simulations on different-sized matrices are conducted. The aim is to obtain the average CI based on random judgements of several matrix sizes (n). It is defined as the Random Consistency Index (RCI), which calculates the degree of inconsistency of a square matrix. Figure 53 outline the matrix size versus RCI. The Consistency Ratio (CR) can now be calculated with equation 14 were for a specific set of judgments (CI, equation 13) divided by the randomized comparisons of an equally sized matrix (RCI) (average of CI). If judgements are deemed consistent, $CR \leq 0.1$.

$$CR = \frac{CI}{RCI} \tag{14}$$

Size of the matrix (n)	1	2	3	4	5	6	7	8	9	10
RCI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Figure 53: Size of matrix (n) versus RCI

5.4 AHP Design

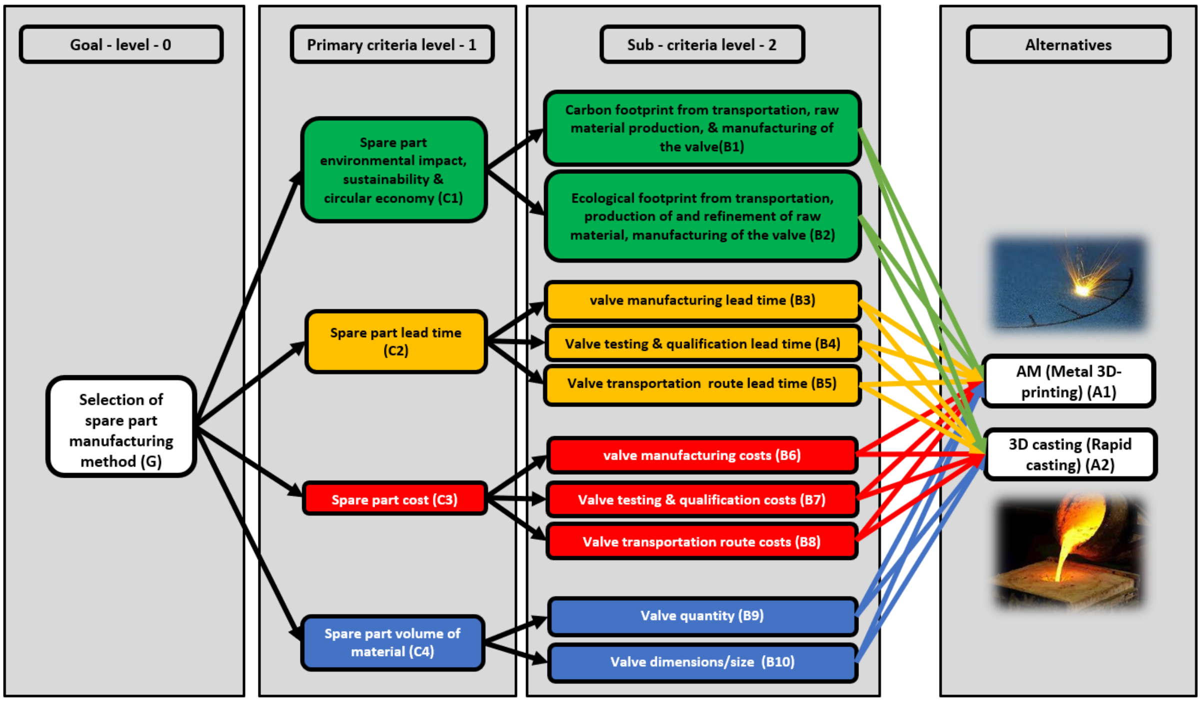


Figure 54: AHP overview

Figure 54 above presents the criteria chosen by their level of influence and have been screened for activity dependencies. The output of this analysis originates from the thesis sections, where interviews and questionnaires have accumulated expert judgements. A description of the hierarchy purpose levels is described below. Figure 55 represent the specific criteria of the AHP overview.

- **Goal level - 0:** This level represents the objective of the AHP. It is related to figure 41 where valve manufacturing criticality and manufacturing method are decided.
- **Primary criteria level - 1**: The level identifies the essential criteria that influence the decision for the goal. The four criteria, environmental impacts, cost, lead time, and volume of material, are fundamental for selecting a valve manufacturing method. The environmental aspects criteria were defined during talks with Moreld Capnor. These are not the most critical ones, but ads value in terms of future implementations for a life cycle analysis.
- **Sub-criteria level - 2:** These criteria are based on the previous node (criteria). The amount of sub-criteria levels can, in theory, be extended to $n + 1$ levels but must be evaluated carefully to mitigate dependencies between them.
- **Alternatives:** AM and rapid casting define the two manufacturing alternatives. These options are pairwise compared relative to each option on level 2. The two alternatives were chosen based on the original challenge of acquiring one-to-one replacement valves for the offshore installations. The subtractive and hybrid methods are left out of the alternatives due to the technological maturity of handling large dimensions with complex geometries.

Goal level – 0	Definition	Description
C_1	Selection of spare part manufacturing method	It is based on the reverse engineering process where realistic manufacturing options for the valve have been discussed and revised.

Criteria level – 1	Definition	Description
C_1	Spare part environmental impact, sustainability & circular economy	Regulations increase the demand for documentation related to supply chain activities that may negatively affect the environment.
C_2	Spare part lead time	The lead time is dependent on material and machine/process availability, part quantity, manufacturing location, amount of manufacturing activities, qualification needs, transport, and border customs.
C_3	Spare part cost	The main factors controlling spare part costs are manufacturing method, material, spare part quantity, qualification needs, and transportation.
C_4	Spare part volume of material	Part quantity, dimensions, geometry, and density controls the total amount of material volume.

Sub – criteria level – 2	Definition	Description
B_1	Carbon footprint from transportation, raw material production, & manufacturing of the valve	The direct effects of activities that produce emissions that contribute to global warming
B_2	Ecological footprint from transportation, production of & refinement of raw material, manufacturing of the valve	It aims at activities that harm the atmosphere, environment, and biological systems. Examples are CFCs, acid water, heavy metals, etc.
B_3	valve manufacturing lead time	Manufacturing activities include operations provided by personnel and machines such as pre-processing (CAD), building or casting the part, and post-processing (heat treatment, machining, etc.)
B_4	Valve testing & qualification lead time	Activities within qualification depend on the needs but can be destructive or NDT. The preparations and activities for analysis must also be included.
B_5	Valve transportation route lead time	Local or non-local manufacturing and testing options may impact the total lead time together with border customs.
B_6	valve manufacturing costs	Main costs are dependent on personnel, manufacturing method, and material selection.
B_7	Valve testing & qualification costs	Costs depend on the criticality of manufacturing, i.e., qualification requirements and testing personnel.
B_8	Valve transportation route costs	Type of transportation (sea, air, land), local or non-local (customs) influence the total transportation costs of the valve.
B_9	Valve quantity	The amount of valves that are needed, the valve has an initial batch request of 26 parts but can be increased.
B_{10}	Valve dimensions/size	The dimension and size determine the geometry that controls the valve's total volume.

Alternatives	Definition	Description
A_1	AM (Metal 3D-printing)	The valve is manufactured layer-by-layer by direct energy deposition or powder bed fusion.
A_2	3D casting (Rapid casting)	The valve is manufactured by producing sand molds by using binder jetting (3D-printing) and pouring the metal into the finished sand molds

Figure 55: Description of goal, criteria, and alternatives

5.5 Hierarchy Results

Expert Choice is a software that combines a straightforward user interface with easy interpretation of the results from a multi-criteria decision hierarchy [44]. The results are generated when all judgments have been registered and can be interpreted both graphically and numerical.

5.5.1 Hierarchy Weighting & Synthesis

Figure 56 displays the inputs of the hierarchy in Expert Choice, where each criterion is weighted in correspondence to the inputs from expert participants.

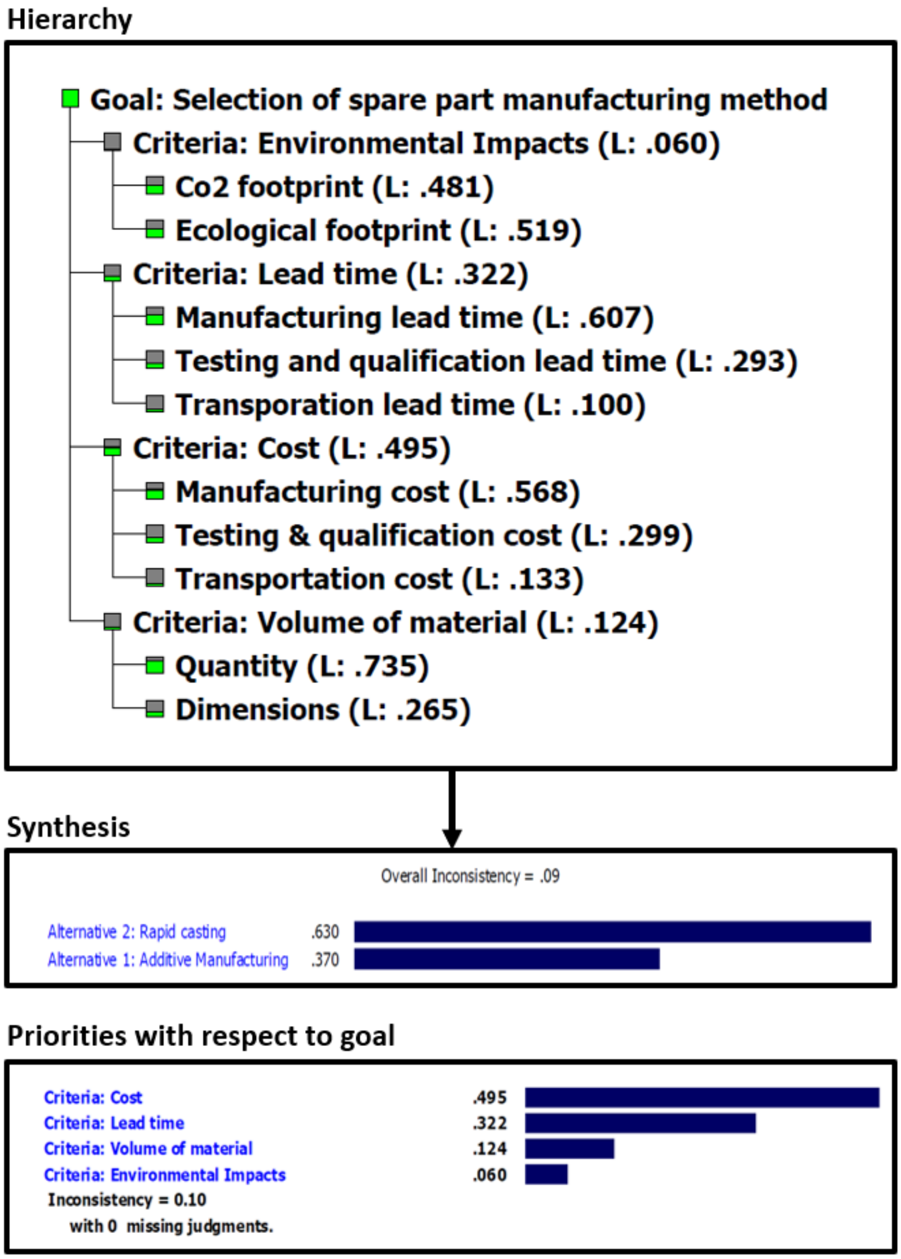


Figure 56: Hierarchy criteria weighting, synthesis, and priorities

- **The weighting** of each node (priority) relatively to its neighbour node is represented with a corresponding value which can be seen on the right-hand side behind all nodes. Comparing the weighting for environmental impacts with lead time, cost, and material volume clearly shows that the cost and lead time criteria influence the decision heavily.

- **Synthesis** represents the output results together with the overall inconsistency of the hierarchy valued at 9%, indicating a consistent comparison. The largest nodal inconsistency of nodal comparisons measured 10%.

- **Priorities** describe the priority of the criteria in decreasing order. Figure 56 compares the four main criteria were cost (49.5%), lead time (32.2%), the volume of material (12.4%), and environmental impacts (6.0%).

5.5.2 Sensitive Analysis

Analyzing the sensitivity of the goal node relative to the alternatives allows the user to understand how the objectives below the goal change concerning the alternative. It can also be used on sub-criteria (nodes) where the criteria priority variations change the alternative's priority. There are five types of sensitivity analyses; Performance, dynamic, gradient, head-to-head, and two-dimensional.

The performance sensitivity in figure 57 displays the alternative prioritization relative to each other regarding the objectives and the overall performance. It is clear from the figure that alternative 2 (rapid casting) outperforms alternative 1 (AM) for both lead times, cost, volume and overall result. However, regarding the environmental impact, Alternative 1 (AM) is better than alternative 2 (rapid casting).

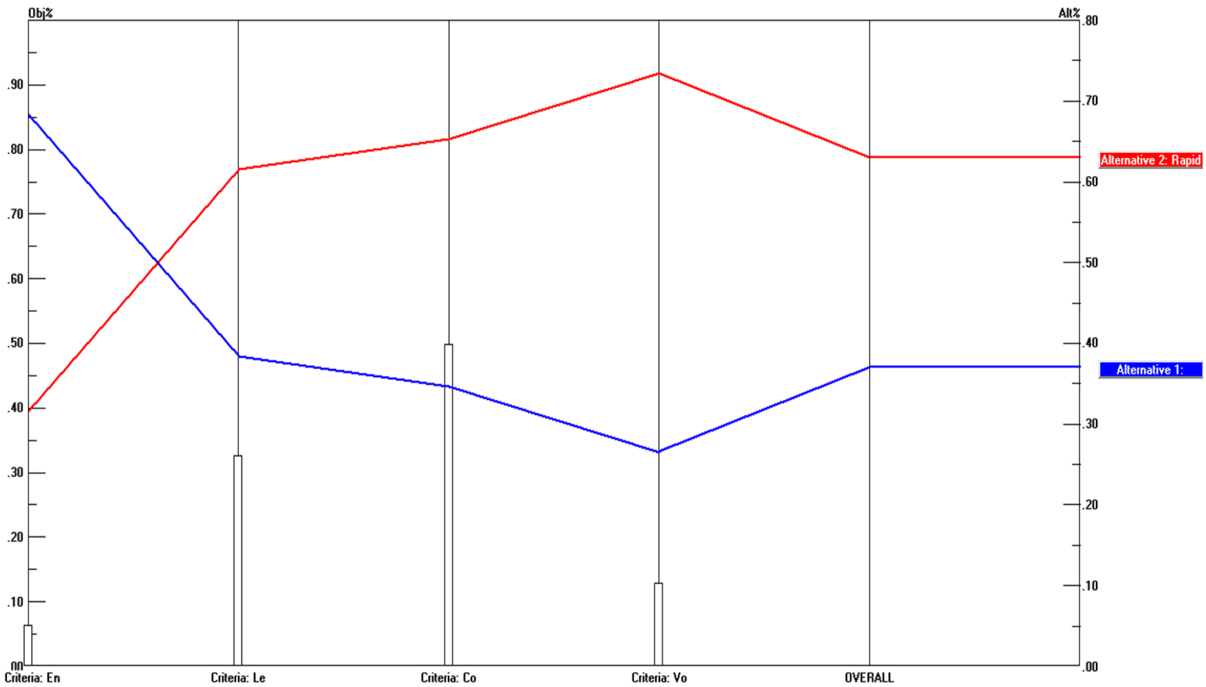


Figure 57: Performance sensitivity. Alternative 1 (blue) and alternative 2 (red)

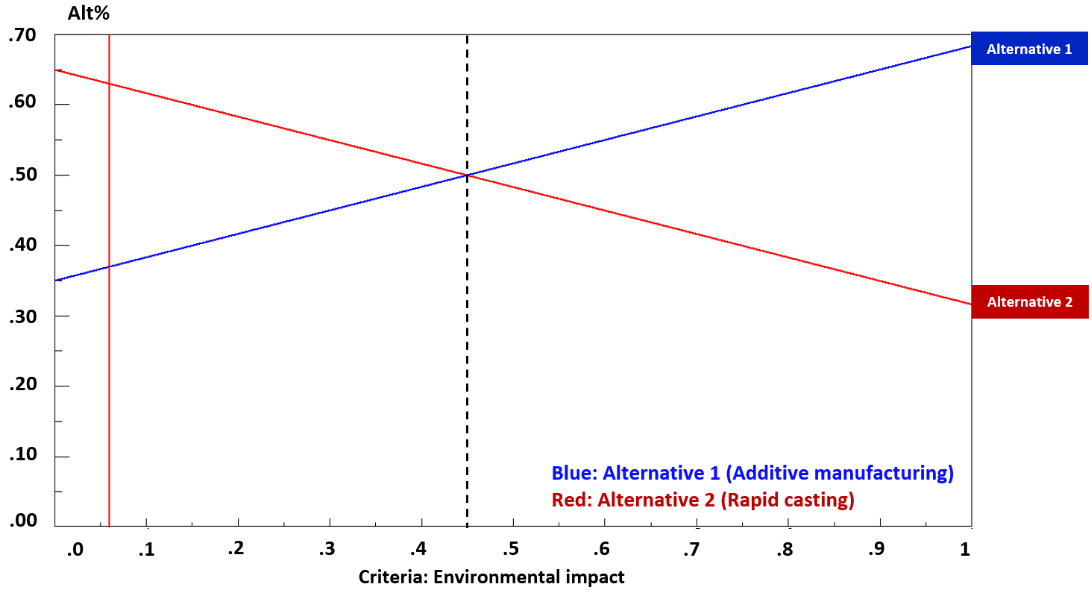


Figure 58: Gradient sensitivity of Goal relative to alternatives

The gradient sensitivity seen in figure 58 above compares the priorities of the alternative relative to the criteria (one at a time). The vertical line at 0.06 is the priority of the criteria made by the pairwise comparison of the decision-maker. The stipulated line at .45 indicates where the priority of a criteria changes. Alternative 1 (AM) is more favourable as the criteria for the environmental impact increase. However, in the overall decision, the contribution to the final results is minimal since the weighting of environmental impacts is low (6%). Gradient sensitivity for lead time, cost, and volume are given in Appendix D.

The dynamic sensitivity in figure 59 display the outcome for criteria level 1 and explain how these criteria affect the alternatives. The most influential criteria are clearly visible as cost and lead time, where the volume of material and environmental impact induce a lower significance. The criteria can be changed while simultaneously affecting the priorities of the alternative. An example is provided in figure 60 where an evaluation of the limit at which alternative 1 becomes favourable as a manufacturing method.

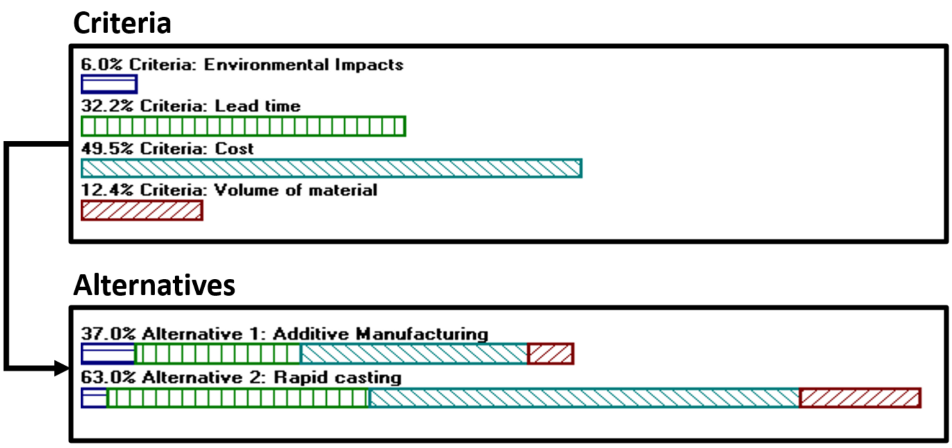


Figure 59: Dynamic sensitivity of objective relative to alternatives

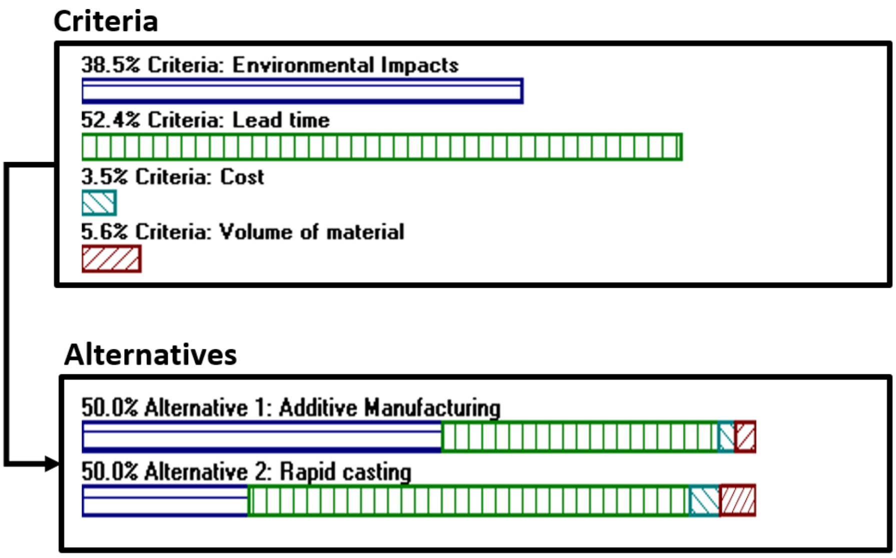


Figure 60: Dynamic alteration of criteria related to alternatives

The limit is based on the criteria for when environmental impacts and lead time increase to 38.5% and 52.4%, respectively. At the same time, the cost and volume of material are reduced to 3.5% and 5.6%, respectively.

Two-dimensional sensitivity describe the priorities for the alternatives relative to two criteria that are evaluated simultaneously. Figure 61 describes the relationship between cost and lead time where alternative 2 (rapid casting) is the most favourable. There are four quadrants where the preferable alternatives relative to the criteria are positioned in the upper right quadrant. It implies that the closer an alternative is to the absolute corner of the top right, the more favourable the alternative will become. If an alternative is in the lower-left quadrant, the less favourable the alternative is, and an alternative position in the upper left quadrant indicates a contradiction.

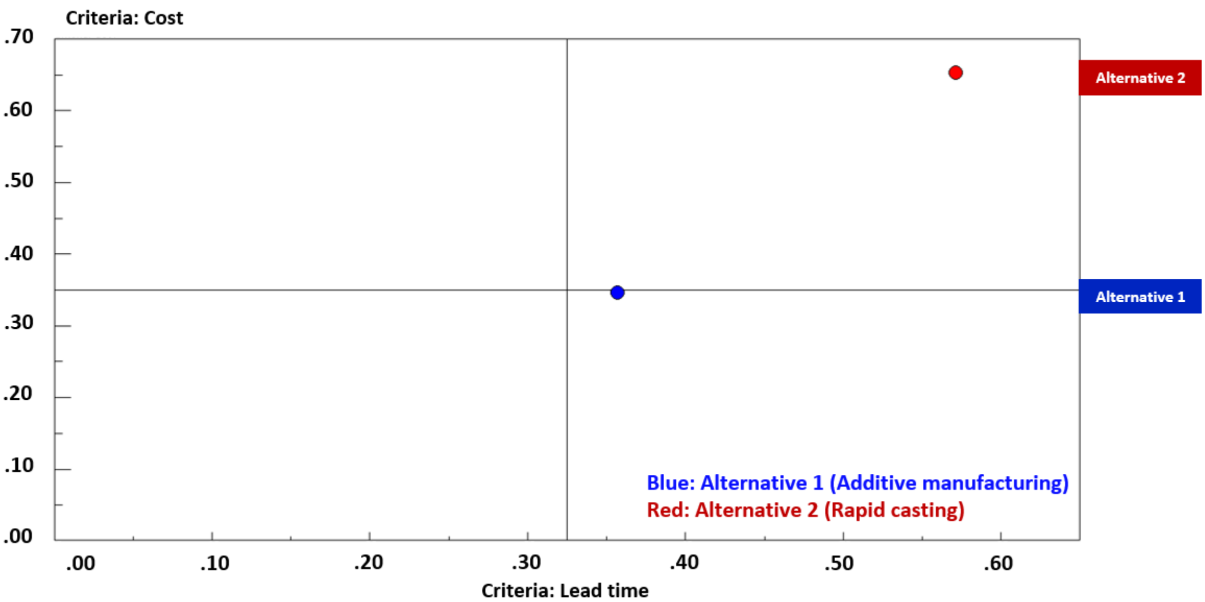


Figure 61: Two dimensional sensitivity of cost versus lead time

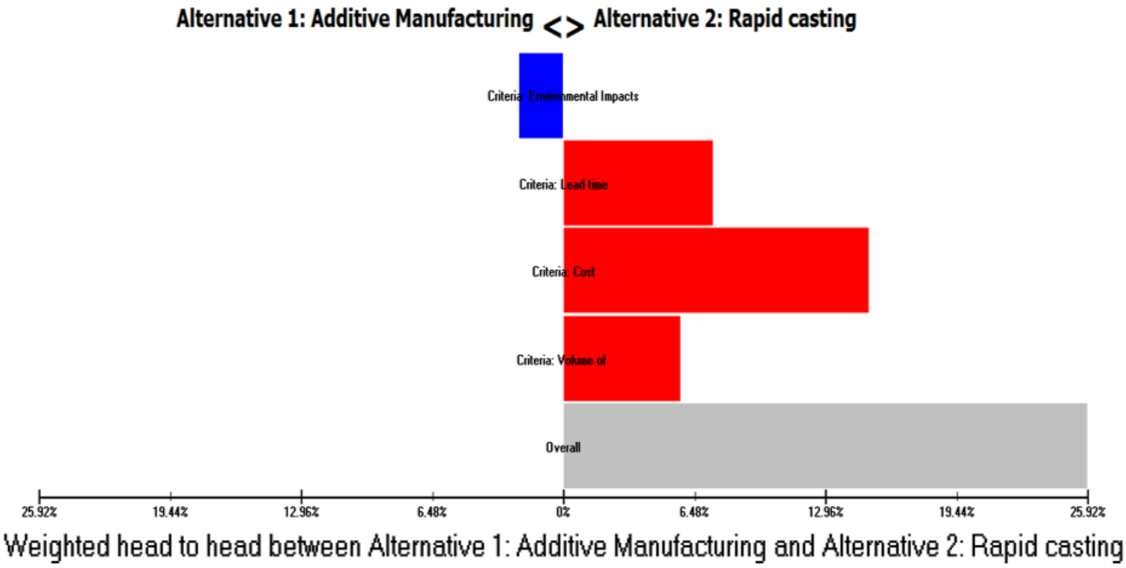


Figure 62: Head-to-head sensitivity of level 1 criteria relative to alternatives

The head-to-head sensitivity seen in figure 62 directly compares the weighted criteria of level 1 against the alternatives. Here, only the environmental criteria favour AM, and it is clear that cost and lead-time are the primary indicators of what drives the decision for rapid casting.

5.5.3 AHP Conclusion

The results should be used as a tool and assist in the overall decision of the final manufacturing selection. Still, the hierarchy analysis has concluded that 3DSC (rapid casting) would be the most favourable method for manufacturing the valve body. Figure 63 correlate contributions from thesis sections to the result of the AHP and the manufacturing method.

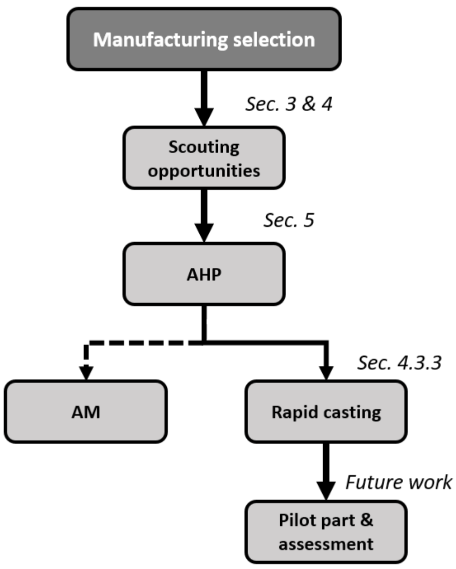


Figure 63: Manufacturing selection route

6 The Digital Ecosystem

This subsection investigates three subjects that can integrate each other within a business. First, an overview of the Digital Ecosystem (DE) is given; it facilitates understanding of the possibilities for stakeholders adopting the technology by providing a general framework used as requirements before venturing into DEs. Secondly, an overview of the digital warehouse used by Equinor is presented and describes the importance of using blockchain for improving reliability and access. Finally, A proposition for asset monitoring and identification is performed to close the loop between the asset (valve body) and the roadmap.

6.1 An Introduction to the Digital Ecosystem

The following content is inspired and adapted from Omar Valdez-De-Leon's article *"How to develop a Digital Ecosystem: A Practical Framework"* [45]. The emerging technologies within automation, robotics, artificial intelligence (AI), and the Internet of Things (IoT) have introduced the fourth industrial revolution (Industry 4.0). The rapid development in optimizing businesses within several industries, such as the marine, offshore and O&G industries. It includes the implementation of the DE, which is presented in an overview in figure 64. In addition, a definition of the digital ecosystem is provided by Jacobides (2019) [46, p. 14]

"interacting organizations that are digitally connected and enabled by modularity, and are not managed by hierarchical authority (like in a supply chain)".

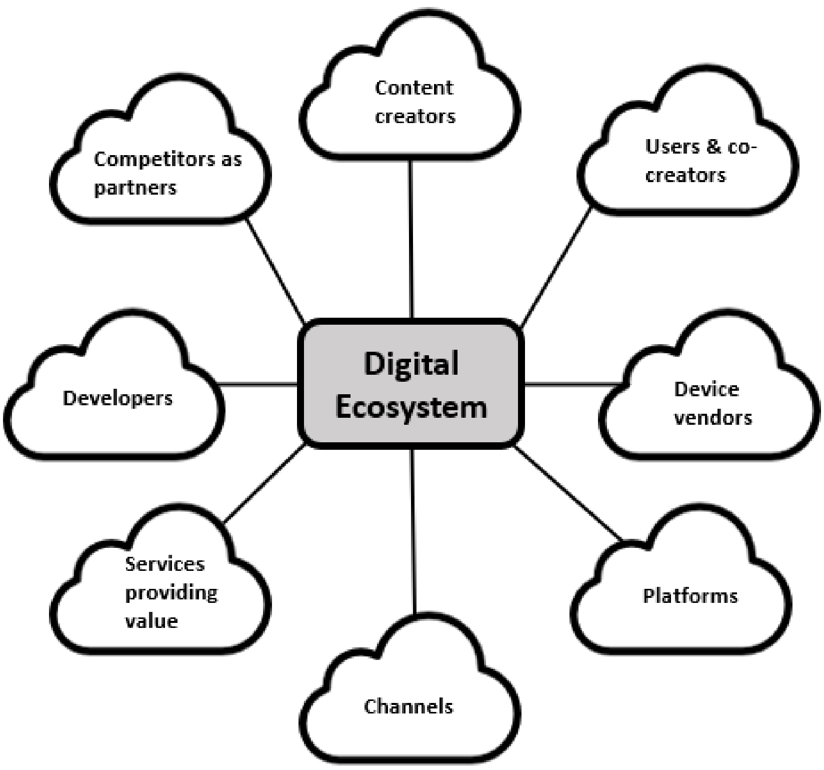


Figure 64: The symbiosis of digital ecosystem [45, p. 45]

The layout of a DE may differ depending on the application. However, it can describe company subsidiaries or cloud platforms dependent on sub-systems such as application programming interfaces (APIs), stakeholders, and app developers. Figure 64 represents the symbiotic relationship between cloud platform owners, users & co-owners, developers, device vendors, competitors and partners, services, channels, and creators. The DE aims to generate value by engaging the end-users, platform owners, and other participants using the ecosystem. It reduces the transaction cost, mitigating the risk by decentralizing in-house manufacturing and storing to third-party collaborators and digital warehousing. The success of the DE is highly dependent on its usability, and network users are sharing the DE profits from adapting it to their business.

6.2 Digital Assets Within the Oil & Gas Industry

The implementation of DE within the O&G industry is relatively new; some proof-of-concept, proof-of-value, and pilot projects performed by Shell and Wilhelmsen incorporate blockchain technology to control and protect digital assets. [47]. Figure 65 conceptualizes the agreement of blockchain. It is, in its essence, a network based on blocks of transactions (data) that are added to an existing block which then forms a chain, i.e., ”blockchain”. This network is not dependent on mediators or third parties to handle data (transactions) of digital assets. It is based on consensus within the network. It provides decentralized and immutable ledgers, meaning that a transaction is irreversible, stored across the whole system, and is public by all system users, i.e., full transparency [48].

Due to the transparency of the blockchain system, security is exceptionally tight. Thus, distributing digital assets between partners, OEMs, and AMs within a digital warehouse would be regarded as safe. Furthermore, as competitors within the industry implement DE strategies, those relying only on a traditional value chain may lose current market shares to rival companies. As a point of reference, a Joint Industry Project (JIP) between marine shipping, OEMs, and service providers is using a DE to acquire spare parts for their fleet of vessels [49]. It currently has the world’s most extensive catalogue of printable spare parts. However, another JIP has the option of starting their own DE, competing with each other. Also, since ecosystems can spread beyond their original domain, well-working DE could adapt to other industries. Omar Valdez points out that the DE can become a competitive entity where the competition is between the DE and not the companies.

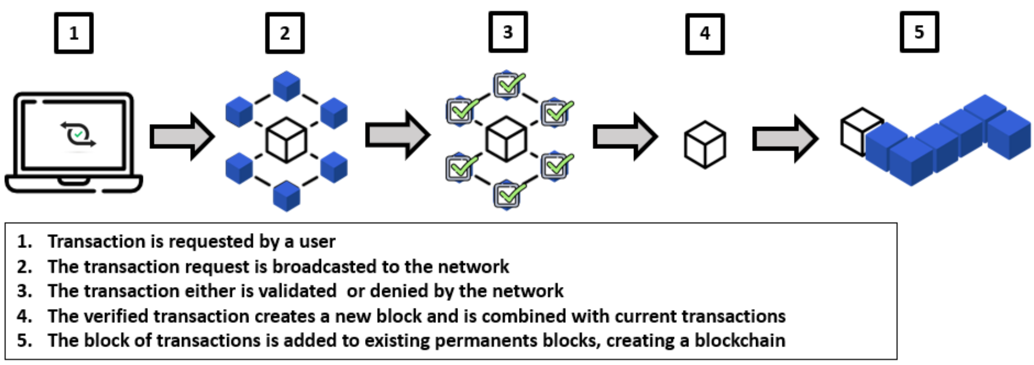


Figure 65: The symbiosis of digital ecosystem

6.3 Framework for Digital Ecosystem Development

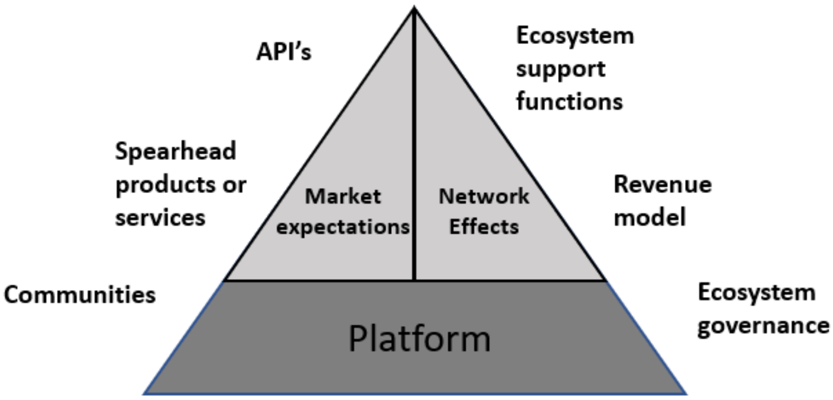


Figure 66: DE framework dependencies [45, p. 48]

Figure 66 describes the three fundamental elements and drivers for the development of digital ecosystems.

1. **The platform:** Is essential for permitting platform resource access through the programmers' point of view and imposing modularity, enabling organizations to establish and build their solutions and services.

2. **Network effect:** Considers the continuous increase of solutions and services provided by ecosystem partners (participants). The activity will engage more end-users, boosting interest from other DE participants. An important consideration is to have a clear strategy for the ecosystem such that participant revenue can be balanced with end-user value.

3. **Market expectation:** Tests the feasibility of the long-term potential of the ecosystem by establishing a market deemed trustworthy by the users and users' interaction. A start is to use enablers such as spearheading products. The valve used as a case review is a perfect example of implementing a spearheading product that can introduce new cooperating that aids in market growth and ecosystem development.

- **APIs:** Application programming interfaces are designed by developers or "communities" of developers. An API is essential for allowing other applications to communicate with one another. Therefore it is regarded as one of the primary drivers of DEs. Furthermore, it generates flexibility that promotes increased user experience by allowing developers to design with the participants (ecosystem partners) in mind.

- **Spearhead products and services:** By encouraging initial products and services through the ecosystem, managers promote their devotion to the system and maintain market expectations while establishing a base of customers. One of the main activities the managers should focus on is to select the product or service which will be used for promotion to this customer base. If internal resources are not available, the community of developers is critical to enabling product or service development. An example is Fieldmade AS, responsible for the platform and the digital warehouse development used to create the spare part market.

- **Communities:** Participants who form the communities are essential for product and service development through API. This driver benchmarks the reputation of the ecosystem, which will attract developers and increase the user base that utilizes products and services.

- **Revenue model:** A financial income (revenue model) plan must be evaluated before DE investment. The model will strengthen the validity of the ecosystem and gain more attraction for early initiations of participants. There will also be a need for additional management and decision-making systems due to licensing, fixed royalty and revenue sharing options between organizations and OEMs .

- **Ecosystem support functions:** It is essential to maintain ecosystems and provide them with regular support functions within technical, marketing, and operational support.

- **Ecosystem Governance:** Regulations controlling the interaction between stakeholders are needed to maintain a continuous and well-running ecosystem. These regulations should be bounded by ecosystem development and goals, which will create and sustain value for the stakeholders involved.

6.4 The Digital Warehouse

From the introduction of the digital ecosystem, the spearheading of products and services fits the introduction of the digital warehouse (DW). During the introduction to this project, Equinor provided access to an early version of a cloud platform used for part manufacturing and distribution of parts. This platform can consolidate a large part of the supply chain with the principle of an on-demand acquisition of spare parts. Furthermore, this platform intends to provide stakeholders such as customers, OEMs, AMs, and intellectual property (IP) owners access to documentation (part files, drawings) ready for manufacturing. Figure 67 describe a basic outline of the cloud layout for handling parts.

- **Work packages:** Also called a project, includes the parts' documentation related to part files, drawings, standards, and manufacturing specifications.

- **Local market parts:** Parts are available for internal use by relevant personnel within the internal organization or approved partners who have access to the local market.

- **Global market parts:** It provides access to external manufacturers, purchasers, and IP owners that want to bid for orders, place order inquiries or add parts.

- **Internal distribution:** This includes engineering and technical personnel directly involved in work packages under development or distributed between approved partners. Management related to warehouse projects is responsible for the organization and overseeing the development of the warehouse.

- **External distribution:** This distribution aims at customer inquiries and exposure of work packages to OEMs and AMs.

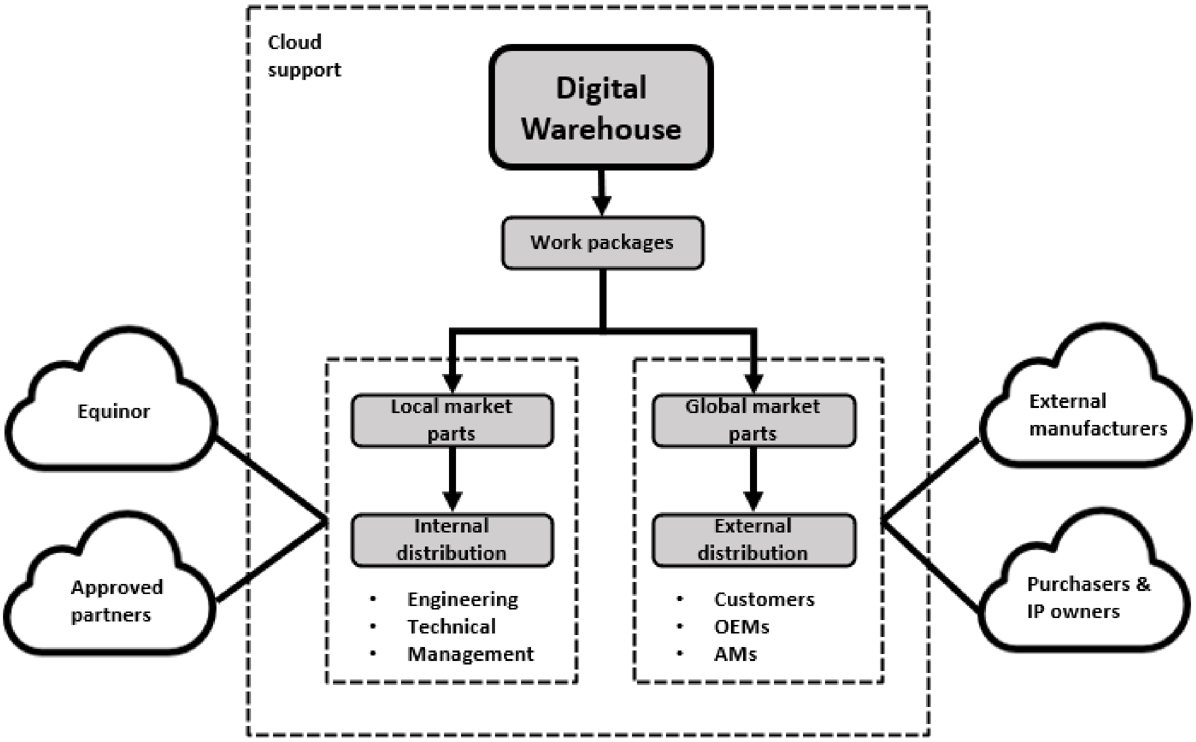


Figure 67: Digital warehouse layout

The main reason for applying the digital warehouse is the increasing use of on-demand services, which reduces the need for physical space dedicated to storing equipment and spare parts. It applies to components that are in reach for an on-demand acquisition. Again, the valve provided in the case review is an example of a part in a regular spare part supply chain that needs a storage facility dependent on utilities and staffing. The objective of this application is in line with the digital ecosystem, where the platform extends to a local section where the drivers related to the DE framework should be revived.

6.5 Intellectual Property

Intellectual property (IP) specify inventions defined as the *"creations of the mind"*. It includes; designs, artwork, literature, images and names with the intention of a business application. The objective of using IP recognition is to nourish innovation and creativity while protecting the public interest and innovators [50]. For example, the valve body is a component beyond the limit of patent rights (20 years). In fact, according to World Intellectual Property Organization (WIPO), one of the five conditions for patenting states [50].

"The invention must show an element of novelty; that is, some new characteristic which is not known in the body of existing knowledge in its technical field".

"The protection is granted for a *limited period, generally 20 years from the filing date of the application".*

WIPO's other conditions are related to industrial application, subject matters, and novelties that are not further discussed. However, before distributing a patented part to a public market within the DW, the patent owner must permit the organization to reproduce the part. In addition, quantity, period, and distribution area should be specified.

6.6 Proposition for Monitoring & Identification

The increased realization of IoT and blockchain services have boosted the incorporation of real-time tracking and monitoring components such as high critical parts. For example, Radio-Frequency Technology (RFID) combined with AI and machine learning provides almost real-time spare part inventory in part of the marine industry. Accordingly, increased accuracy and cost savings are achieved [51] [49].

While tracking can be used for maintaining and ordering disposable parts, monitoring critical assets on an offshore installation such as Statfjord can increase the life span of these assets while reducing the probability of an unwanted accident [52]. Figure 68 presents a layout of tracking and monitoring which is connected to a digital ecosystem. The installation's local network may obtain the information where both micro and macro data are gathered.

- **Micro data** is related to monitoring structural and mechanical components deemed critical for operations and may be placed in areas where significant contributors to degradation are expected. Vibrations, flow, corrosion, and stress & strains can be used as markers for predictive maintenance analysis and part health assessments. It may detect anomalies resulting in part or system failure and accurately pinpoint preventative maintenance. Within the DE, a dedicated interface for digital monitoring should be applied.
- **Macro data** links to the digital warehouse where all information about sub-components, material, manufacturing specifics, and availability is stored and updated. Classification of AM parts could also include multi-criteria decision tools for deciding whether it is feasible for AM, rapid casting, or other manufacturing methods. Redundancy should be maintained where RFID technology and physical marking of assets are considered.

The digital monitoring of the asset (valve body) could link to the digital warehouse, where the asset screening can indicate a current or developing problem. This screening determines the available options for replacing the asset and may consider questions like:

- Is the asset critical, or is the system linked to the asset critical, maybe both?
- Does the system have enough redundancy until the new asset arrives?
- Are there other considerations that may introduce further issues if no redundancy is available and the asset must operate until a new spare arrives?

The asset study would be initiated based on the input from the *microdata monitoring*, which would identify a problem with the asset. This identification could alert technical personnel to look at the issue, relate the problem to inventory, and initiate screening for

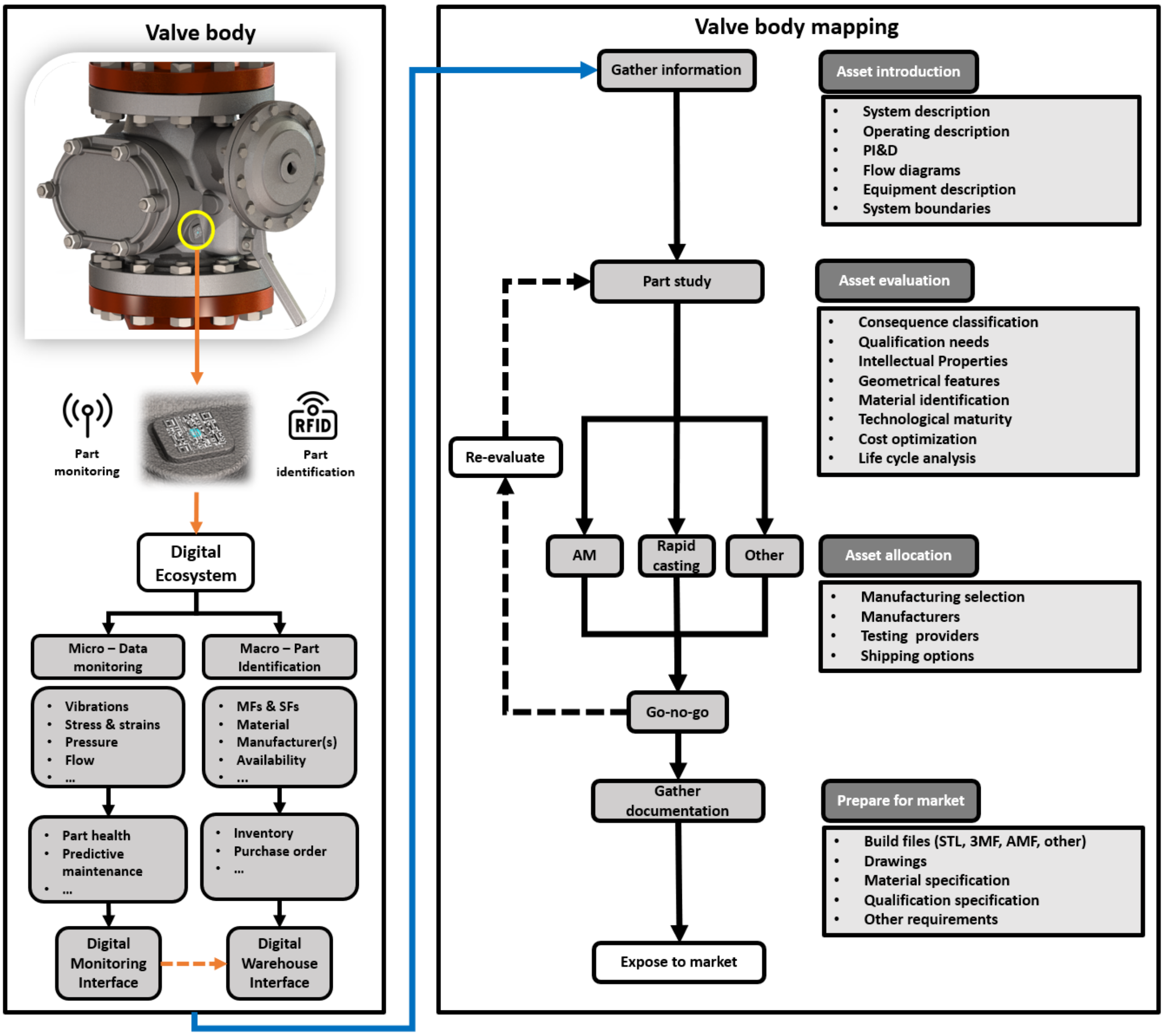


Figure 68: Part monitoring, identification, and asset activity mapping

asset replacement. The screening may be done simultaneously with *asset introduction*, where an overview of MFs and SFs are outlined together with system boundaries and other needs to understand the case. Then, *asset evaluation* proceeds where asset characteristics aid in classifying the part related to criticality before *asset allocation* to manufacturing selection. The "Go-no-go" condition may need re-evaluation if a non-consensus or misjudgement about the manufacturing selection is detected. Finally, when a decision is made, customer approval and asset documentation needed for manufacturing are gathered and exposed to the market.

The proposed mapping above has applied the valve body as the asset but should be able to apply generic components based on the initial screening.

7 Case Review

7.1 Valve Body Cloning

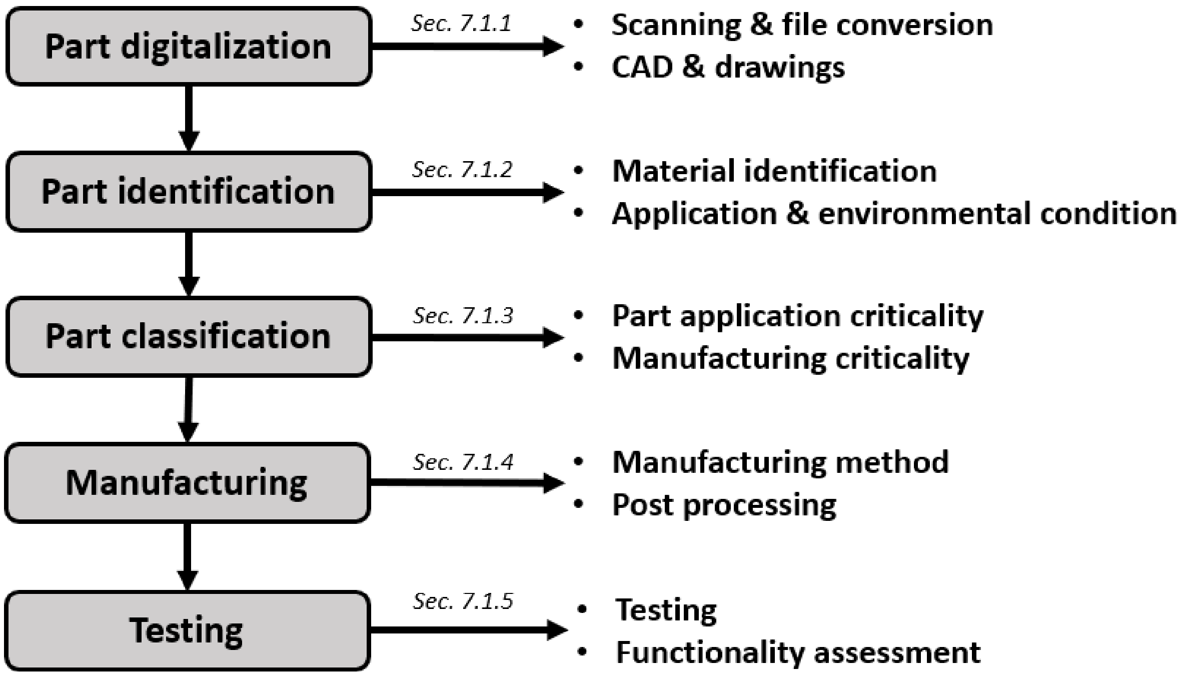


Figure 69: Reverse engineering process activities

The case review aims to apply parts of the REP from the literature review regarding the valve body. As a result, the thesis will be one of the few documents that consolidate the part cloning process for the O&G industry on the NCS by combining the findings from the class adoption of criticality, AHP and the mapping proposal. Figure 69 above represents the REP from the literature review.

7.1.1 Part Digitalizaiton

Scanning & file conversion: The scanning process is a critical step where the final geometry depends on the scanner's quality and resolution. The 3D printed valve body was re-scanned at UiS using the EinScan HX handheld scanner. MRC Global initially scanned the part at Equinors' physical warehouse in Mongstad, Norway, and shared it with Moreld Capnor for further work.

Figure 70 describes the scanning and conversion of the point cloud data, which reference local geo-locations of the valve body relative to its geometry. Next, the point cloud data is processed through Geomagics Essentials 2, where it was converted to a mesh body and repaired to represent the full version of the part [53]. Finally, the file is exported as STEP (Standard for the Exchange of Product Data) to Autodesk Inventor, where preparations for optimization is performed, choosing to re-design or preserve the geometry. If no design changes are required, the part can be analyzed based on the activity outputs relevant to the valve body.

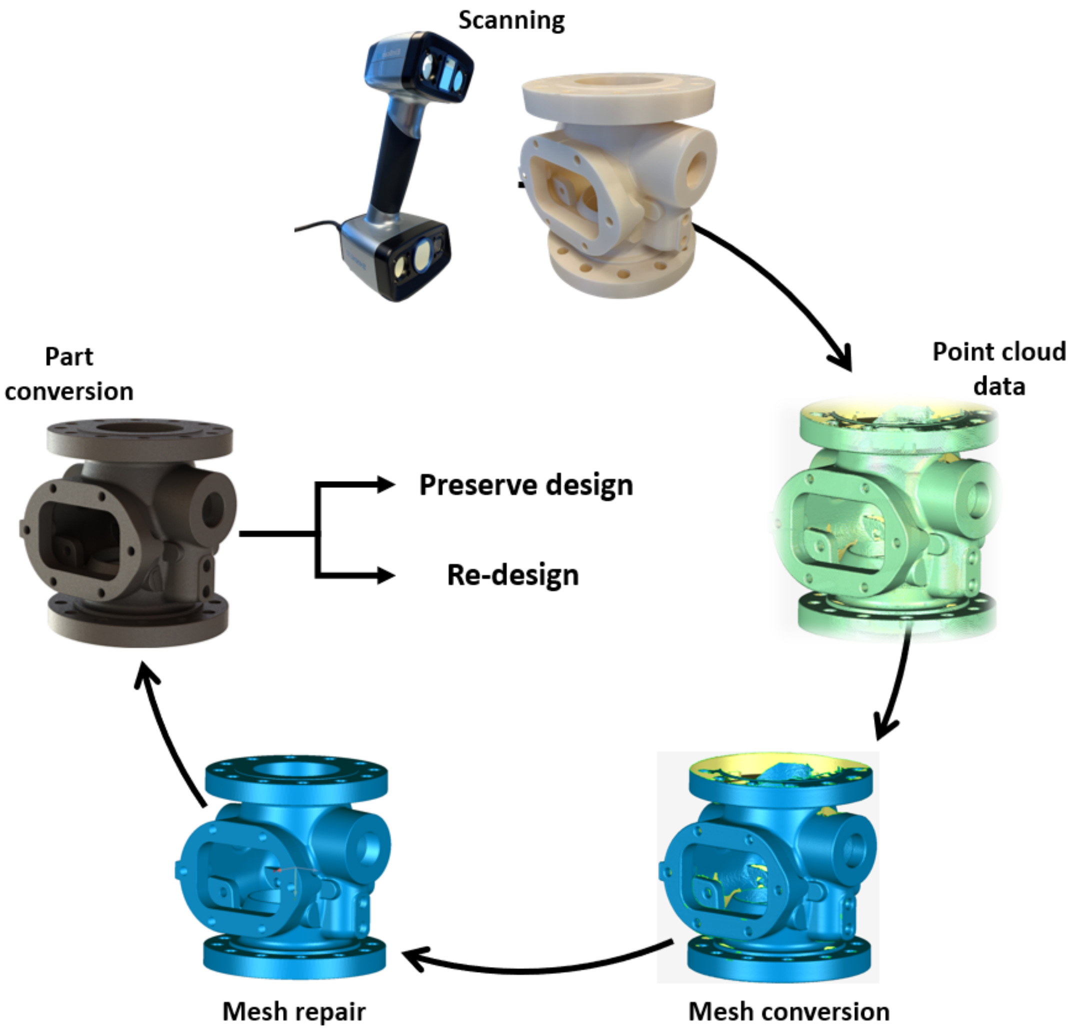
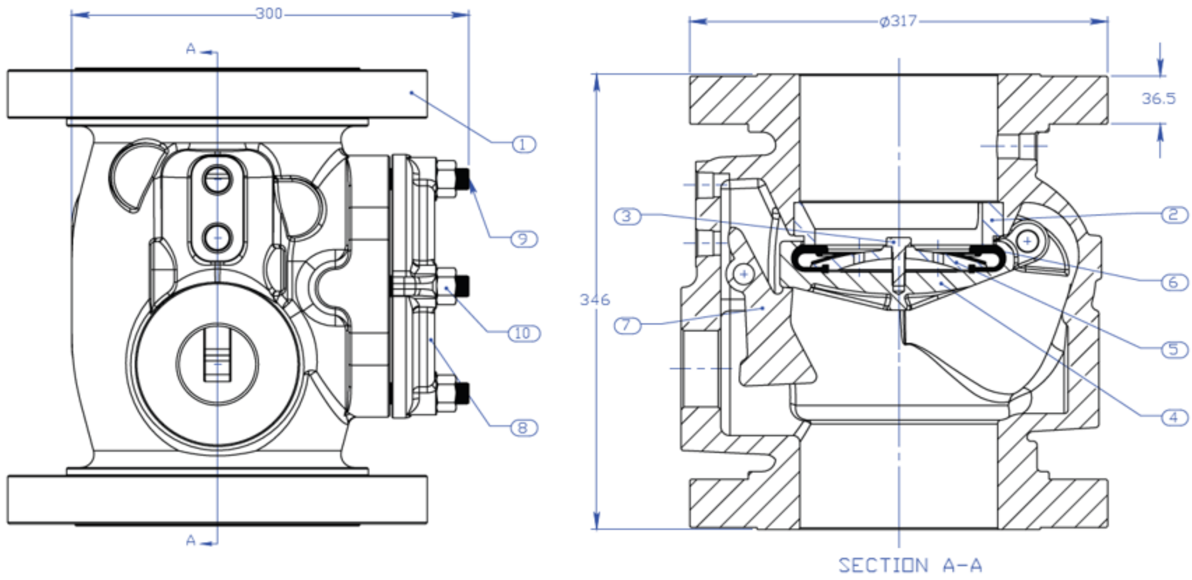


Figure 70: Geometric documentation of the valve body

CAD & Drawings: The manufacturer receiving (or taking the order through a digital warehouse) must be provided with the necessary documentation to produce the valve body. The original scan documentation was obtained by MRC seen in figure 71. A new revision of the drawing is attached to Appendix A. The provided documentation for manufacturing (AM and rapid casting) should, at minimum, contain the following:

- **Part build file**
- **Drawings**
- **Material specifications**
- **Post build specification**

The build part file can either be STEP, STL, or other specified by the manufacturer. Drawings provide definitions related to functions and can be combined with material specifications. Also, post-processing information for heat treatment, machining, and other surface treatments should be specified or guided through the manufacturing standards provided by NORSOK-L001, NORSOK-M630, NORSOK-M650, DNVGL-ST-B203, or API20S.



ITEM NO.	QTY.	MATERIAL	PART NUMBER	DESCRIPTION
10	6	AISI 316	70001043-33	HEX NUT 5/8-11 BSW
9	6	AISI 316	70001043-32	5/8-11UNC x 75 STUD
8	1	UNS S31254	70001043-31	COVER PLATE
7	1	UNS S31254	70001043-10	RELEASE LATCH
6	1	RUBBER	70001043-06	RUBBER SEAT
5	1	AISI 316	70001043-05	CLAMP PLATE
4	1	AISI 316	70001043-04	CLACK
3	1	AISI 316	70001043-03	HEX HEAD SCREW M10 x 30
2	1	AISI 316	70001043-02	SEAT
1	1	UNS S31254	70001043-01	VALVE BODY

Figure 71: Original Drawing and material documentation provided by MRC

Figure 72 summarizes the action and output created from part digitalization of the REP. The figure below describes the activity, if it has been performed (investigated) and if the activity has been concluded. The comments specify any method, software, or files that have been generated to obtain the output from the REP activities within the specific section.

Part digitalization

Activity	Performed	Concluded	Comment
Scan	**Yes**	**Yes**	- Reference part scanned twice with Einscan HX at UiS - printed with Fortus 450mc in ABS at UiS
File conversion	**Yes**	**Yes**	- Cloud data processing, scan alignment, and file conversion performed with Geomagics Essential 2
CAD & drawings	**Yes**	**Yes**	- Drawings and build files (STEP, STL) made in Autodesk Inventor - Optimization suggestions from valve theory performed in Fusion 360 (generative design study), SolidWorks Fluid (Fluid velocity)

Figure 72: Part digitalization

7.1.2 Part Identification

Mechanical properties

		Yield strength Rp0.2, MPa	Tensile strength Rm, MPa	Elongation [%]	Hardness [HB]	Impact, Charpy-V, -46C [J]	Pre
• SVERDRUP STEEL • SOLID	6Mo UNS S31254						
	All products	≥ 310	655 – 850	≥ 35	≤ 310	≥ 45	≥ 40

		Yield strength Rp0.2, MPa	Tensile strength Rm, MPa	Elongation [%]	Hardness [HB]	Impact, Charpy-V, -46C [J]	Pre
• SVERDRUP STEEL • SOLID	Super duplex UNS S32750						
	Bar	≥ 550	750	≥ 25	≤ 310	≥ 45	≥ 40

		Yield strength Rp0.2, MPa	Tensile strength Rm, MPa	Elongation [%]	Hardness [HRC]	Impact, Charpy-V, -46C [J]	Pre
• SVERDRUP STEEL • SOLID	Titanium Grade 5						
	Min	828	897	10		N/A	N/A
	Max	910	1000	18	36	N/A	N/A

		Yield strength Rp0.2, MPa	Tensile strength Rm, MPa	Elongation [%]	Hardness [HB]	Impact, Charpy-V, -46C [J]	Pre
• VELO3D • AM FEEDSTOCK	Titanium Ti-6V-4V						
	HT	819	994	≥ 21	N/A	N/A	N/A
	HIP	819	994	≥ 21	N/A	N/A	N/A

HT, Heat Treatment
HIP, Hot Isostatic Pressing

		Yield strength Rp0.2, MPa	Tensile strength Rm, MPa	Elongation [%]	Hardness [HV]	Impact, Charpy-V, -46C [J]	Pre
• SANDVIK • AM FEEDSTOCK • DNVGL-ST-B203 • ASTM-F2924	Titanitum Ti-6V-4V						
	HT Horizontal	957±7	1076±6	14±0.6	344±4	23±0.5	N/A
	HT Vertical	997±6	1094±4	15±0.5	346±0.9	22±0.9	N/A

		Yield strength Rp0.2, MPa	Tensile strength Rm, MPa	Elongation [%]	Hardness [HV]	Impact, Charpy-V, -50C [J]	Pre
• SANDVIK • AM FEEDSTOCK	Super duplex UNS S32750						
	HT Horizontal	627	956	39	282±8	198	43
	HT Vertical	626	923	43	282±8	235	43

Figure 73: Mechanical properties of the original material and proposed options

Material identification: An material investigation would be needed if equal performance should be acquired. The drawings provided by MRC contain the original material specification, which eliminate a microstructural analysis for determining the material. However, Titanium (Ti-6Al-4V) for AM and super-duplex for 3DSC have been considered due to customer requests and manufacturing options.

Figure 73 above presents the mechanical properties of the original casted material (6M0). In addition, super-duplex and titanium are also provided. Following DNVGL-ST-B203, the suitable material for AM is Ti-6AL-4V. In addition, a super-duplex (not yet qualified through the mentioned standard) is also available. It is seen that these materials have the minimum requirements for replacing the valve body.

Application & Environmental Conditions: The application and environmental conditions have been described in the introduction and in the valve theory section. However, it should be noted that the most extreme condition should be the basis for analysis and re-design.

Figure 74 displays the part identification activities, which all have been performed and concluded. The main and sub-functions were established with the aid of NORSOK-Z008.

Part identification

Activity	Performed	Concluded	Comment
Material ID:	**Yes**	**Yes**	- **Original Material:** 6Mo (UNS S31254), provided by MRC global (original drawings) - **Proposed Material:** Super-duplex, Titanium - **Material guidance:** - **AM:** DNVGL-ST-B203 and API20S - **Rapid casting:** NORSOK-M001, NORSOK-M630, NORSOK-M650
Part application	**Yes**	**Yes**	- **Main function:** Valve body - **Sub-functions:** Disc (clack) and release mechanism
Environemental conditions	**Yes**	**Yes**	- Dependent on the position of the valve body (inside or outside the facility, aggressive environments, Etc)

Figure 74: Part identification

7.1.3 Part Classification

A review of the criticality for part application and environmental conditions affecting the valve body aids in evaluating the technological possibilities for the production regarding part material, complexity, and size. In addition, consideration should be taken for the production size, availability (machines and material) and manufacturing options (AM, rapid casting). The initial request was 26 valve bodies.

Criticality of application: The valve body has been evaluated based on its function and is part of a system essential for maintaining a functional barrier. NORSOK-Z008 has been used to rate the criticality related to application, and it is evaluated as high.

Criticality for manufacturing: The valve body would be classified as AMC-2 (AMSL-2) for AM manufacturing. There is no corresponding casting evaluation since NORSOK already specified the qualification path, whether the part is critical or non-critical. Therefore, the AM method depends on criticality evaluation related to AMC levels. Figure 75 specify the activities for part classification. Both activities has been performed and concluded.

Part classification

Activity	Performed	Concluded	Comments
Part application criticality	**Yes**	**Yes**	- **Operational criticality:** High - **Classification guidance:** NORSOK-Z008
Manufacturing criticality	**Yes**	**Yes**	- **Manufacturing criticality (AM):** AMC-2, AMSL-2 - **Manufacturing guidance** - **AM:** DNVGL-ST-B203 and API20S - **Rapid casting:** NORSOK-M630 and NORSOK-M650

Figure 75: Part classification

7.1.4 Manufacturing

Part manufacturing

Activity	Performed	Concluded	Comments
Manufacturing method	**Yes**	**Yes**	- Market scouting deemed AM non feasible due to part size, batch size, and material - Analytical hierarchy process favoured rapid casting as manufacturing option - Equinor has requested two valve bodies to be manufactured by rapid casting
Post processing	**Partly**	**No**	- Machining, and threading of the valve body is required - Other post processing activities has not been mapped

Figure 76: Part manufacturing

Manufacturing method & post-processing: Two companies provided the most promising AM and rapid casting offers. The conclusion for AM revealed that the six-inch valve body was too large to be produced by PBF. Furthermore, the required material was not available. However, options for four-inch valves could have been built; this is not part of this thesis.

A domestic provider offered to build the part by Wire Arc Additive Manufacturing (WAAM), a DED process. The price is around 400,000 NOK, with a lead-time of 8 weeks per part. The inquiry for the rapid casting option allowed the whole batch request of 26 valves to be produced. The cost estimate is close to 400,000 NOK with a lead time of 10 weeks. Post-processing (machining) is excluded. Figure 76 above consolidates the activities where the extent of post-processing has been discussed but not fully mapped.

7.1.5 Testing

Testing & functionality assessment: When choosing the manufacturing method, the final points within REP consider the testing related to the respective standards for AM and casting processes specified within their respective standard. For AM, section 3.2.1 can be revised to see the test requirements for AMC-2. The tests for a casted valve body are detailed in NORSOK-M630 and NORSOK-M650. The conclusion is that the test requirements for AM are generally considerably more extensive than for casting.

The functionality assessment could not be performed on a pilot part, however. Instead, a reference component was manufactured at UiS with all its accessories. It allowed an inspection of valve functions and identification of points that may be of interest for a re-design (optimization). Figure 77 concludes the REP where functionality was partially performed and is presented in figures 78 and figure 79

Part testing

Activity	Performed	Concluded	Comments
Testing	**Yes**	**Partly**	- **AM:** Testing requirement have been identified - **Rapid casting:** Testing requirements are specified by NORSOK
Functionality	**Partly**	**No**	- Functionality have been assessed by the 3D printed reference valve body

Figure 77: Part testing

Figure 78: 3D-printed components of the reference valve

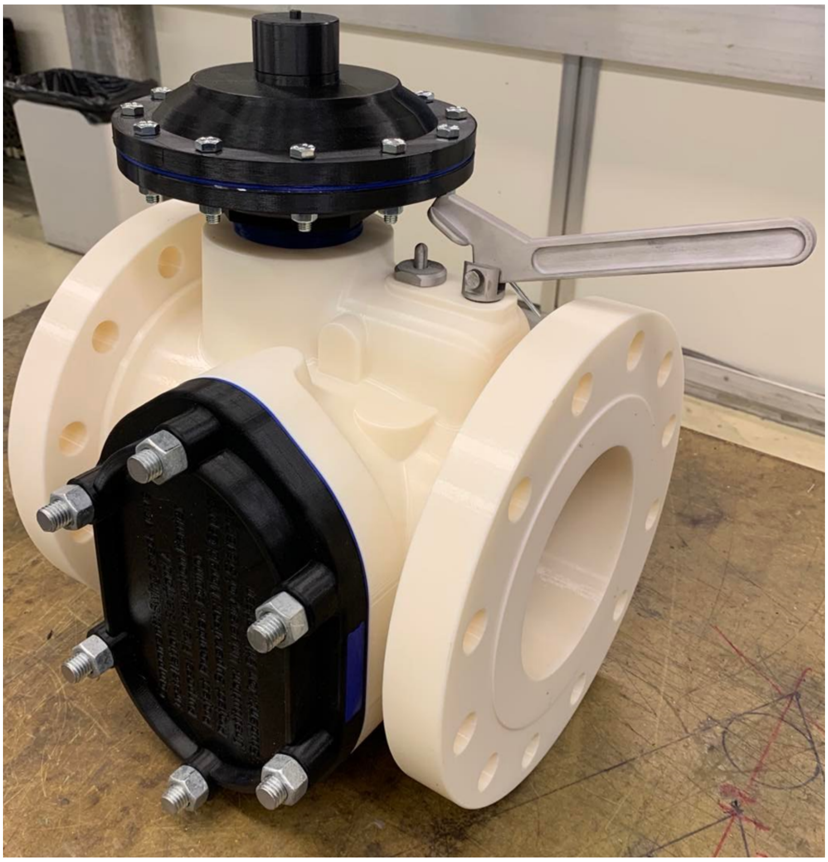


Figure 79: Assembled valve, used for reference

8 Results

The results present the output from the literature review (standards, manufacturing selection, and digital warehouse) and the case review.

8.1 Standards

Due to its cumbersome path and strict demands, a more significant investigation within Additive Manufacturing (AM) relative to casting was performed. The proposition for the AM adaption of aviation classes aided in selecting the Additive Manufacturing Class (AMC) for AM. The valve body was ranked an AMC-2 out of 3, medium level for powder bed fusion (PBF), where testing specimens could be produced in the same build as the valve body, reducing time and cost. However, most importantly, it eliminates the need for an AMC-3 part which requires a separate sacrificial part, i.e., a sacrificial valve body.

Due to a well-implemented network of NORSOK certified (material and process) casting providers, the valve body qualification route for casting is straightforward and is directly outlined in section 4.2.2.

AM adaption	Pressurized systems	Applications
Class 4 AMC-3, AMSL-3	**Part that contain or transport** • High pressurized gas • Large amount of flammable fluids • Aggressive corrosive mediums **Consequence of failure may be** • Loss of life • Large Structural damages • Large economical losses • Large Environmental damages	➢ **Safety valves (hydrocarbon) with high pressure** • Turbine fan blade • Specific fasteners • ...
Class 3 AMC-2, AMSL-2	**Part the contain or transport** • Medium pressurized gas • Limited amount of flammable fluids • Corrosive mediums **Consequence of failure may be** • Local shutdown • Injuries • Local structural damages • Limited economical losses • Local environmental spills • Increased workload	➢ **Deluge valves with medium pressure** • Gear • Impeller • ...
Class 2 AMC-1-2, AMSL-1-2	**Part the contain or transport** • Low pressure fluids or inert gas • Non-corrosive mediums **Consequence of failure** These parts may affect daily routines but does not inflict class 3 or class 4 consequences	➢ ***Fresh water valve with low pressure*** • Pipe support • Bolts and nuts • ...
Class 1 AMC-1, AMSL-1	Part that does not have any effects on daily operations nor safety for personnel or installation.	• Tooling • Accessories (spacers, levers, etc) • ...

Quality Control Requirement Matrix		PBF-LB AMC-2		
Testing	**Standard(s)**	**BPQT**	**PQT**	**PT**
Bending	ASTM E384 ISO 7438 (WAAM)			
Porosity	ASTM B311	x		
Chemical	ASTM A751	x		
Tensile	ISO 6892-1 ASTM E8/E8M	x		x
Impact	ISO 148-1 ASTM E23	x		x
Hardness	ISO 6507-1 ASTM E290 ASTM E384	x		
Microstructure	ASTM E3 ASTM E407	x		
Visual	NS-EN 13018			x
Surface (NDT)	ISO 3452 ISO15549 ISO 9934 ISO 17296-3			x
Volumetric (NDT)	ISO5579 ISO15708-B ISO 16810			x
Dimensions	By agreement			x

Needed for part qualification

BPQR [X]
- Porosity
- Chemical
- Tensile
- Impact
- Hardness
- Microstructure

PQT [X]
- None

PT [X]
- Tensile
- Impact
- Visual
- Surface (NDT)
- Volumetric (NDT)
- Dimensions

Figure 80: Aviation adaption for valve body AM criticality evaluation

8.2 Manufacturing Selection

A fundamental topic of the thesis concerns the decision on the valve body manufacturing method. The initial discussions pointed heavily to the use of AM, but were not fully evaluated regarding the weighting of cost and benefits. Therefore, the Analytical Hierarchy Process (AHP) was used to strengthen the manufacturing decision-making.

8.3 Analytical Hierarchy Process Results

The results of the analysis are presented below, starting with the criteria influencing the final output of the manufacturing alternatives.

- **Cost:** 49.5%
- **Lead time:** 32.2%
- **Environmental impacts:** 6%
- **The volume of material:** 12.4%

The manufacturing alternatives below conclude that *rapid casting (Three-dimensional sand casting-3DSC)* is the favoured method for producing the valve body.

- **Additive manufacturing:** 37%
- **Rapid casting:** 63%

Figure 81 describes the path for selection and the criteria results which have dynamical attributes, meaning that each criterion can be adjusted to analyze the outcome. These criteria are based on the questionnaire in Appendix C and the input from expert judgments.

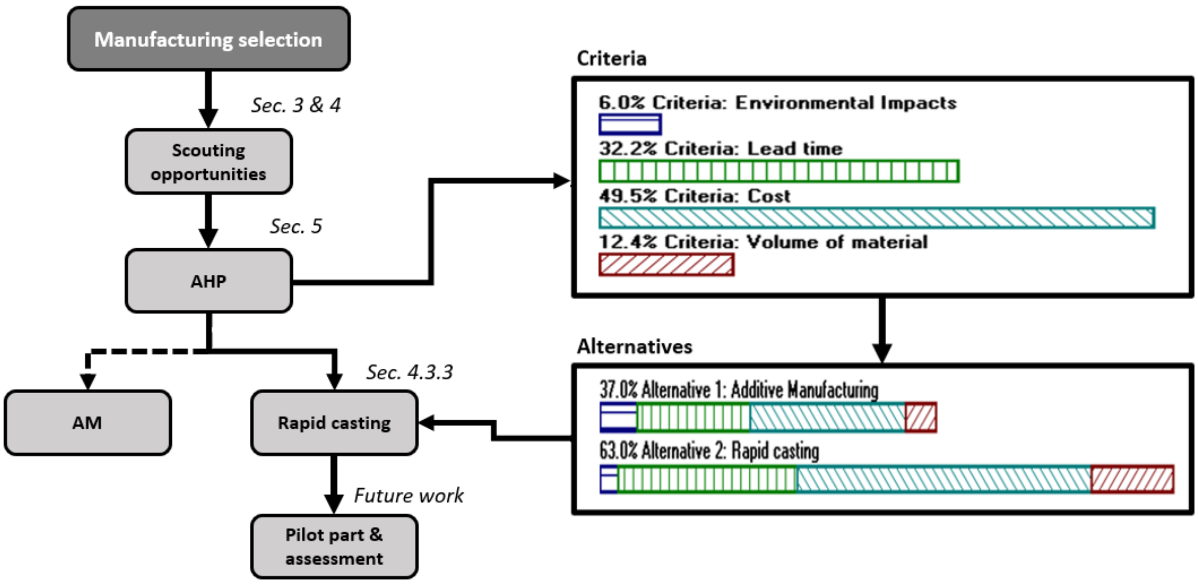


Figure 81: Manufacturing selection path and AHP results

8.4 The Roadmap

The *roadmap* have been constructed as a result based on the defined thesis question (TQ):

How can the path from notification to installation of legacy spare parts be mapped in the O&G industry?

Figure 82 has proposed an adaptable solution developed upon a systematic approach linked to the valve body (asset) and thesis sections. The roadmap below has five elements, where the second to last and final elements integrate the on-demand asset acquisition solution. The mapping is generated with a general mechanical spare part in mind and could be modified with decision-making tools such as (AHP) on several levels. Finally, a concluded description is provided for all five levels.

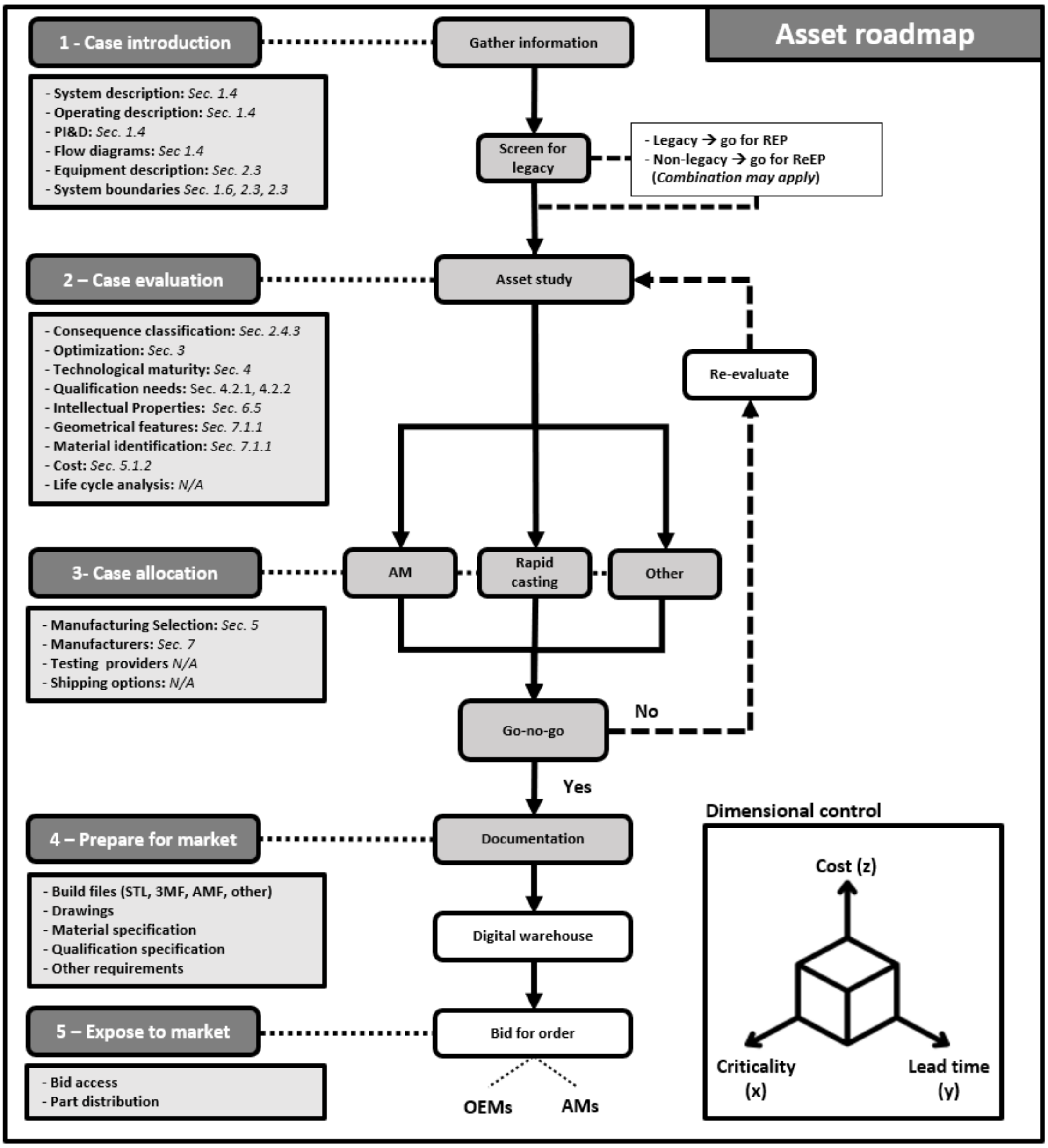


Figure 82: Roadmap proposition for legacy parts aimed at the O&G industry on the NCS

1. **Introduce case:** The introduction of the case defines the asset (valve body) and screens it for legacy (obsolete) dependency. It suggests that if the part has gone out of production and lacks documentation, a complete Reverse Engineering Process (REP)should be applied. However, if the part may include limited or full access to documentation, only parts of the REP need to be applied.

   A combination of REP and Re-Engineering Process (ReEP) process may be used when any re-design (optimization) of the asset is requested by the customer or required by regulations. The case introduction gathers information from the customer and obtains all related and available documentation about the asset and its related functions.

2. **Evaluate case:** Evaluating the case includes an asset study where the REP, ReEP, or a combination is implemented. Attributes related to asset classification, qualification needs, intellectual properties, material identification, cost, optimization, geometry features, and life cycle analysis. The study will create a set of criteria that can be used for case allocation, i.e., deciding the manufacturing method.

3. **Allocate case:** In addition to inputs from the customer and manufacturers, the manufacturing method selection may apply decision models such as the analytical hierarchy process (AHP) used in section 5, based on the criteria from the case evaluation. Furthermore, this phase may also scout the market for *other* manufacturing options, which could be used for total production or implementation of parts of the production. Finally, the customer should be included in the final decision assessment and provide a *"Go-no-go"* scenario based on the output from qualitative and quantitative analytical decision-making tools and expert inputs. If a no-go is considered, a re-evaluation may be required.

4. **Market preparation:** The go decision for the appropriate manufacturing method allows documentation created in the case evaluation to be accumulated and *market preparation*. Build files, drawings, material specifications, qualification specifications (AMC level), or other requested documentation should be available.

5. **Expose to market:** The asset should then be *"exposed to the market"* where approved manufacturers have access to bidding or asset documentation.

Dimensional control: The main contributors to asset evaluation related to purchasing are the total cost and lead time. However, introducing criticality as a third dimension (related to AM) and on-demand solutions could help the purchaser make effective economic decisions.

8.5 Case Review Report

The case review implemented the Reverse Engineering Process (REP), where input from the literature review contributed directly to the results summarized in figure 83.

Part digitalization

Activity	Performed	Concluded	Comment
Scan	Yes	Yes	- Reference part scanned twice with Einscan HX at UiS - printed with Fortus 450mc in ABS at UiS
File conversion	Yes	Yes	- Cloud data processing, scan alignment, and file conversion performed with Geomagics Essential 2
CAD & drawings	Yes	Yes	- Drawings and build files (STEP, STL) made in Autodesk Inventor - Optimization suggestions from valve theory performed in Fusion 360 (generative design study), SolidWorks Fluid (Fluid velocity)

Part identification

Activity	Performed	Concluded	Comment
Material ID:	Yes	Yes	- **Original Material:** 6Mo (UNS S31254), provided by MRC global (original drawings) - **Proposed Material:** Super-duplex, Titanium - **Material guidance:** - **AM:** DNVGL-ST-B203 and API20S - **Rapid casting:** NORSOK-M001, NORSOK-M630, NORSOK-M650
Part application	Yes	Yes	- **Main function:** Valve body - **Sub-functions:** Disc (clack) and release mechanism
Environemental conditions	Yes	Yes	- Dependent on the position of the valve body (inside or outside the facility, aggressive environments, Etc)

Part classification

Activity	Performed	Concluded	Comments
Part application criticality	Yes	Yes	- **Operational criticality:** High - **Classification guidance:** NORSOK-Z008
Manufacturing criticality	Yes	Yes	- **Manufacturing criticality (AM):** AMC-2, AMSL-2 - **Manufacturing guidance** - **AM:** DNVGL-ST-B203 and API20S - **Rapid casting:** NORSOK-M630 and NORSOK-M650

Part manufacturing

Activity	Performed	Concluded	Comments
Manufacturing method	Yes	Yes	- Market scouting deemed AM non feasible due to part size, batch size, and material - Analytical hierarchy process favoured rapid casting as manufacturing option - Equinor has requested two valve bodies to be manufactured by rapid casting
Post processing	Partly	No	- Machining, and threading of the valve body is required - Other post processing activities has not been mapped

Part testing

Activity	Performed	Concluded	Comments
Testing	Yes	Partly	- **AM:** Testing requirement have been identified - **Rapid casting:** Testing requirements are specified by NORSOK
Functionality	Partly	No	- Functionality have been assessed by the 3D printed reference valve body

Figure 83: case study results

8.6 Report Outcome

- Figure 84 summarizes the two manufacturing options face-to-face, where cost estimate, lead time, quantity and additional costs due to extra processing activities are stated. The costs are estimates based on the manufacturing method, material, batch quantity, and qualification needs, where Additive manufacturing (AM) uses Wire Arc Additive Manufacturing (WAAM), a Direct Energy Deposition (DED) method for building the part. Both methods use domestic providers where only the moulds for rapid casting are manufactured in a European country.

- Equinor (customer and project provider) have decided to go ahead with ordering two valve bodies through the rapid casting method. More valve bodies may be ordered if the economic and operational aspects are achievable.

Cost & lead time

Manufacturing	Total Cost (NOK)	Lead time	Quantity	Material	Expected additional costs	Additional processing
AM (DED)	~400,000 (1 valve body)	~8 weeks	1	Super-duplex	Yes	• Machining • Threading • Surfacing
Rapid casting (3DSC)	~360,000 (27 valve bodies)	~10 weeks	26 + 1 sacrifical	Super-duplex	Yes	• Machining • Threading • Surfacing

Figure 84: case study results, AM versus rapid casting

9 Discussion

This thesis research has investigated subjects including standardization, reverse engineering, manufacturing, digital warehouse, and part monitoring. The case review tested the Reverse Engineering Process (REP). Furthermore, it connected the subjects with the central motivator of the thesis, where the roadmap proposition outlines the path for undocumented spare parts (legacy assets) within the O&G industry on the Norwegian Continental Shelf (NCS).

9.1 Standards - The Baseline for an On-demand Solution

The strict policies and regulations on the NCS demand a good understanding of the documentation behind the on-demand solution. The resulting outcome of a level two category for additive manufacturing (AM) is based on the customer and the additive consultation parties. The current aim is to avoid exposing the valve body to an AMC-3 level. The qualification cost is so expensive that it may reach the cost of manufacturing, doubling the total cost (excluding machining activities). This was also visible in the AHP, where cost and lead time were the most important criteria for deciding the manufacturing method.

A section of the thesis was dedicated to establishing a more straightforward evaluation of the criticality levels related to AM of metallic parts. The proposition included a class adaption of criticality levels from the aviation industry where the load-bearing system used in aviation is compared to proposed options for a pressurized system within the O&G industry. Also, it was explicitly related to the valve body to enable a clearer view of the Additive Manufacturing Class-2 (AMC-2) decision and compare it to the adaption proposition.

A suggestion is to establish a catalogue of a selection of cases clearly defined in terms of asset requirements related to AMC levels due to their specific attributes (size, material, geometrical complexity). It could help stakeholders increase their knowledge of their asset inventory, machine capabilities, and the required path for qualification dependent on the level of criticality related to their asset inventory.

9.2 The Roadmap - Consolidation of Activites

The introductory meetings with Equinor and Moreld Capnor supported several valve body replacement options, which have been discussed for several years. The prolonged discussions are due to a non-unification regarding the solution options for replacing the valve bodies. As the on-demand solution has matured enough to be a real option, *the need for consolidation and mapping of activites* has followed.

Current work regarding thesis subjects is cumbersome since most assets have specific attributes. Hence, they often need separate case-level consultations. Therefore, the roadmap proposition attempts to consolidate these subjects deemed necessary for applying the on-demand solution to stakeholders in the O&G industry on the NCS.

9.3 AHP - Unbiased Selection of Alternatives

A critical part of the roadmap includes an analytical selection of the manufacturing method regarding the valve body where the results of the AHP favoured rapid casting as the solution.

The influencing factors, such as the cost and lead times, were the main contributors to the final decision, where material volume was second to last. Nonetheless, according to several decision-makers, the volume of material is also related to physical storage. It means that projects dedicated to screening assets related to their compatibility with AM can enable the transfer of an asset in physical storage to the digital warehouse.

The environmental impacts came in last. The reason may seem cynical, but according to some decision-makers, comparing the criteria with cost or lead time is unrealistic. Moreover, the implication leading to a situation where the $C_0 2$ emission and ecological footprints would influence the decision of a manufacturing method is unreasonable. Primarily when an on-demand acquisition is used in a situation where the spare part must be installed quickly to reduce downtime and resolve safety issues.

The results are based on the evaluation made by expert judgment. However, since more than one decision-maker answered the pairwise comparisons, human error or misunderstanding could have affected the results. In addition, due to time limitations, most of the decision-maker inputs were processed but not secured for mistakes by the same decision-maker. Ultimately, decision modelling analysis can help the organization make an unbiased selection based on pure data.

9.4 Case Review

The Reverse Engineering Process (REP) for the valve body was direct. The literature study delivered most of the details used in the case review, except tangible (realistic) manufacturing offers provided by companies within the AM and casting industry.

The selection for AM diverted from powder bed fusion (PBF) to the Direct Energy Deposition (DED) process, primarily due to the size of the valve body. Also, the availability of domestic AM providers with the required machinery and expertise aimed at the NCS contributed to the change in AM process.

The bids that have been provided in the report outcome related to the service provider are concealed. The reason is that the bids have been obtained as a second party and not directly from the manufacturer. Also, to present a neutral result in the decision-making between manufacturers.

10 Conclusion & Further Work

- **Standards:** The additive manufacturing class (AMC) can adopt aviation classes, which may streamline the criticality selection process for manufacturing metallic AM parts.
- **The On-demand Solution:** The literature review has proposed the *on-demand solution* integration with live monitoring. It could be used parallel with the existing conventional supply chain within the Norwegian O&G industry. In addition, there is an untapped resource in terms of an extensive catalogue of mechanical assets within offshore operators' inventory that has the opportunity to be manufactured by AM and rapid casting.
- **Analytical Hierarchy Process:** Deciding the current manufacturing process is done ad-hoc. Applying the non-biased decision-based modelling (AHP) has concluded that the method of rapid casting should add to the overall decision-making for valve body manufacturing.
- **The Roadmap:** The outcome of the thesis section has been consolidated into a step-by-step roadmap where individual sections can be applied and analysed. *The roadmap* has been applied to the valve body and allows the generic user to quickly assess the requirements for applying the on-demand solution and implementing part-specific decision analysis for other legacy assets.
- **Case Review**: The essential aspect of the case review is the tangible result related to the valve. The investigations concluded that both AM and rapid casting could be used for production. However, the face-to-face comparison of the two methods resulted in the order of two valve bodies manufactured with the rapid casting method. The primary enabler was the cost.

Further Work

This thesis has covered many topics related to asset-specific subjects. However, the fundamental element has been establishing a comprehensible overview of obtaining re-placement parts within the O&G industry on the NCS. The thesis is important regarding the continuation of subjects that are correlated and derived from the roadmap. Three of them are mentioned below

- **Classifying assets for AM & rapid casting:** There are a vast amount of legacy and non-legacy parts that have the possibility of being converted from a physical storage asset to a digital storage asset. A recommendation is to obtain access to asset inventories and initiate screenings based on step one in the proposed roadmap. However, instead focus on the physical aspects of existing machines, materials, and availability. The study could be based on a cost decision model of when one of the two manufacturing methods outperforms another for specific components.
- **Improved decision modelling:** The AHP used in this thesis is simplified, excluding process-specific technical factors and life cycle analysis. It can also be developed by constructing decision models for a range of goals in the roadmap. For example,

it would be interesting to look at the possibilities of implementing decision models directly into a system that can classify assets based on their attributes. It could then be linked to the goal of selecting the manufacturing method based on direct user input, which may decrease the need for ad-hoc decision-making.

- **Batch or method qualification:** AM has problems regarding the qualification of high criticality parts where sacrificial components must be manufactured in addition to the production part. A promising subject is to study the requirement for qualifying the method for a set of equal parts used for periodic production runs. The aim would be to diminish the need for sacrificial components during AMC-3 levels and increase AM use and productivity.

These subjects have the possibility of strengthening the activities proposed in the roadmap and increasing the rigidity of applying an on-demand solution. A significant contributor to implementing a digital ecosystem, digital warehousing and on-demand services are, in the end, dependent on the user experience. Therefore, it is advised to include the stakeholders on different levels from an early start.

The future aim should be to increase the catalogue of assets together with stakeholders and use it as benchmarks for attracting new users. In addition, the on-demand solution should strive to implement asset monitoring and identification, where the on-demand supply chain can be fully adapted to fit the requirements for the O&G industry on the NCS.

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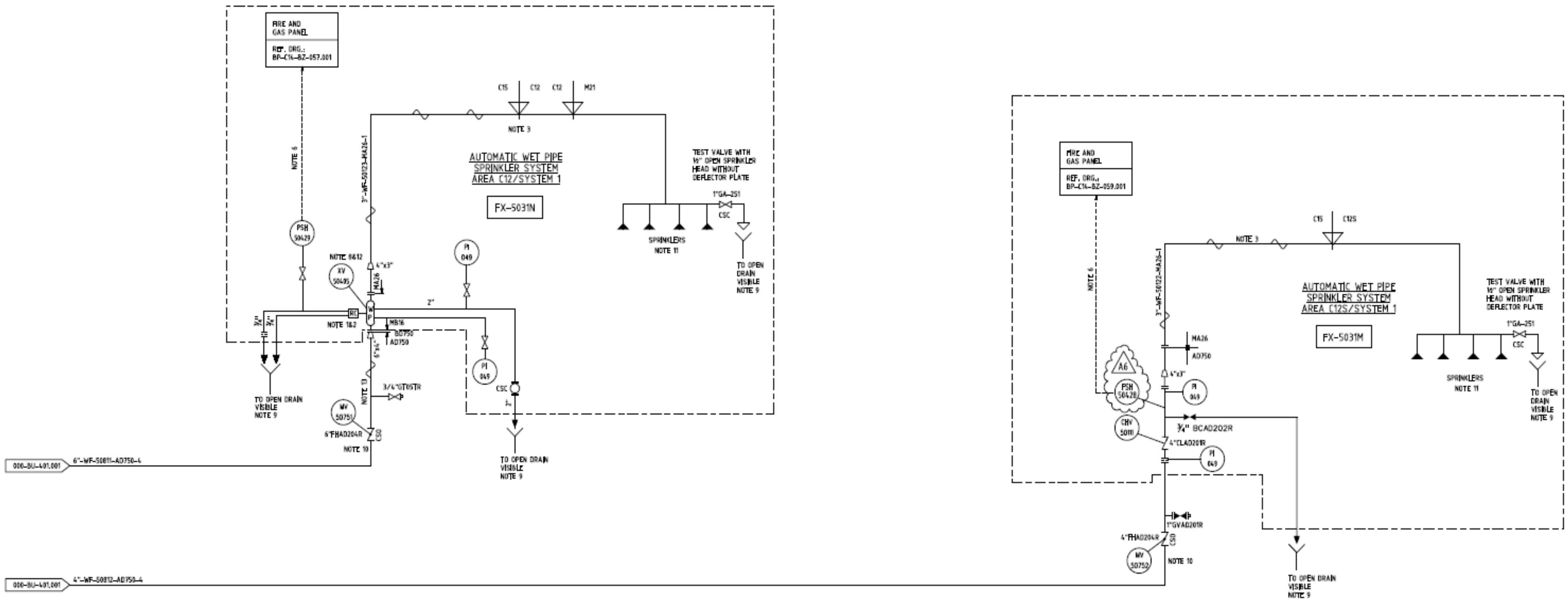
Appendix A - Valve Documentation

This Appendix contains documents related to piping diagrams, valve drawing, and pictures of the produced reference valve.

- **page 1:** Flow diagram of the existing solution
- **Page 2:** Flow diagram of the homemade solution
- **Page 3:** Updated drawing of the valve body
- **Page 4-5:** 3D printed reference valve with all sub-components

VALVE TAG NO	XV-50405	XV-50404
SERVICE	WET PIPE SPRINKLER SYSTEM VALVE	WET PIPE SPRINKLER SYSTEM VALVE
MIN FLOW m^3/h	87	57
MIN.PRESS BARG NOTE 1	10.58	10.58
LOCATION/SYSTEM NO	C15/C12-1	C15/C12S-1
VALVE TRIM NO	FX-5031N	FX-5031M



1. EMC/FIRE PROTECTION CONTRACTOR HYDRAULIC ANALYSIS INTERFACE.
2. LOCATED OUTSIDE C15.
3. PIPE TO BE HEAT TRACED AND INSULATED UP TO PENETRATION IN TO MODULE.
4.
5. FOR LOSS PREVENTION SYMBOLS SEE B00-BB-011.00.
6. SYSTEM INPUT FOR INITIALING SAFETY FUNCTIONS.
7. * TO BE SUPPLIED BY WORMALD INTERNATIONAL.
8. WET PIPE SPRINKLER VALVE WITH EXTERNAL TRIM. WORMALD INTERNATIONAL SUPPLY SEE DRAWING No. 90815/MISC/504 VALVE TO BE MOUNTED VERTICALLY WITH UPWARD FLOW.
9. DISCHARGE TO BE LOCALLY VISIBLE.
10. TO BE LOCATED ADJACENT TO SPRINKLER VALVE.
11. SPRINKLER AND TEST VALVE ARRANGEMENTS ARE DIAGRAMATIC ONLY. SEE WORMALD DRAWING No. 90815/C12-1/101 & 90815/C15-1/101 FOR DETAILS.
12. SYSTEM CONTROL VALVE GENERALLY LOCATED 15M MINIMUM FROM THE SYSTEM PROTECTED AREA.
13. SPOOL TO BE LINED WITH TK236.

NOTES

REV No.	DESCRIPTION	BY	CHKD	DATE	APP.D	DATE
A1	97-EB-017/EM-105248/D-39715	ØRK		26.03.98	RJ	05.98
A2	P103055/SB01-0121/QS03	ØRK	JKF	24.11.01	ÅK	24.11.01
A3	21155380	JOFR4	SUGEE	10.12.12	GIHAN	10.12.12
A4	22764552	MARMAD	YAQIN		LIJAA	27.08.14
A5	24587427	ANBJ2	ZIGIL	18.11.19	LIJAA	18.11.19
A6	24587427	ANBJ2	ZIGIL	13.05.20	LIJAA	13.05.20

DWG REF

CONTRACTOR

PROJECT No. 97 EB 017

equinor

PLTF: STATFJORD "B"

DRAWING TO BE KEPT UPDATED: YES [X] NO [ ]

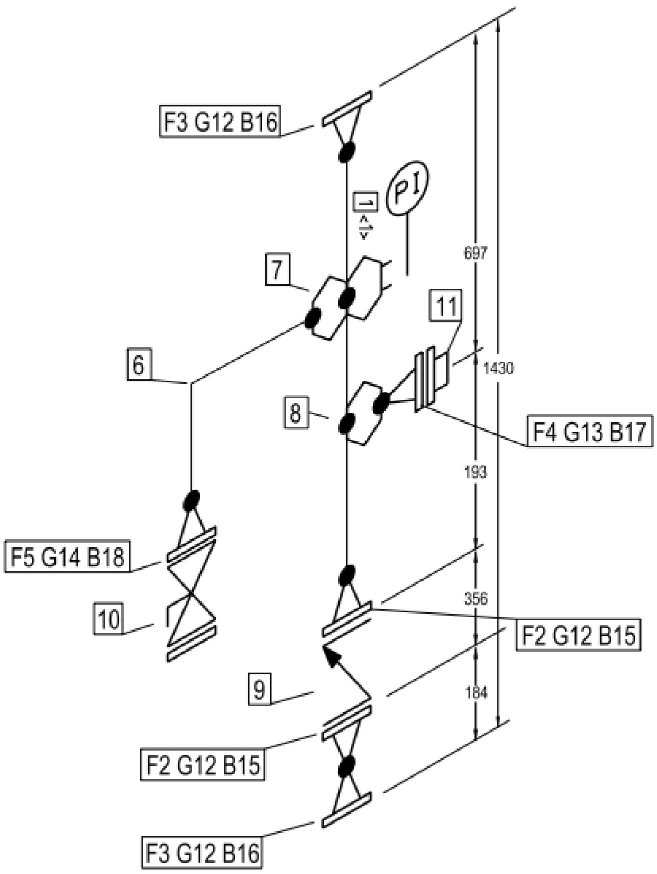
STATOIL SIGN.

TITLE

UTILITY FLOW DIAGRAM
WATER/AFFF FIRE PROTECTION
SYSTEM AREA C12, C12S

SYSTEM	DRAWING No.	REV.
SC	BP - C00 - BU - 401.001	A6

ST 1810



PT NO	DESCRIPTION	N.S. (INS)	QTY	WEIGHT	IFS ARTICLE NO
1	PIPE SMLS Sch 10S ASME B36.10/19 A790 Gr S32760	6	0,4		
2	FLANGE CL150 RF WN Sch 10S ASME B16.5 A182 F55	6	2		
3	ORIFICE FLANGE CL300 RF WN Sch 10S ASME B16.36 A182 F55	6	2		
4	FLANGE CL150 RF WN Sch 10S ASME B16.5 A182 F55	2	1		
5	FLANGE CL150 RF WN Sch 10S ASME B16.5 A182 F55	3/4	1		
6	ELBOW 90 LR Sch 40S ASME B16.9 A815 Gr S32760-S	3/4	1		
7	WELDOLET Sch 40S	3/4	1		
8	WELDOLET Sch 10S	2	1		
9	CHECH VALVE CL150 VDS CLAD201R	6	1		
10	BALL VALVE FB RF CL150 VDS BCAD202R	3/4	1		
11	FLOW SWITCH RF 150#	2	1		
12	GASKETASME B16.21 1mm COMPRESSED GLASSFIBRE	6	2		
13	GASKETASME B16.21 1mm COMPRESSED GLASSFIBRE	2	1		
14	GASKETASME B16.21 1mm COMPRESSED GLASSFIBRE	3/4	1		
15	BOLT STUD/2 nuts 3/4" X 110MM A193 B7 HDG/ A194 2H HDG		16		
16	BOLT STUD/2 nuts 3/4" X 150MM A193 B7 HDG/ A194 2H HDG		16		
17	BOLT STUD/2 nuts 5/8" X 90MM A193 B7 HDG/ A194 2H HDG		4		
18	BOLT STUD/2 nuts 1/2" X 70MM A193 B7 HDG/ A194 2H HDG		4		

Statoil

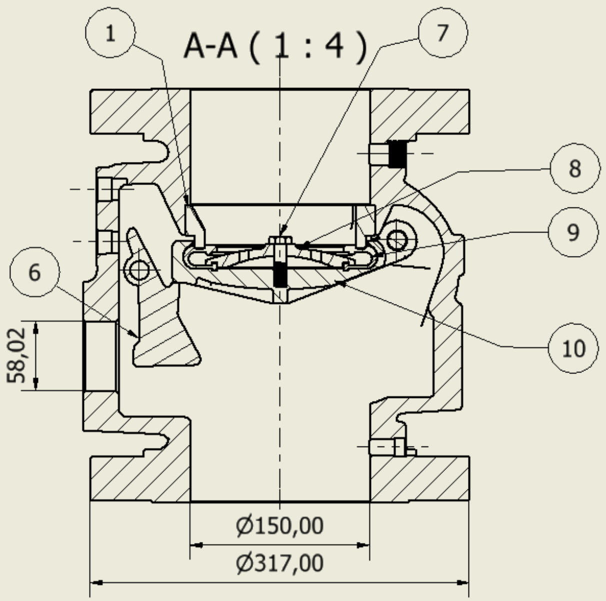
PLANT: PLANT NAME

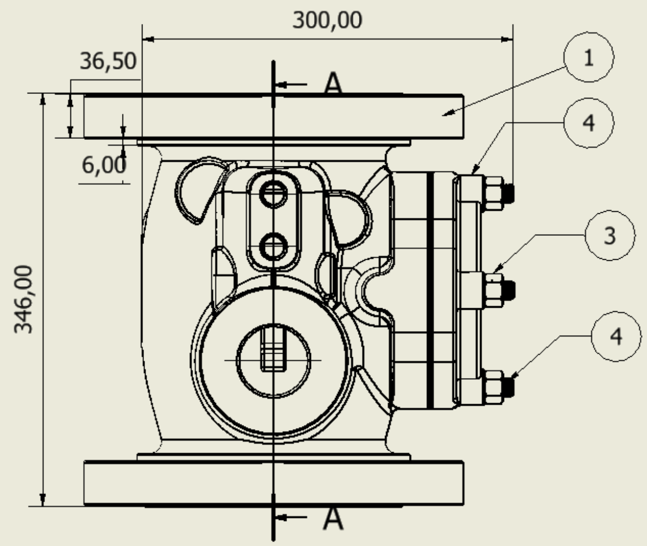
DRAWING TITLE: ASSEMBLY 6" 150# -

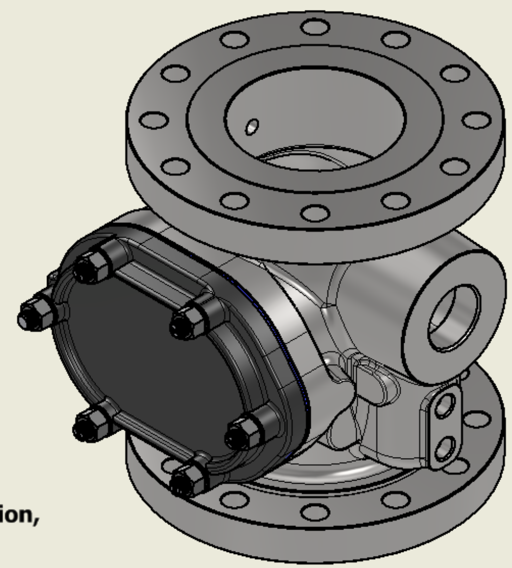
CONTR. NO -

REV.	DATE	REASON FOR ISSUE	PREPARED	CHECKED	APPROVED	SCALE	SIZE	AREA	SYSTEM	DRAWING NUMBER	REV.
						-	AT A4	-	-	-	01

BORDER: CP_A4







PARTS LIST			
ITEM	QTY	MATERIAL	DESCRIPTION
1	1	N/A	VALVE BODY
2	1	N/A	COVER PLATE
3	6	N/A	HEX NUT 5/8-11 BSW
4	6	N/A	5/8-11 UNC X 75 STUD
5	1	N/A	RELEASE LATCH
6	1	N/A	DISC SEAT
7	1	N/A	HEX HEAD SCREW M10X30
8	1	N/A	RUBBER SEAL CLAMP PLATE
9	1	N/A	RUBBER SEAL
10	1	N/A	DISC (CLACK)

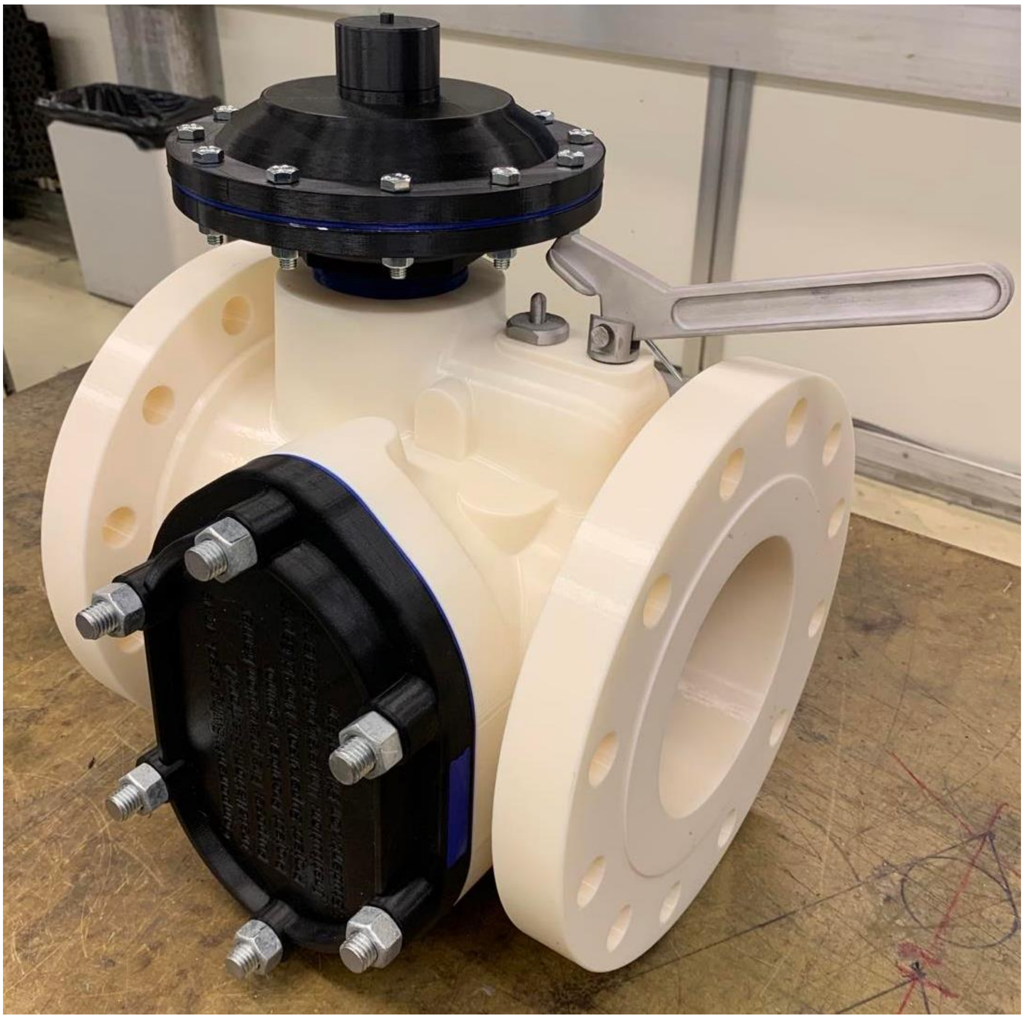
NOTE: To use suitable materials for qualification, follow DNVGL-ST-B203, API20S or NORSOK M001-NORSOK-M630, NORSOK-M650

Designed by	Checked by	Approved by	Date	Date
JEK				15.05.2022

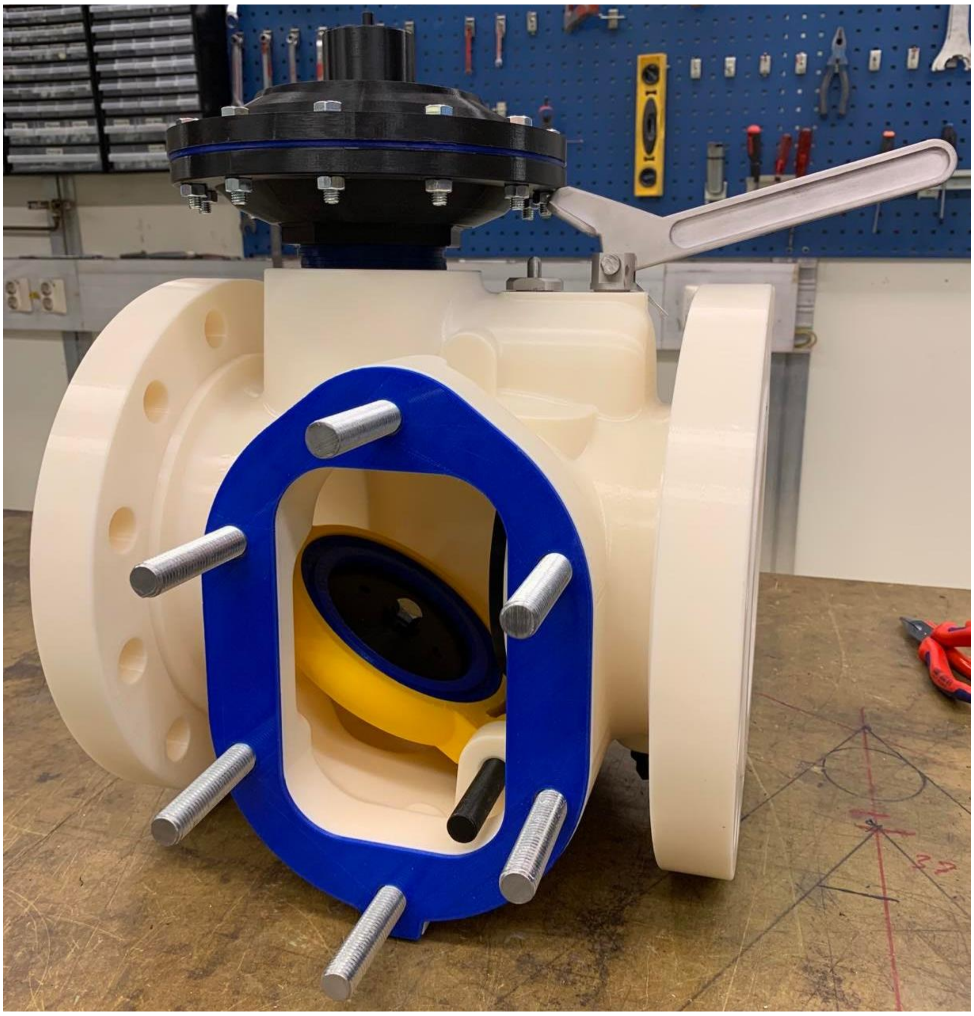
6" VALVE BODY

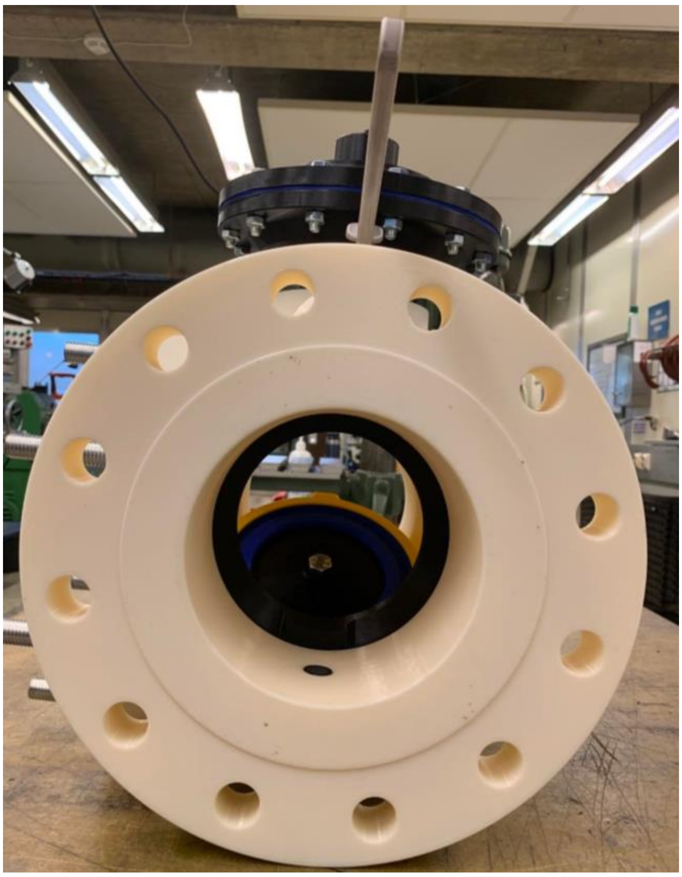
Edition	Sheet
	1 / 2

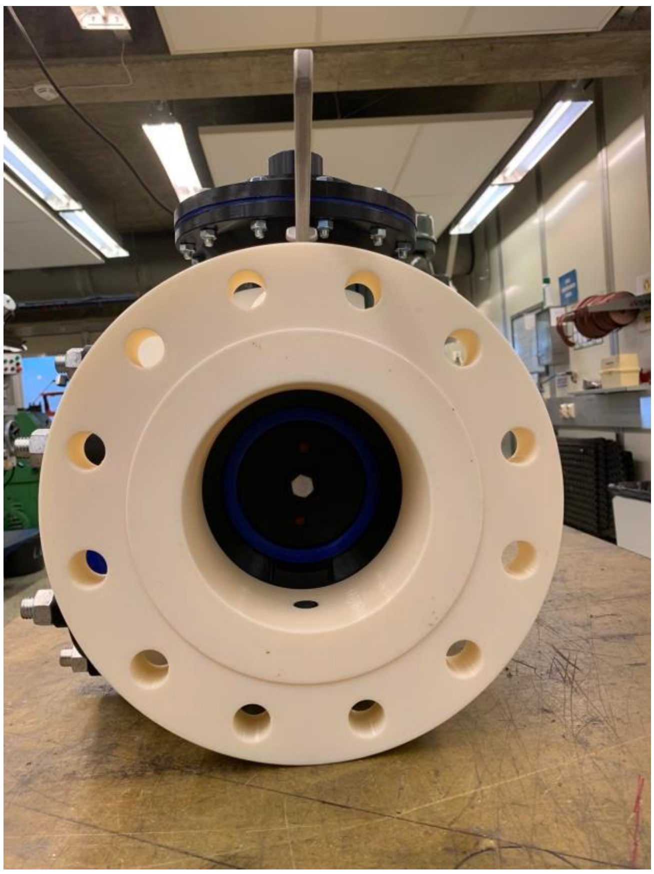
3D Printed Reference Valve



3D Printed Reference Valve







Appendix B - Standards & Material Documentation

This appendix reference to NORSOK standards. Pages are defined below:

- **page 1:** NORSOK overview
- **Page 2-3:** NORSOK-M001 utility system specification
- **Page 4-6:** 6Mo casting material specification
- **Page 7-9:** Titanium casting material specification
- **Page 10-11:** Requirements for material, dimensions, and design for valve accessories
- **Page 12:** Example of Qualification Test Record (QTR) of casting in sand moulding (obtained from Elingsen Indutech: www.ellingsenindutech.no

NORSOK Standards
for use in the oil and gas industry

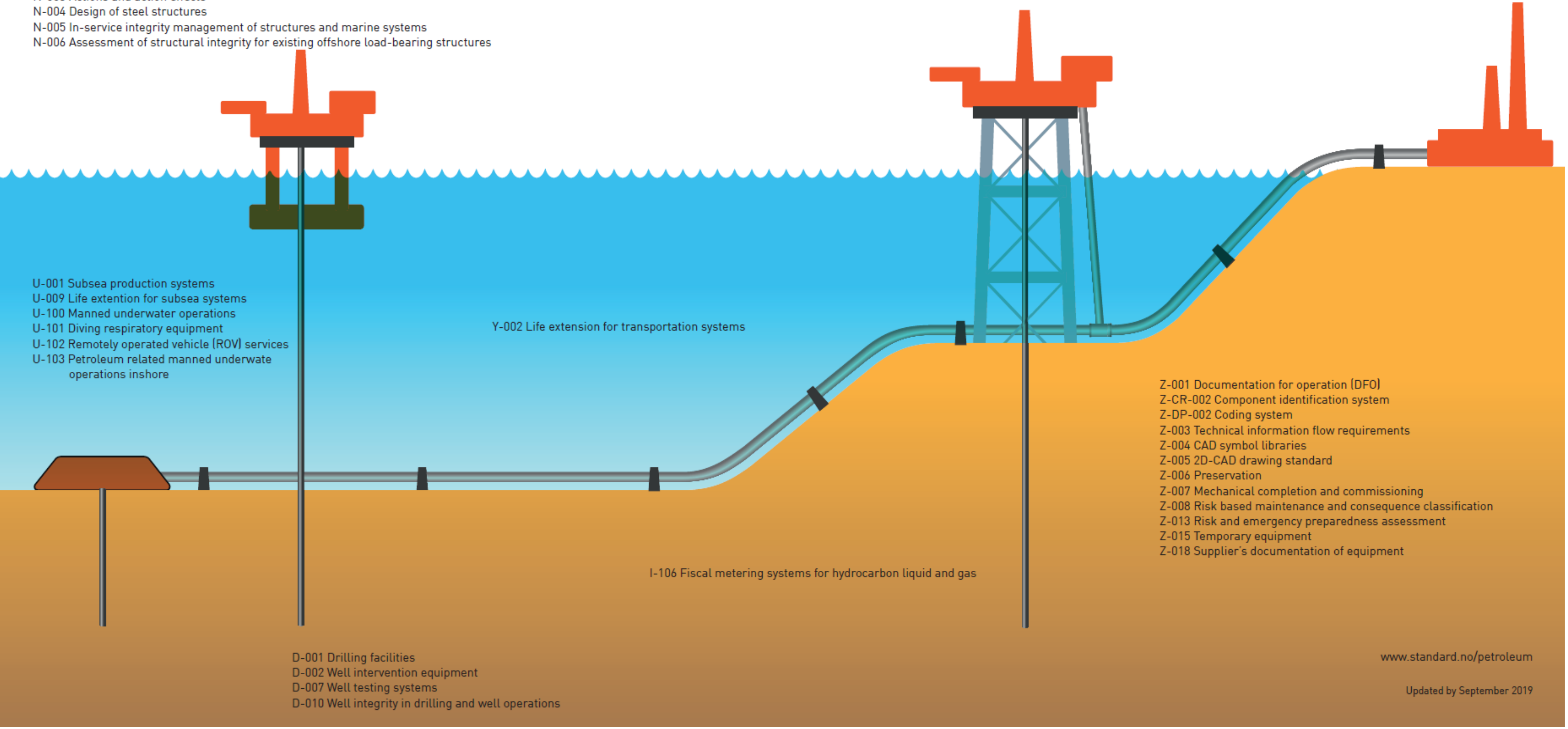
M-001 Materials selection
M-004 Piping and equipment insulation
M-101 Structural steel fabrication
M-102 Structural aluminium fabrication
M-120 Material data sheets for structural steel
M-121 Aluminium structural material
M-122 Cast structural steel
M-123 Forged structural steel
M-501 Surface preparation and protective coating
M-503 Cathodic protection
M-506 CO2 corrosion rate calculation model
M-601 Welding and inspection of piping
M-630 Material data sheets and element data sheets for piping

P-002 Process system design
R-001 Mechanical equipment
R-002 Lifting equipment
R-003 Safe use of lifting equipment
I-001 Field instrumentation
I-002 Safety and automation system (SAS)
L-001 Piping and valves
L-002 Piping system layout, design and structural analysis
L-003 Piping details
L-004 Piping fabrication, installation, flushing and testing
L-005 Compact flanged connections
H-003 Heating, ventilation and air conditioning (HVAC) and sanitary systems

S-001 Technical safety
S-002 Working environment
S-003 Environmental care
T-101 Telecom system design
T-003 Telecom systems for mobile offshore units
E-001 Electrical systems
C-001 Living quarters area
C-002 Architectural components and equipment
C-004 Helicopter decks on offshore installations

M-650 Qualification of manufacturers of special materials
M-710 Qualification of non-metallic sealing materials and manufacturers
S-WA-006 HSE-evaluation of contractors
R-005 Safe use of lifting and transport equipment in onshore petroleum plants

N-001 Integrity of offshore structures
N-003 Actions and action effects
N-004 Design of steel structures
N-005 In-service integrity management of structures and marine systems
N-006 Assessment of structural integrity for existing offshore load-bearing structures



U-001 Subsea production systems
U-009 Life extention for subsea systems
U-100 Manned underwater operations
U-101 Diving respiratory equipment
U-102 Remotely operated vehicle (ROV) services
U-103 Petroleum related manned underwate operations inshore

Y-002 Life extension for transportation systems

Z-001 Documentation for operation (DFO)
Z-CR-002 Component identification system
Z-DP-002 Coding system
Z-003 Technical information flow requirements
Z-004 CAD symbol libraries
Z-005 2D-CAD drawing standard
Z-006 Preservation
Z-007 Mechanical completion and commissioning
Z-008 Risk based maintenance and consequence classification
Z-013 Risk and emergency preparedness assessment
Z-015 Temporary equipment
Z-018 Supplier's documentation of equipment

I-106 Fiscal metering systems for hydrocarbon liquid and gas

D-001 Drilling facilities
D-002 Well intervention equipment
D-007 Well testing systems
D-010 Well integrity in drilling and well operations

www.standard.no/petroleum

Updated by September 2019

5.7.4 Other utility systems

ISO 21457, subclause 7.4.4 applies with the following additional requirement:

- Material selection for utility systems shall be in accordance with Table 6.

Table 6 – Materials for utility use

Service	Equipment	Materials	Notes
Fresh and potable water	Piping and vessels	GRP, type 22Cr duplex SS, Type 316 SS, Copper base alloys.	1
Open drain	Piping and vessels	Type 25Cr duplex SS, GRP/FRP	
Closed drain	Piping and vessels	Type 22Cr duplex SS, type 25Cr duplex SS, GRP/FRP	
Sewage	Piping	Type 316 SS, type 22Cr duplex SS, GRP/FRP.	2
Jet fuel	Piping	Type 22Cr duplex SS	
Dry fuel gas and diesel	Piping	Type 22Cr duplex SS	
	Tanks and vessels	Type 316 SS, type 22Cr duplex SS, carbon steel	3
Instrument air	Piping and vessels	Type 316 SS, type 22Cr duplex SS.	4
Instrumentation	Tubing	HVAC controlled environment: type 316 SS Marine: Type 6Mo SS, type 25Cr duplex SS	5
	Cable trays	Type 316 SS, aluminium, carbon steel HDG	6
Fire-fighting systems	Dry CO_2 systems	Carbon steel, CRA	
	Deluge system	See table 4	
	AFFF piping	Type 316 SS, type 22Cr duplex SS, FRP/GRP	
Freshwater / plant air / nitrogen	Piping, vessels and tanks	Type 316 SS, type 22Cr duplex SS, PEX	10
Lubrication and seal oil	Piping, vessels and tanks	Type 316 SS, type 22Cr duplex SS	5, 10
Hydraulic fluid	Piping and tanks	Type 316 SS, type 22Cr duplex SS.	10
Glycol	Piping, vessels and tanks	Type 316, type 22Cr duplex SS	10
Methanol	Piping, vessels and tanks	Type 316, type 22Cr duplex SS	10
Heating/cooling media	Piping and vessels	Carbon steel, type 22Cr duplex SS, CRA in heat exchangers	7, 8, 11
HVAC	Ventilation/air intake ducts	Type 316 SS, LDSS, Al alloys, carbon steel HDG	6
	Air handling units	Type 316 SS, LDSS, Al alloys	
	Seawater coils	Titanium.	
Miscellaneous chemical injection systems	Piping and tanks	FRP/GRP, type 316 SS, type 22Cr duplex SS, titanium grade 2	9

Notes

1. Large diameter piping and tanks can be made in internally coated carbon steel.
   Tanks not intended for potable water, shall in addition be cathodically protected. The national health authorities shall accept GRP, polypropylene and coating used for potable water tanks.
2. type 22Cr duplex SS for outdoor application
3. Diesel tanks in carbon steel should have a 3 mm corrosion allowance in the bottom section. In addition, the bottom and roof should be coated. Cathodic protection should be used only if corrosion products from the sacrificial anodes do not cause damage to the down-stream equipment. The same applies for use of Zn primers. No corrosion allowance is required for cathodically protected surfaces. Consider coating the entire diesel tank if corrosion products can be detrimental when stored product is utilized.
4. Type 316 SS is acceptable up to operating temperature 70°C provided located indoor in fully HVAC controlled environment and un-insulated.
5. In marine atmosphere there may be a high risk for localized corrosion of type 316 SS, in particular crevice corrosion under clamps. The use of alternative tubing material should be evaluated.
6. Hot dip galvanised carbon steel in fully HVAC controlled areas only.
7. Fresh-water heating and cooling media are normally treated with a corrosion inhibitor and an oxygen scavenger. In a freezing environment, it is normally mixed with TEG.
8. Requirements on internal cleanliness shall be considered when choosing materials for systems containing filters, nozzles and compact heat exchangers.
9. The combination of chemical and material should be considered in each case. Titanium grade 2, GRP or chlorinated polyvinyl chloride should be used for hypochlorite systems.
10. Lean duplex SS (LDSS) may be applicable for tanks, not for piping and pressure vessels
11. Plates in plate heat exchangers shall be made in titanium grade 1, alternatively in alloy 276 or C22

Materials selection for seawater systems as given in Table 4 of this standard shall apply. Temperature limitations for the different materials shall be as given in Table 10.

Table 4 – Materials for seawater systems

Systems/equipment	Materials	Notes
Vessels	Titanium, FRP/GRP, type 25Cr duplex SS	
Piping valves and inline instruments	Type 25Cr duplex SS, FRP/GRP, type 6Mo SS, titanium, carbon steel with polymeric lining.	1
Valves in GRP systems	FRP/GRP, Carbon steel with polymeric lining, NiAl bronze, titanium, type 25Cr duplex SS.	
Normally drained systems	Type 25Cr duplex SS, titanium.	
Pumps	Type 25Cr duplex SS	
Notes 1. For inline instruments alloy 625, alloy C276 and alloy C22 may be used in addition to materials listed		

MATERIAL DATA SHEET	MDS R16	Rev. 5

TYPE OF MATERIAL: Austenitic Stainless Steel, Type 6Mo

PRODUCT	***STANDARD***	***GRADE***	***ACCEPT. CLASS***	***SUPPL. REQ.***
Castings	ASTM A 351	CK-3MCuN CN-3MN	-	S6, S20
				Page 1 of 3

1. SCOPE	This MDS specifies the selected options in the referred standard and additional requirements which shall be added or supersede the corresponding requirements in the referred standard.
2. QUALIFICATION	Manufacturers and the manufacturing process used for manufacturing of product to this MDS shall be qualified in accordance with NORSOK Standard M-650.
3. MANUFACTURE	The manufacturing of products according to this MDS shall be carried out according to the M-650 qualified manufacturing procedure.
4. STEEL MAKING	The steel melt shall be refined with AOD or equivalent process. Remelting of AOD or equivalent steel in an electric furnace is acceptable. Use of internal scrap is not acceptable.
5. HEAT TREATMENT	Solution annealed at temperature ≥ 1225 °C. Components shall be placed in such a way as to ensure free circulation of heating and cooling media around each component during the heat treatment process including quenching.
6. CHEMICAL COMPOSITION	P ≤ 0,030 %
7. CORROSION TESTING	Corrosion test according to ASTM G 48 Method A is required. Test temperature shall be 50 °C and the exposure time 24 hours. The corrosion test specimen shall be at the same location as those for mechanical testing. Cut edges shall be prepared according to ASTM G 48. The complete specimen shall be pickled before being weighed and tested. Pickling may be performed for 5 minutes at 60 °C in a solution of 20 % HNO_3 + 5 % HF. The acceptance criteria are: - No pitting at 20 X magnification. - The weight loss shall be less than 4,0 g/m^2.
8. EXTENT OF TESTING	Tensile test and corrosion test shall be made for each melt and heat treatment load including any PWHT. A test lot shall not exceed 5000 kg.
9. TEST SAMPLING	Samples for mechanical testing shall realistically reflect the properties in the actual components. For castings with weight 250 kg or more the test block shall be integrally cast or gated onto the castings and shall not be removed from the castings until after the final quality heat treatment. Thickness of the test block shall be equal to the thickest part of the casting represented. For flanged components the largest flange thickness is the ruling section. Dimensions of test blocks and location of test specimens within the test blocks are shown in figures 1 and 2 for integral and gated test blocks respectively. The test specimens shall be taken within the cross hatched area and in a distance of T/4 from the ends. During any PWHT the test block shall be tack welded onto the casting.

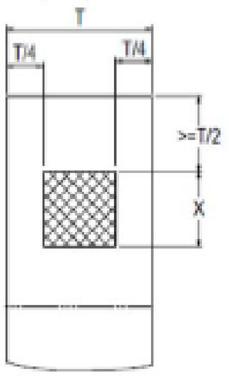


Fig.1 - Integral test block

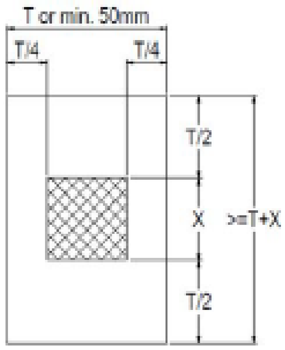


Fig. 2 - Gated test block

MATERIAL DATA SHEET			MDS R16	Rev. 5
TYPE OF MATERIAL: Austenitic Stainless Steel, Type 6Mo				
PRODUCT	***STANDARD***	***GRADE***	***ACCEPT. CLASS***	***SUPPL. REQ.***
Castings	ASTM A 351	CK-3MCuN CN-3MN	-	S6, S20
				Page 2 of 3

10. NON DESTRUCTIVE TESTING

NDT operators shall be qualified in accordance with ISO 9712 or equivalent.

Liquid penetrant testing:

- All accessible surfaces (including internal surfaces) of all castings shall be examined with Liquid Penetrant (PT). Surface examination of steel castings shall be in accordance with ASME VIII, Div. 1 Appendix 7. The testing shall be carried out after final machining. Non-machined surfaces shall be pickled prior to the testing.

Radiographic testing (RT):

- Method of radiography and acceptance criteria shall be in accordance with ASME VIII, Div. 1 Appendix 7.
- Extent of radiographic examination (RT) for valve castings shall be according to table below.

Extent of RT based on pressure class and valve size:							
Pressure Class:		*≤ 150*	*300*	*600*	*900*	*1500*	*≥ 2500*
Extent of RT	10 %	≥ 10"	≥ 10"	≥ 2"	≥ 2"	≥ 2"	≥ 2"
	100 %	Not applicable	Not applicable	≥ 20"	≥ 16"	≥ 6"	≥ 6"

- *Valve castings* shall be examined in the areas as defined by ASME B16.34 for special class valves and other critical areas as defined by valve designer. In addition castings shall be examined at abrupt changes in sections and at the junctions of risers, gates or feeders to the castings. When random examination (10 %) is specified, minimum one casting of each pattern including feeder and riser system in any purchase order with the foundry shall be examined. If defect outside acceptance criteria is detected, two more castings shall be tested, and if any of these two fails all items represented shall be tested.
- *Other type of castings:* Each casting shall be examined unless agreed otherwise. Testing shall be at abrupt changes in sections and at the junctions of risers, gates or feeders to the castings and other critical areas as defined by designer. Sketches of the areas to be tested shall be established and agreed.

11. SURFACE FINISH

White pickled. Shall be carried out after any blasting and shall include finished machined surfaces.

12. REPAIR OF DEFECTS

All major repairs shall be documented according to ASTM A 703 SR S20.

Post weld heat treatment (PWHT) is required after all weld repairs. For minor weld repairs, as defined by ASTM A 995, the PWHT may be excluded provided the welding procedure qualification shows that all specified properties, as specified in this MDS, can be fulfilled.

Repair welding shall be carried out with Ni-based consumable with enhanced Mo or Cr content compared to the base material. The S content shall not exceed 0,015 %. Welding consumables with matching chemical composition are acceptable provided solution annealing heat treatment after welding.

The repair welding procedure shall be qualified in accordance with ASTM A 488 and this MDS. The repair welding procedure qualification shall include the following:

- A cast plate shall be used for the test welding.
- A macro and corrosion test as specified above shall be carried out.
- Change specific make of filler metal (brand name) requires requalification.

All casting with major repairs shall be given a solution heat treatment after welding.

MATERIAL DATA SHEET			MDS R16	Rev. 5
TYPE OF MATERIAL: Austenitic Stainless Steel, Type 6Mo				
PRODUCT	***STANDARD***	***GRADE***	***ACCEPT. CLASS***	***SUPPL. REQ.***
Castings	ASTM A 351	CK-3MCuN CN-3MN	-	S6, S20
				Page 3 of 3

13. MARKING	The component shall be marked to ensure full traceability to melt and heat treatment load.
14. CERTIFICATION	The material manufacturer shall have a quality system certified in accordance with ISO 9001 and the system shall have undergone a specific assessment for the relevant materials. The material certification shall be in accordance with EN 10204 Type 3.1, and shall include the following information: - NORSOK M-650 Manufacturing Summary identification or QTR No. used; - Steel manufacturer in case remelted ingots are used, ref. Section 4. above; - Steel melting and refining practice; - Heat treatment condition. (Solution annealing temperature, holding time and quench medium shall be stated.)

MATERIAL DATA SHEET			MDS T02	Rev. 5
TYPE OF MATERIAL: Titanium Grade 2				
PRODUCT	***STANDARD***	***GRADE***	***ACCEPT. CLASS***	***SUPPL. REQ.***
Castings	ASTM B 367	C2	-	S2
				Page 1 of 2

1. SCOPE	This MDS specifies the selected options in the referred standard and additional requirements which shall be added or supersede the corresponding requirements in the referred standard.
2. QUALIFICATION	Manufacturers of product to this MDS shall be qualified in accordance with NORSOK Standard M-650.
3. MANUFACTURING PROCESS	The manufacturing of products according to this MDS shall be carried out according to the M-650 qualified manufacturing procedure.
4. HOT ISOSTATIC PRESSING	All castings shall be subject to Hot Isostatic Pressing (HIP). All castings, which due to size limitations cannot be HIP, shall be heat treated and radiographed. Heat treatment is also required for all weld repairs carried out after HIP.
5. α-CASE	For castings manufactured to this MDS α-case in the casting surface shall be completely removed at the foundry from following locations: - All surfaces, which shall be machined. - All weld bevels including an area of 20 mm on each side of the bevel. - All highly stressed areas including areas prone to fatigue. Otherwise the acceptance of α -case shall be agreed between the foundry and the customer at order placement. Procedure for removal of α-case shall be established. NOTE: Alpha-case (TiO) is a very hard and brittle surface layer, which is formed as a result of reaction between the molten titanium and some type of mould binders, e.g. periclase. The thickness of the alpha-case is dependent on the cooling rate during solidification. The heavier the casting wall, the thicker the alpha-case layer. The alpha case makes machining difficult, may cause cracking during welding and shallow micro cracks may appear during liquid penetrant examination.
6. EXTENT OF TESTING	Tensile testing is required for each heat and HIP batch or heat treatment load.
7. TEST SAMPLING	Samples for mechanical testing shall realistically reflect the properties in the actual components. Samples for production testing shall be cut from the gating system of the casting. For castings with weight 150 kg and above the test blocks shall be integrally cast with the casting. Size of the test block shall be 140 mm in length and 80 mm in height with thickness (T): - T = 22 mm for t ≤ 30 mm. - T = 50 mm for 30 < t ≤ 60 mm - T = 75 mm for t > 60 mm *NOTE: t = section (shell) thickness of castings. For flanged components the largest flange thickness is the ruling thickness.* Test samples shall accompany the castings through HIP and any heat treatment, chemical cleaning process or any other operation that may alter metallurgical or mechanical properties.

MATERIAL DATA SHEET			MDS T02	Rev. 5
TYPE OF MATERIAL: Titanium Grade 2				
PRODUCT	***STANDARD***	***GRADE***	***ACCEPT. CLASS***	***SUPPL. REQ.***
Castings	ASTM B 367	C2	-	S2
				Page 2 of 2

8. NON DESTRUCTIVE TESTING

NDT operators shall be qualified in accordance with ISO 9712 or equivalent.

Liquid penetrant testing:

- All accessible surfaces (including internal surfaces) of all castings shall be examined with Liquid Penetrant (PT). Surface examination of steel castings shall be in accordance with ASME VIII, Div. 1, Appendix 7.

Radiographic testing (RT):

- Method of radiography and acceptance criteria shall be in accordance with ASME VIII, Div. 1, Appendix 7.
- Extent of radiographic examination (RT) for valve castings shall be according to table below.

Extent of RT based on pressure class and nominal size:			
Pressure Class:		*≤ 150*	*300*
Extent of RT	10 %	≥ 10"	≥ 10"
	100 %	Not applicable	Not applicable

- *Valve castings* shall be examined in the areas as defined by ASME B16.34 for special class valves and other critical areas as defined by valve designer. In addition castings shall be examined at abrupt changes in sections and at the junctions of risers, gates or feeders to the castings. When random examination (10 %) is specified, minimum one casting of each pattern including feeder and riser system in any purchase order with the foundry shall be examined. If defect outside acceptance criteria is detected, two more castings shall be tested, and if any of these two fails all items represented shall be tested.
- *Other type of castings:* Each casting shall be examined unless agreed otherwise. Testing shall be at abrupt changes in sections and at the junctions of risers, gates or feeders to the castings and other critical areas as defined by designer. Sketches of the areas to be tested shall be established and agreed.

9. MARKING

The component shall be marked to ensure full traceability to melt and heat treatment lot.

10. CERTIFICATION

The material manufacturer shall have a quality system certified in accordance with ISO 9001 and the system shall have undergone a specific assessment for the relevant materials.

The material certificate shall be issued in accordance with EN 10204 Type 3.1 and shall include the following information:

- NORSOK M-650 Manufacturing Summary identification or QTR No. used;
- Name of HIP manufacturer.
- HIP parameters (e.g. temperature, time at temperature and pressure).
- If HIP is replaced by radiography.
- If heat treated, ref. Section 4, the heat treatment conditions shall be stated.

<table>
<tr><td colspan="3">MATERIAL DATA SHEET</td><td>MDS T02</td><td>Rev. 5</td></tr>
<tr><td colspan="5">TYPE OF MATERIAL: Titanium Grade 2</td></tr>
<tr><td>PRODUCT</td><td>STANDARD</td><td>GRADE</td><td>ACCEPT. CLASS</td><td>SUPPL. REQ.</td></tr>
<tr><td>Castings</td><td>ASTM B 367</td><td>C2</td><td>-</td><td>S2</td></tr>
<tr><td colspan="4"></td><td>Page 2 of 2</td></tr>
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- *Valve castings* shall be examined in the areas as defined by ASME B16.34 for special class valves and other critical areas as defined by valve designer. In addition castings shall be examined at abrupt changes in sections and at the junctions of risers, gates or feeders to the castings. When random examination (10 %) is specified, minimum one casting of each pattern including feeder and riser system in any purchase order with the foundry shall be examined. If defect outside acceptance criteria is detected, two more castings shall be tested, and if any of these two fails all items represented shall be tested.
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9. MARKING

The component shall be marked to ensure full traceability to melt and heat treatment lot.

10. CERTIFICATION

The material manufacturer shall have a quality system certified in accordance with ISO 9001 and the system shall have undergone a specific assessment for the relevant materials.

The material certificate shall be issued in accordance with EN 10204 Type 3.1 and shall include the following information:

- NORSOK M-650 Manufacturing Summary identification or QTR No. used;
- Name of HIP manufacturer.
- HIP parameters (e.g. temperature, time at temperature and pressure).
- If HIP is replaced by radiography.
- If heat treated, ref. Section 4, the heat treatment conditions shall be stated.

ELEMENT DATA SHEET	EDS NBO2	Rev. 3
Title: Body/Bonnet bolting for valves		Page 1 of 2

1. SCOPE

This document specifies acceptable bolting materials for body/bonnet bolting for valves in different body/bonnet materials.

2. ACCEPTABLE BOLTING MATERIALS

The table below lists acceptable materials for body/bonnet bolting. Where a MDS is referred to, the requirements on the MDS shall apply. The valve manufacturer shall verify the suitability of material selection with respect to thermal expansion and allowable stress.

Bolting that can be exposed directly to a sour environment, or buried, insulated, equipped with flange protectors or otherwise denied direct atmospheric exposure, shall be in M-grade material.

"Through-bolted" fastener is used in through holes that are not threaded, while "integrated" bolting is used in threaded holes.

Fastener material grade	MDS	Note	Valve body & bonnet material							
			CS	LTCS	SS316	22Cr duplex	25Cr duplex	6Mo HC	6Mo SW	Ti
A 320 Gr L7/A 194 Gr 7	X07	1	I/TB	I/TB	I/TB	I/TB	I/TB	I/TB	I	
A 320 Gr L7M/A 194 Gr 7M	X07	1	I/TB	I/TB	I/TB	I/TB	I/TB	I/TB	I	
A 320 Gr B8M/A 194 Gr 8M	S03	3			I/TB					
A 320/A 194 UNS S32750/ S32760	D59/ D60					I/TB	I/TB		I/TB	I/TB
A 468/F 467 Gr Ni625	N03				I/TB			I/TB	I/TB	I/TB
A 468/F 467 Gr Ti5		2								I/TB
A 453 Gr 660 Class D	N04	3, 4			I	I	I	I	I	
A 1014 UNS N07718	N05				I/TB	I/TB	I/TB	I/TB	I/TB	I/TB
NOTES			6	6	5, 6	6	6	6	6	6

NOTES

1. All items shall be hot dip galvanized in accordance with ASTM A 153 (or equivalent coatings in accordance with BS 729 or NS 1970).
2. Each bolt and nut shall be marked on the end/head to ensure full traceability to melt and heat treatment lot.
3. Load bearing part of the bolt shall not be exposed to the marine environment.
4. Special considerations with respect to thermal expansion are required when used in ferritic and duplex stainless steels. Stress rupture test is not required.
5. For integral bolting other type 316 bolting material from ASME B31.3 table A-2 is also considered acceptable.
6. Valve manufacturer to check the bolt material suitability with respect to thermal expansion and allowable stress.

Legends

CS	carbon steel
LTCS	low temperature carbon steel
6Mo HC	type 6Mo for hydrocarbon service
6Mo SW	type 6Mo for seawater service
Ti	titanium grade 2

Legends

I	accepted for integrated fasteners
TB	accepted for "Trough-bolted" fasteners
VDS	valve data sheet

ELEMENT DATA SHEET	EDS NBO2	Rev. 3
Title: Body/Bonnet bolting for valves		Page 2 of 2

3. GENERAL REQUIREMENTS TO VALVE BOLTING

3.1 Dimensions and shape

Bolts: Threading shall be in accordance with ASME B1.1, class 2A fit for diameters 1 inch and smaller (UNC series) and 8 pitch thread series for 1 1/8 inch and larger.

Nuts: Threading shall be in accordance with ASME B1.1, UNC series for diameters 1 inch and smaller with a class 2B fit, and 8 UN series for diameter 1 1/8 inch and larger with a class 2B fit.

Nuts shall be ASME heavy HEX. series, double chamfered. Dimensions shall conform to ASME B18.2.2.

3.2 Hardness

Hardness shall be tested and the maximum hardness shall not exceed 35 HRC or 328 HB.

3,3 Surface protection

All low alloyed steel bolts, nuts and washers shall be hot dipped galvanized according to ASTM A 153 or ISO 10684.

The zinc coating on threads shall not be subjected to cutting, rolling or finishing tool operation.

Nuts may be tapped after galvanizing.

3.4 Valve design rules for bolting

For valves that are required to comply with ASME B16.34, rules of par. 6.4, shall apply. Otherwise, allowable stress shall be evaluated according to ASME VIII, Div. 1 or 2.

3.5 Certification

The material manufacturer shall have a quality system certified in accordance with ISO 9001 and the system shall have undergone a specific assessment for the relevant materials.

The material certificate shall be issued in accordance with EN 10204 as follows:

- Studs Grade B7, B7M: Type 2.2
- Nuts Grade 2H, 2HM: Type 2.2
- Studs Grade L7, L7M: Type 3.1
- Nuts Grade 4, 7, 7M: Type 3.1
- All stainless steel and non ferrous grades and products: Type 3.1

FAS TEKeVOLUTION	Qualification Test Record (QTR) NORSOK-M650	QTR. No.: 5A-S Rev.No.: 5

Manufacturer name/address/ Web Page:	FAS Fonderia Acciai Speciali S.p.A. S.S. 78, km 6 Urbisaglia MC (Italy) www.fonderiafas.it		
Reference Standard	NORSOK M-650 Ed.4		
Material designation and MDS No.:	ASTM A995 Gr. 5A; MDS D56 rev 4		
Manufacturing summary doc. No.:	MS 5A-S	Rev.No.:	4
Products and manufacturing process(es):	CASTING IN SAND MOULDING		
Mandatory condition and sub-contractors:	RAW MATERIAL by: VALBRUNA S.p.A. (VC - ITALY) PICKLING by: DAFRAM (MC - ITALY)		
Other information:	Renewal of qualification of the present QTR is to meet and satisfy point 6.2 of the NORSOK M-650 Ed.4. The complete dossier consisting of hystorical records and statistical data has been produced to confirm the aforementioned requirements		
Qualification Expires:	Aug 2021		

Tested and Qualified Thickness and weight

Products and manufacturing process(es):	Test record No.	Tested thickness mm	Qualified thickness Up to mm	Test piece weight kg	Qualified weight Up to kg
Casting Valve Body in sand moulding	(see detail on dossier)	95	95	263	All

Qualification/Acceptance signature

Manufacurer:	*Prepared by/Date: 31/08/2016* Andrea Vitali	*Checked by/Date: 31/08/2016* Simone Baldoni

The manufacturer and this QTR are evacuate and found to be in compliance with the requirements of NORSOK M-650 for supply of the above listed products and materials.

This acceptance does not exempt any purchaser from his responsibility to ensure that this qualification is valid for his products within the essential variables of NORSOK M-650.

Qualified/Accepted by *(company name/address):* *DNV GL* *Via Energy Park 14* *20871 Vimercate (MB)*	*Signature/Date:* 2016-09-5

Appendix C - AHP Documentation

Appendix C presents the questionnaire that is used for providing data for the decision making analysis related to the analytical hierarchy process.

- **Page 1:** Description
- **Page 2:** Example of pairwise comparison
- **Page 3:** The hierarchy
- **Page 4:** Criteria definition and descriptions
- **Page 5-8** The pairwise comparisons
- **Page 9-10:** Results from the sensitivity analysis

Analytical Hierarchy Process by Pairwise Comparison

Prepared by Jon Erik Karlsen

Abbreviations

- **AM – Additive manufacturing → (3D printing)**

Goal

The selection of a *manufacturing method based on a pairwise comparison of key performance indicators related to supply chain parameters such as cost, lead time, the volume of material, environmental impacts, etc*

Approach

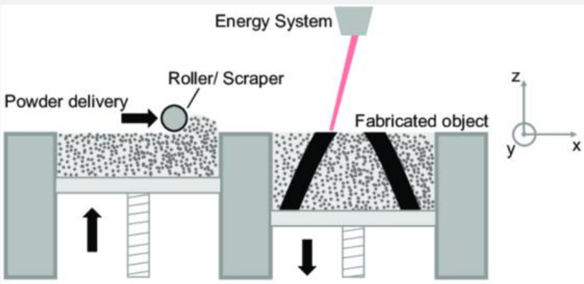
Experienced personnel answer the pairwise comparisons questions, which then are accumulated and processed based on a decision-making algorithm

Output

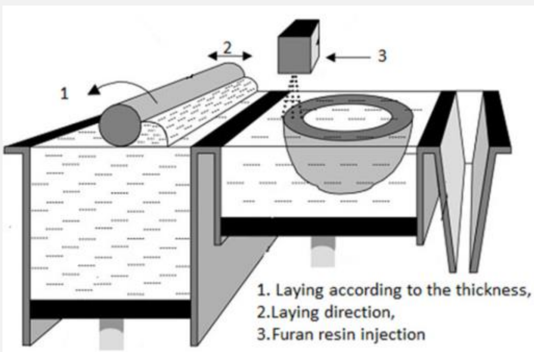
The results provide a rational benchmark for the selection of a manufacturing alternative. **The result will be used for further guidance, NOT as a definitive selection**

Manufacturing alternatives

- **AM (Metal 3D-printing):** 3D printing process is used for producing the valve where a metal powder is distributed on a build plate and solidified by a high-powered laser beam layer by layer. When completed, the part can be recovered for further processing



- **3D-casting (Rapid Casting):** a sand mold is produced by AM, then the mold is used for pouring liquid metal into the mold cavities. When solidified, the part can be recovered for further processing



Example of a Pairwise Comparison

- ➢ Read one question and compare the alternatives against each other
- ➢ From the table, select a value of the intensity of importance.
- ➢ Mark your choice of value into the pairwise comparison

Scale of relative importance

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contributes equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7 ✖	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Compromise of adjacent intermediate values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the *selection of spare part manufacturing method?*

Spare part lead time																*Spare part cost*
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
		R7						X						R7		
Left (L)								**L=R**	**Right (R)**							

Scenario 1:
If your evaluation of "*spare part cost*" *is strongly favoured compared to "Spare part lead time*" then enter X *on the right-hand side (R)* → *R7*

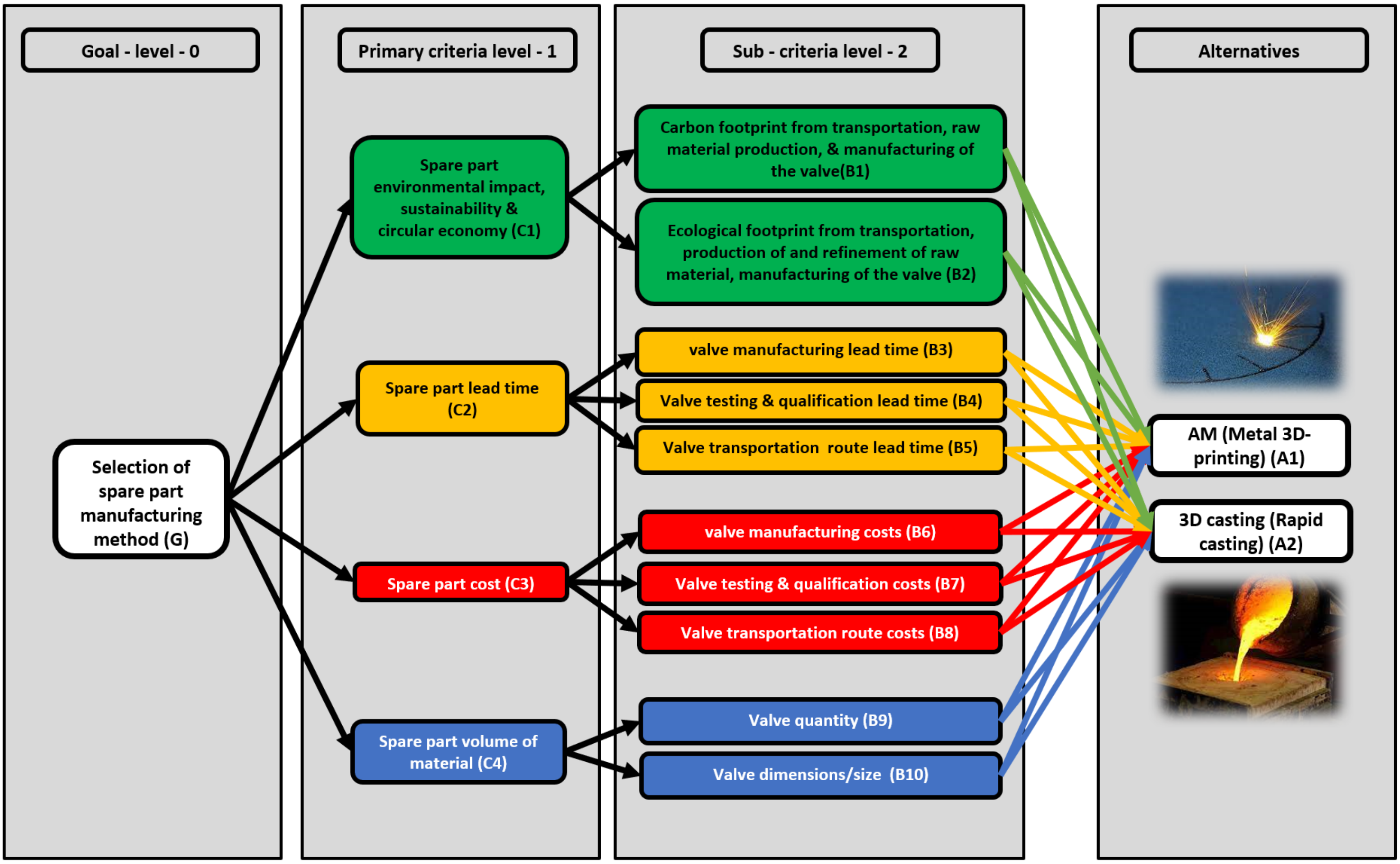
Scenario 2:
If your evaluation of "*spare part cost*" *is equally important compared to " Spare part lead time*" then enter X *in the centre* → *1*

Scenario 2:
If your evaluation of "*spare lead time*" *is strongly favoured compared to "Spare cost" then enter X* on *the left-hand side (L)* → *L7*

- **Use the provided link to answer the questions of pairwise comparison**
- https://docs.google.com/forms/d/e/1FAIpQLScgLQH6-0BMjGzeZAmxGM7FNNU1ShX1u2o-cg9kVya2P-82nw/viewform?usp=sf_link

Analytical Hierarchy Process – The Hierarchy

The following pages are for *bookkeeping and specifics* of the hierarchy criteria. No further reading is necessary to answer the comparison questions provided in the link on the previous page.



Analytical Hierarchy Process – Hierarchy Specifics

Goal level – 0	Definition	Description
G	**Selection of spare part manufacturing method**	**It is based on the reverse engineering process where realistic manufacturing options for the valve have been discussed and revised**

Criteria level – 1	Definition	Description
C_1	**Spare part environmental impact, sustainability & circular economy**	Regulations increase the demand for documentation related to supply chain activities that may negatively affect the environment.
C_2	**Spare part lead time**	The lead time is dependent on material and machine/process availability, part quantity, manufacturing location, amount of manufacturing activities, qualification needs, transport, and border customs.
C_3	**Spare part cost**	The main factors controlling spare part costs are manufacturing method, material, spare part quantity, qualification needs, and transportation.
C_4	**Spare part volume of material**	Part quantity, dimensions, geometry, and density controls the total amount of material volume.

Sub – criteria level – 2	Definition	Description
B_1	**Carbon footprint from transportation, raw material production, & manufacturing of the valve**	The direct effects of activities that produce emissions that contribute to global warming
B_2	**Ecological footprint from transportation, production of & refinement of raw material, manufacturing of the valve**	It aims at activities that harm the atmosphere, environment, and biological systems. Examples are CFCs, acid water, heavy metals, etc.
B_3	**valve manufacturing lead time**	Manufacturing activities include operations provided by personnel and machines such as pre-processing (CAD), building or casting the part, and post-processing (heat treatment, machining, etc.)
B_4	**Valve testing & qualification lead time**	Activities within qualification depend on the needs but can be destructive or NDT. The preparations and activities for analysis must also be included.
B_5	**Valve transportation route lead time**	Local or non-local manufacturing and testing options may impact the total lead time together with border customs.
B_6	**valve manufacturing costs**	Main costs are dependent on personnel, manufacturing method, and material selection.
B_7	**Valve testing & qualification costs**	Costs depend on the criticality of manufacturing, i.e., qualification requirements and testing personnel.
B_8	**Valve transportation route costs**	Type of transportation (sea, air, land), local or non-local (customs) influence the total transportation costs of the valve.
B_9	**Valve quantity**	The amount of valves that are needed, the valve has an initial batch request of 26 parts but can be increased.
B_{10}	**Valve dimensions/size**	The dimension and size determine the geometry that controls the valve's total volume.

Alternatives	Definition	Description
A_1	**AM (Metal 3D-printing)**	The valve is manufactured layer-by-layer by direct energy deposition or powder bed fusion.
A_2	**3D casting (Rapid casting)**	The valve is manufactured by producing sand molds by using binder jetting (3D-printing) and pouring the metal into the finished sand molds

Pairwise Comparison – Level 1

1

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***selection of spare part manufacturing method?***																
Spare part environmental impact, sustainability & circular economy									***Spare part lead time***							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

2

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***selection of spare part manufacturing method?***																
Spare part environmental impact, sustainability & circular economy									***Spare part cost***							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

3

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***selection of spare part manufacturing method?***																
Spare part environmental impact, sustainability & circular economy									***Spare part volume of material***							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

4

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***selection of spare part manufacturing method?***																
Spare part lead time									***Spare part cost***							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

5

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***selection of spare part manufacturing method?***																
Spare part lead time									***Spare part volume of material***							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

6

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***selection of spare part manufacturing method?***																
Spare part cost									***Spare part volume of material***							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Pairwise Comparison – Level 2

7 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or *benefit the* ***spare part environmental impact, sustainability & circular economy*** ?

Carbon footprint from transportation, raw material production, & manufacturing of the valve	*Ecological footprint from transportation, production of and refinement of raw material, manufacturing of the valve*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

8 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***spare part lead time?***

valve manufacturing lead time	*Valve testing & qualification lead time*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

9 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***spare part lead time?***

valve manufacturing lead time	*Valve transportation route lead time*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

10 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***spare part lead time?***

Valve testing & qualification lead time	*Valve transportation route lead time*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

11 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***spare part cost?***

valve manufacturing costs	*Valve testing & qualification costs*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

12 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***spare part cost?***

valve manufacturing costs	*Valve transportation route costs*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
x																

13 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***spare part cost?***

Valve testing & qualification costs	*Valve transportation route costs*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
						x										

14 How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***spare part volume of material?***

Valve quantity	*Valve dimensions/size*

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Pairwise Comparison – Alternatives

15

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit *Carbon footprint from transportation, raw material production, & manufacturing of the valve*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

16

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit *Ecological footprint from transportation, production of and refinement of raw material, manufacturing of the valve*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

17

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the *valve manufacturing lead time*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

18

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the *valve testing & qualification lead time*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

19

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the *valve transportation route lead time*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

20

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the *valve manufacturing costs*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

21

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the *Valve testing & qualification costs*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

22

How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the *Valve transportation route costs*																
AM (Metal 3D-printing)									*3D casting (Rapid casting)*							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Pairwise Comparison – Alternatives Continued

23

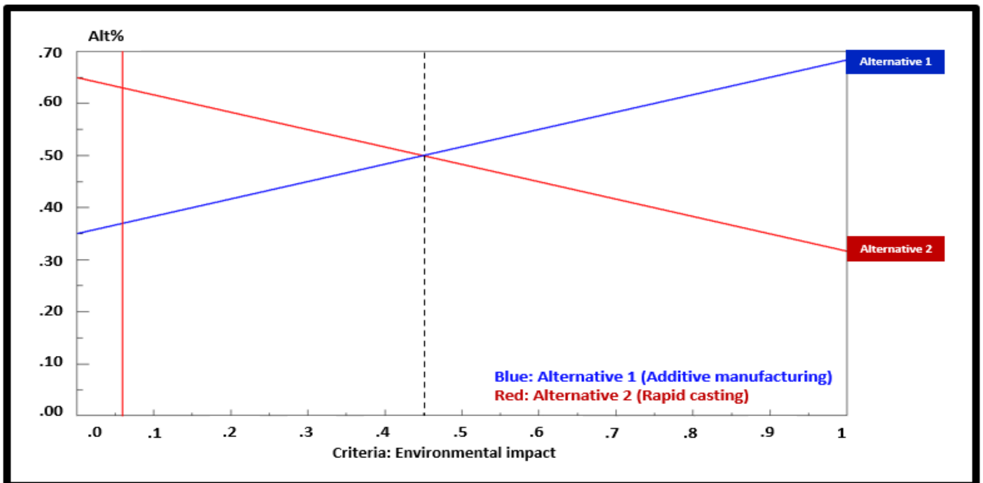
How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***Valve quantity***																
AM (Metal 3D-printing)																*3D casting (Rapid casting)*
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

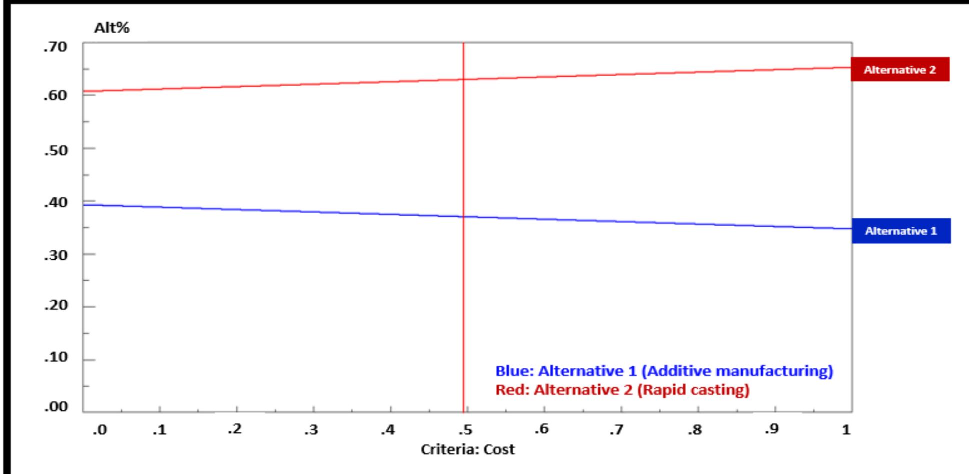
24

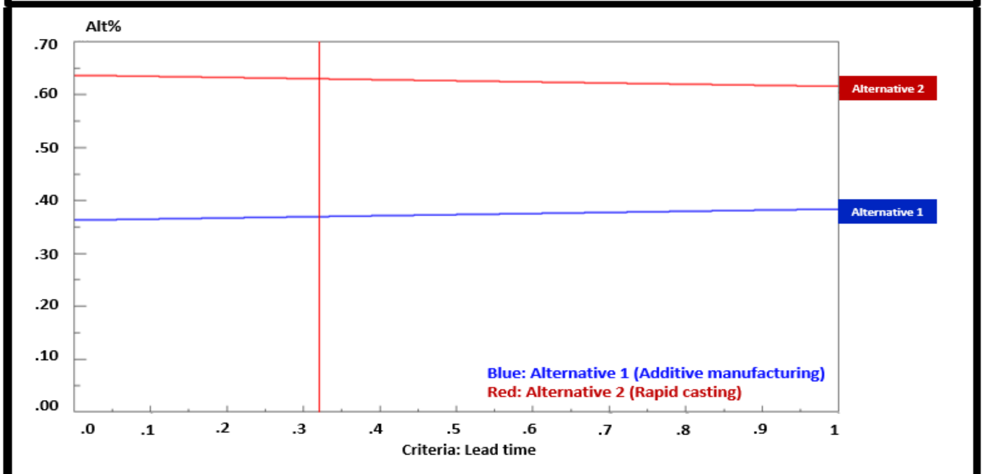
How strongly does one of the alternatives below contribute to dominate, influence, satisfy, or benefit the ***Valve dimensions/size***																
AM (Metal 3D-printing)																*3D casting (Rapid casting)*
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

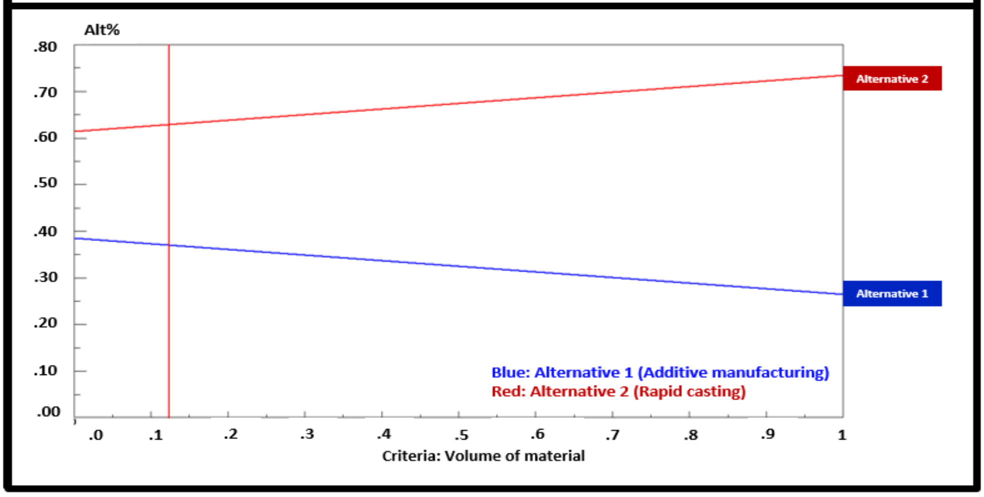
Thank you for your participation!

Results – Gradient Sensitivity Analysis

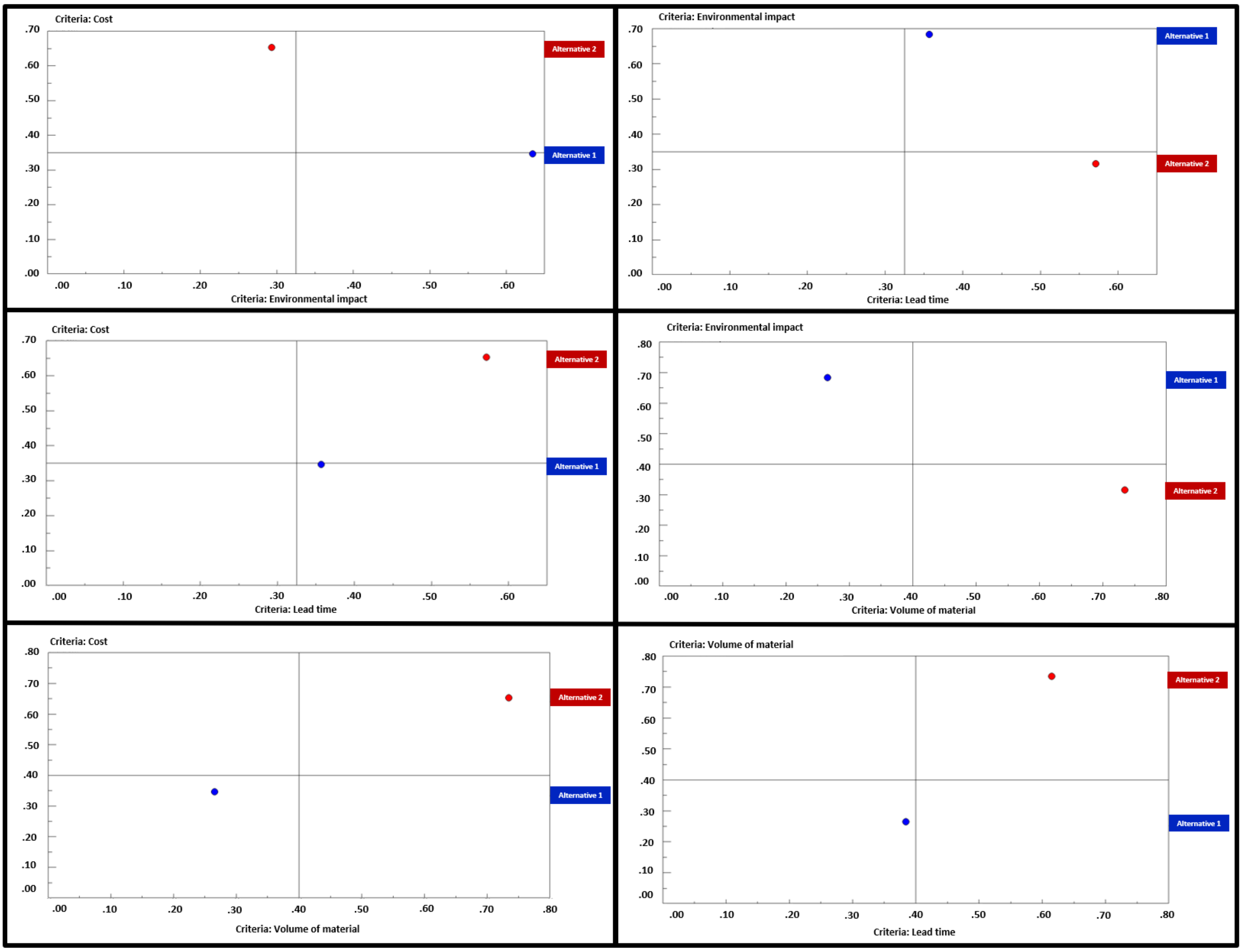






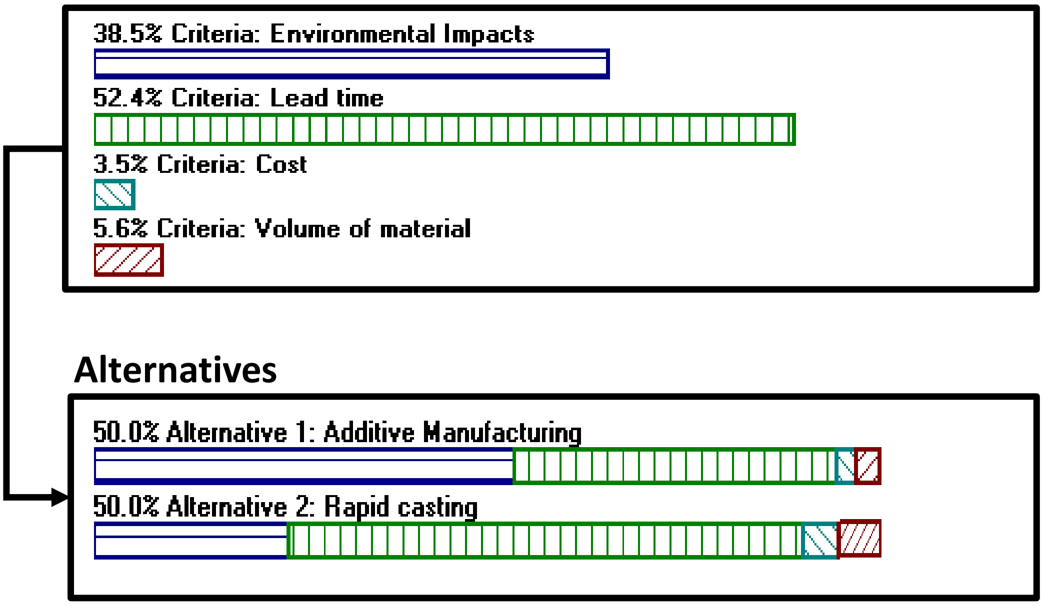


Results – Two Dimensional Sensitivity Analysis



Results – Dynamic Sensitivity Alteration

Criteria



Appendix D - Meeting Log & Tentative Abstracts

Appendix D stores the project meeting log used for thesis references and the tentative abstracts based on the thesis topic.

- **Page 1-4:** Abstracts based on the thesis topic
- **Page 5:** Project meeting-log verified by the supervisor at Moreld Capnor

Meeting log

MSc Thesis – Jon Erik Karlsen

University of Stavanger

07.01.22 – *Introduction-1*: Moreld Capnor and Equinor

- Equinor is scouting for parts that can be manufactured by AM
- 26 check valves used in fire barrier systems on Stafjord should be replaced
- They have been in service for 30+ years (2 x lifetime), material is 6Mo
- **Options for replacements are:**
  - Reverse engineering: Cost: To be concluded
  - Homemade solution: Cost – 500,000-1,000,000 NOK
  - Acquisition of new valve system: Cost 500,000 NOK and upwards
- The risk related to the aging of deluge valves is the wear and tear of valve flaps and membranes. In addition, there are several threaded components such as manometers and plugs; these may be converted to potential projectiles if the valve fails.
- Installation of the system is not a problem in a general project (planned maintenance) but becomes adversity in separate projects. Today there is no solution to the problem of valve replacement; however, disassembling valves on Statfjord may relieve spare parts to other Statfjord projects
- Equinor had difficulty motivating this project due to the small returns regarding resource savings. However, it is vital to have a solution until the homemade solution is completed (if possible, at all). "*Valves must be accessible in case of an emergency*"
- Most of the reengineering and AM cases are nuanced, and decisions related to "*go or no-go must be feasible before a decision is taken*"
- A re-design option for threaded connections could be applied
- Ni-resist casted material connected to carbon spools (up-downstream) is ok regarding galvanic corrosion
- Parts such as clacks and instruments on the valve has different material specification
- Partly upgraded pipeline in super duplex and 6Mo induce higher galvanic corrosion between the valve and the piping
- Main degradation is cracks and wear of threads (aging effects)
- Threads should be avoided in a re-design (use flanged connections)

10.01.22 – *Introduction-2*: Moreld Capnor & UiS

- Intellectual property (IP) rights, who is the owner and who makes money?
- File type for the end user may depend, STEP, STL, 3MF, OBJ
- Pressurized components such as the deluge valve must be approved according to material certificates requirements (PED, API) and follow standardized manufacturing and material codes (DNVGL-CG-0197, DNVGL-ST-B203, API20, NORSOK M-001)
- CE approval must be checked
- Today, digital files come directly from the manufacturer. Therefore, it is essential to figure out a pathway for the "grey zone." material to be implemented into the digital warehouse.

- It is essential to have a clear picture of the whole playfield and the long haul of spare parts availability and accessibility. The broader scope is investigating how to reduce the supply chain. (Reduce the lead time)
    - Need to investigate the selection of materials, producers/suppliers, delivery time, and facilitate for testing, test type and price and time for testing
- Design standards such a API6D and ASME 8 – 1&2 are used for design of valves
- Full life cycle assessment is needed for optimizing the AM selection

20.01.22 – *Digital warehouse*: Moreld Capnor & Equinor

- A presentation of the digital warehouse provided by Fieldmade AS was given. The **main aim** of this platform is the distribution of both legacy parts and new components accessible by approved stakeholders such as OEMs, AMs, and IP owners
- A part file was presented via teams where an example of licensing or Intellectual Property (IP) buy-out was discussed. The Digital Product Definition (DPD file) could be sold, and IP rights are transferred to the new owner, or they could down pay the engineering costs from the manufacturer and then buy the rights for IP
- The DPD is never owned if the IP rights are not their own
- The foundation is built on blockchain (highly secure and transparent)
- The provided DPD is detached from the blockchain when "purchased" or licensed
- **Market parts:** Makes the job/project/work package available for manufactures
- **Local parts:** Makes the job/project/work package available for internal use
- The manufacturer must comply with the required manufacturing standards
- Manufacturers should be able to make an offer for part online
- Only approved manufacturers should be able to see relevant order requests
- Other IP owners can add parts to the "Market parts"
- Standards depend on the criticality of the part
- There is webpage site input option, machining option, or post-treatments of parts
- Need an option for a quote request and version/revision quotes
- ISO/ASTM 52901 – Requirements for purchased AM parts

01.02.22 – *Joint Venture*: Moreld Capnor, Wilhelmsen & UiS

- Wilhelmsen is conducting a JIP with OEMs, AMs, machine workshops and other contributors with the aim of establishing a solid hub for ordering spare parts on-demand through their digital ecosystem.
- "*It is vital for any reverse engineering project, to understand how the part is affected by the environment and vice versa. Also, it is critical to understand all part features, which helps give a holistic view of the component and its purpose*"
- They want to qualify the manufacturing process instead of singular parts which would increase the productivity and in long term the reliability on a global scale
- Parts are shipped with work certificates (COC)
- Quality management system checklist is used as basis for the process (ISO-9001)
- Their digital ecosystem is based on a marketplace where orders are matched with the technology of the fabricator and their qualification approval to the specific order where bidding options are available.
- Some parts are directly priced from the online catalogue and other are priced directly from the OEM
- Order information: Part info, file format, material data, acceptance criteria, shipping information, biding response information (Bid price per unit, shipping, Total bid price,

proposed manufacturing lead time), manufacturing method (AMC, machines, Etc), inspection levels is available
- *“The spare part market is the holy grail for applying the on-demand solution”*
- The spare part catalogue is used to pilot the system in general
- The most important and difficult point has been to bring interest and maintain development of the digital ecosystem together with manufacturers.
- It is hard to maintain an established relationship with the supply chain, suppliers, data management, warehouse and inventory management, capacity management, and information systems

02.02.22 – *Design*: Moreld Capnor

- The re-design option from the introduction meeting with Equinor was discussed
- Investigating the possibility of integrating flanged connections to the valve body
- The 1/2” and 3/8” instrument connection would not really be feasible to alter
- The line out for the restrictor could be re-designed and will be investigated

02.02.22 – *Additive manufacturing*: Moreld Capnor, Velo3D & UiS

- Opportunities for manufacturing was discussed, PBF→Ti-6Al-4V
- Proposition for 4” valves were verified
- 6” valves could not be produced due to unproven technology
- The part needs an excessive amount of support material
- Future assessment regarding the 6” valves can be made at a later stage
- Post processing: EDM, machining and heat treatment required

16.02.22 – *Rapid Casting*: Karlebo, Moreld Capnor & UiS

- They have a joint venture with companies that have approached an on-demand need with rapid casting as manufacturing options.
- The sand printing process has matured where binder jetting (BJT) mixed with sand is used to build the part.
- Volume of printers varies but have access to 1800x1000x700 mm
- Speed up to 60-80 litres/hours
- Non-reusable mould, highly customized and complex geometries is allowed
- Post processing is required (heat treatment, machining, etc)
- Normal lead time is about 1 month compared to 3 months for normal casting
- A cost perspective is needed for evaluating the economical advantage for low batches

10.03.22 – *Rapid Casting*: Molstad, Moreld Capnor & UiS

- Cost of qualification of part related to AM is around 150,000 NOK.
- The valve would be an optimal candidate for the rapid casting process where 3D sand printing and casting is combined for producing the part
- The printing is provided by external providers and the casting is performed by Frekhaug Stål
- Other parts have the possibility to be produced by the same method
- The method is highly adaptable

10.04.22 – *Weekly meeting compilation:* Moreld Capnor & UiS

- If manufacturing follows NORSOK, most of the technical aspects are fine
- Follow NORSOK-M001, NORSOK-M630, NORSOK-M650
- Part solutions, prices, lead-times, and manufacturing options must be consolidated
- A consolidation of on-demand has not been investigated before in the O&G industry
- Important to make the path understandable to technical personnel
    - Explain why casting may be more favourable than 3D printing
    - Explain why the casting method may be more robust than other methods
    - AM: Time consumer → costly (limiter)
    - High-cost items and large prints are not really feasible
- Correlate standards in an understandable manner
- Data can be accumulated to be used for the predictability (good standard deviation)
- Design optimization could be performed but the question of how much is to much should be asked. Too much optimization could result in increased maintenance and reduced operational life (life cycle)
- Valve body degradation is position dependent (i.e., corrosive environment, Etc)
- Part qualifications increase the lead time, need to reduce AMC for AM
- The digital warehouse should be able to operate with a rapid casting option, a cost evaluation of the minimum required metal should be used in conjunction with geometrical material parameters for calculating the cost profit margin and feasibility of AM versus rapid casting. Nonetheless, AM may be the only option for the DW since the aim is to go for minimal stock
- Numerical analysis (FEM) should be evaluated **carefully**, especially related to AM. Welding physics applies for AM and residual stress and strains must be considered.
- A proper life cycle and life cost evaluation should be performed to be able to decide a manufacturing method, however, approximation could be implemented to make the manufacturing selection decisive If predictions are proven conservative enough, and the range for the application and loads is OK, then the part provider is considered satisfactory. For criticality analysis, the probability analysis is added
- Due to very high customization, it may be hard to maintain spare part. The optimal solution would be a one-to-one replacement
- The homemade solution could use several (off-the-shelf parts) which is combined with AM parts (hybrid solution). The check valve can be switched to ball valve
- Pressure Equipment Directive (PED) should be evaluated
- Conformity assessment should remain solely on the obligation of the manufacturer
- 1.1-1.5 safety factor for design pressure is OK
- Shell test is commonly used together with sharpy-v tests
- Post-processing options must be considered for all manufacturing methods (AM, rapid casting, and hybrid options)
- Risk based thinking should be evaluated for parts with main functions (NORSOK-Z008)

- Signature is provided by Supervisor at Morled Capnor

- I here acknowledge the content of the Meeting Log

Date: 23/6/22 Signature: [signature]

Abstract and Article Proposal for ASME OMAE 2023 Conference in Melbourne, Australia (Tentative)

Abstract-1: (Tentative)

Topic:

- *"A roadmap for re-production of legacy assets on the Norwegian Continental Shelf using an on-demand solution."*

Purpose:

Acquiring legacy assets to the Norwegian oil and gas (o&g) industry by an on-demand solution is today cumbersome. The individual subjects related to standardization and manufacturing are known. However, the holistic understanding of applying subject matters is scattered. Therefore, constructing a roadmap that supply-chain stakeholders can understand is necessary.

Methods:

- **Qualitative study:** Standards related to mapping supply chain requirements (purchase, manufacturing, delivery)
- **AHP:** Selection of an unbiased manufacturing method (based on general criteria for supply chain key parameters)
- **Case review:** Implementation of a mechanical asset for testing the roadmap

Results:

- **Roadmap:** The qualitative study provided a roadmap that can be used for generic mechanical assets aimed at the o&g industry on the NCS.

Conclusions:

- Rapid casting is likely to become a leading solution for legacy assets. (Size and batch dependent)
- AM technology is not ready for high batch production of high criticality parts that are relatively large in dimensions

Relevance:

- Develop a screening tool for assessing AM and rapid casting compatibility, i.e., screen assets for an on-demand solution

Abstract-2: (Tentative)

Topic:

- *"Manufacturing method selection for mechanical legacy assets aimed at the Norwegian Continental Shelf (NCS)."*

Purpose:

The maturity of additive manufacturing and hybrid casting technologies drives the possibility of reducing manufacturing activities, hence decreasing lead times while increasing batch quantity and quality. However, selecting an optimal manufacturing method related to specific assets will become an increasing theme among stakeholders within the oil & gas industry on the NCS. Therefore, using an analytical approach for choosing the optimal method can strengthen and simplify the final evaluation.

Methods:

- Quantitative & qualitative review: Applying the roadmap from the original thesis title
- AHP analysis of spare part component

Results:

- Rapid casting is favoured for the specific component

Conclusions:

- The results are part-specific and are used as an aid in the overall selection process.
- The method strengthens the selection of manufacturing methods.

Relevance:

- This method should be used for a range of different components to establish the validity of the overall process
- The technique could be developed based on the inventories from offshore operators.