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Applications of Additive Manufacturing for Norwegian Oil and Gas Industries

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Abstract

The additive manufacturing or 3D printing (3DP) technologies, particularly in the last few decades, have experienced an exponential growth. Applications of additive manufacturing technologies in large-scale and high-performance manufacturing industries have paved the way for effortless component production. The 3D printing has never been more accessible, and the inception of the desktop 3D printing machines is making 3DP an established tool for producing prototypes and direct parts from a Computer-Aided Design (CAD) file. In an industrial set-up, this technology is being used for a variety of reasons, including the creation and manufacture of tailored and task-specific tools.

This thesis explores the prospects and challenges of installing a 3D printer on offshore facilities to encourage on-site part production, curtail operating costs, and minimize downtime. The thesis yields methods for simplifying and streamlining the development of customized products. The methods used to identify shortcomings and opportunities to improve 3D printing processes at offshore platforms. It also furnishes a comparative analysis of manufacturing techniques which will facilitate the decision-making process. Furthermore, the proposed approach's technical structure will chalk out a way to develop designs for prototypes and tools to address identified issues. The proposed ideas and developed tools will potentially have a beneficial impact on the operations of the oil and gas industries.

The thesis also discusses the machinery required for the post-processing of printed parts and their availability on offshore platforms. The reliability concerns connected to 3D printed parts are also highlighted which will aid the RAMS analysis of printed parts.

Keywords

Additive manufacturing, 3D printing, computer-aided design (CAD), oil & gas industry, centrifugal pumps, post-processing, reliability.

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1 Chapter I

Introduction

- Additive Manufacturing (AM) and Types
- AM Applications
- Applications For Oil & Gas Industries (OIGs)
- Current Developments in OIGs for AM
- Case Studies

1.1 Introduction

Additive manufacturing (AM) or 3D printing (3DP) is a manufacturing process of making products by adding layers of materials over each other. The AM is dissimilar to conventional manufacturing methodologies where materials are machined with tools to form different shapes [1]. The AM is a manufacturing approach which has outshined traditional methods in terms of design flexibility, energy optimization and high production speeds. This innovative approach has ushered in new opportunities for improved manufacturing, and material utilization and has successfully transformed industries and the production lines [2].

The journey of 3D printers started with the first commercially available 3D printer developed by Charles Hulls and the technology has been scaling new heights since then [3]. 3D printing is poles apart from, both formative and subtractive, traditional manufacturing. It is essentially a ‘bottom up’ technology that manufactures parts by using a ‘layer-by-layer’ approach, as shown in Figure 2. This manufacturing approach permits an unrivaled capability to construct convoluted, composite, and hybrid structures with utmost control, accuracy, and precision [4].

AM creates 3D structures based on CAD models by layer-by-layer fabrication method. The AM constructs ‘objects’ from a digital CAD ‘model’ by accumulating one or more materials, or combination of different materials, employing digitally controlled and managed material laying tools. This basic set-up of a 3D printer requires four main components [5]:

i- Model developed by using any 3D design software.

ii- Material that is deposited in different forms like liquid droplets, wire, or powder.

iii- Tool which lays down materials.

iv- Digital control system which controls the tool to set down the material.

Figure 1 Additive manufacturing vs traditional manufacturing processes (Source: 3Dprint.com)

The basic notion is that a model developed using 3D drawing software can be manufactured quickly without the need for planning sequence of processes. Although the process of creating complex 3D objects is not so simple AM technology significantly simplifies it. Other manufacturing procedures demand a detailed evaluation of the component geometry to determine things like the order in which different characteristics can be created, the equipment and processes that must be used, and any additional fixtures that may be required to complete the part.[5]. AM, on the other hand, only requires a few basic dimensions data and a rudimentary understanding of how the AM machine works as well as the materials needed to make the item [5].

1.2 Application of additive manufacturing/3D printing

The AM is distinguished from other manufacturing methods because it is more versatile, flexible and customizable, and highly suitable for many industrial products. The products having low volume, complex and high value-addition can be fabricated rapidly using AM. Different industries have developed processes for large-scale additive manufacturing production.

The automobile sector is one of the largest adopters of AM technologies. Since hundreds of parts make up a car, some of them have low demand and are so specific that manufacturers do not make and sell them. AM/3D printing enables the production of high-quality, custom-designed new and/ or replacement parts for vehicles at a lower cost and, more importantly, at a much faster rate. Many notable automakers are increasingly using additive manufacturing to create engine components, brake rotors, radar antennae, gear levers, pedals, etc [6]. This latest technology has saved billions of dollars and millions of hours in automobile industry by reducing time and optimizing costs[7].

The aircraft industry was a pioneer in implementing 3D printing technologies and continues to contribute to its development. 3D printing technology has become involved in production at very large scales where it has found significant applications. Different aviation industries are using AM/3DP processes to produce several components for example tarmac nozzle bezel, console control part, air flow ducts, and, suspension wishbone [8]. 3D printing technologies have a significant impact on the aerospace industry when the cost of highly complex one-off components can be justified by a significant improvement in aircraft performance: the corporate aircraft, on average, travels 75,000 miles in a month, and a single 3D printed component can reduce the air drag by 2.1 percent, saving 5.41 percent in fuel costs.

Similarly, AM/3DP has made it possible to build things at home, laboratory, and office buildings. The versatile nature of 3DP machines allow the user to print completely different geometries. These machines can produce complex structures which require different processes and tools. Other examples of complex structures being developed using AM technologies include jellyfish robots, locomotive parts, rocket engine components, and even bridge structures [9], [10], [11], [12].

AM/3DP not only brings positive impacts to the manufacturing side of industries but also can contribute constructively towards supply side of organizations. This latest manufacturing technology carries a huge impact on global transportation costs, which continue to diminish significantly ever since the inception of 3D printing. The reason is that the 3D printers can be employed close to destinations, which saves transportation costs. The company's logistics could be altered by 3D printing technology. Companies' logistics departments can handle the entire process and provide more complete and end-to-end services [13]. A relevant example can be the international space station (ISS) which carries a 3D printing machine for making parts in the space [14]. This model can be replicated at different places to make in-house products.

The materials which were, previously, not easy to the machine can now be formed into products using additive manufacturing processes. AM can create operational components out of a variety of materials, e.g., metals, ceramics, polymers, composites, hybrids, and functionally graded materials (FGMs). The inherent inhomogeneity of additive manufacturing processes paves the way for the creation of FGM products. The weld-deposition-based AM techniques can be the employer for creating FMG products [15].

1.3 3D printing types

There have been several different 3D printing technologies developed, each with its own set of features. The 3DP is divided into 7 types according to ASTM Standards [16]. A brief introduction of each kind is given below:

Binder jetting creates a layer by spraying a chemical binder over the dispersed powder. The method begins with the application of a layer of powder and the printing of the binder onto the powder bed using typical ink-jet printing processes. The procedure is repeated until the required 3D structure is obtained. Later layers are supported by the unhardened loose powder.

Direct energy deposition (DED) works by depositing metal powder layers utilizing a laser beam as an energy source and a closed-loop control system, direct energy deposition is used to make fully dense, functioning metal objects. The material integrity and dimensional accuracy are high and this method is used to both repair and produce new components.

Material extrusion is a type of AM in which heated material, in a filament form, is extruded, via a nozzle. To construct the 3D product, the extruded filament is deposited layer over layer on a printing platform. The heating elements in the nozzle are connected to spools of construction and support materials. Examples include fused deposition modeling (FDM) and fused filament fabrication (FFF).

Material jetting, also called inkjet 3D printing, involves using printing heads to deposit droplets of liquid photopolymers and curing them with UV lights. Material jetting systems, particularly inkjet-based 3D printers, have gained popularity in recent years because of their capacity to print multi-material objects utilizing the drop-on-demand printing approach.

Powder bed fusion processes melt and fuse powder in particular locations. The building platform is lowered by a predetermined distance after one layer of powder has been melted, and the next layer of powder is laid down. The technique is repeated until the desired portion is fully created with successive layers of powder. Powder bed fusion procedures include selective laser sintering (SLS), electronic beam melting (EBM), and selective laser melting (SLM).

Sheet lamination technique entails using a laser to cut sheets of construction material, then attaching them one by one with an adhesive or by welding the laser cut sheets together to create the 3D design.

VAT photopolymerization is the most widely used 3D printing process, which uses laser, light, or UV to cure photo-reactive polymers. UV laser traces and cures the model's cross-section, while the remaining area remains liquid. When the trace is complete, the platform is lowered, and the part is covered with a new resin covering. Two examples are stereolithography (SLA) and digital light processing (DLP). In Vat Photopolymerization, the exposure time, wavelength, and power supply are all important factors.

Table 1 3D printing types, materials and applications [16]

Types	Materials	Advantages	Disadvantages
Binder Jetting	Stainless steel Ceramic beads Inconel Alloy	Large variety of materials. Capable of producing ceramic moulds for metal casting. Supports are included	Rough appearance Poor strength Post-processing required
Direct Energy Deposition	Industrial metal powders Copper Aluminium Titanium Nickel	High material utilization. High efficiency for repair. Suitable for large parts. Ability to plat thin wear-resistant metals layers on components.	Low to medium part complexity. Abysmal surface quality and accuracy. Limited materials.
Material Extrusion	Thermoplastics materials like ABS, ASA, PC etc	Variety of available raw materials. Versatile and easily customizable.	Low precision. Problems with building sharp external corners.
Material Jetting	Digital ABS Fullcure RGD 720 Rigur RG 450	Low material wastes and high resolution. Various materials and colors.	Thin damaged by post-processing. Unrecyclable support materials.
Powder Bed Fusion	Titanium Stainless steel Aluminium Cobalt-chrome	Support is not required. Recyclable powder materials. High levels of complexity. Good accuracy.	Coarse surface finish for polymers. Small to medium parts only
Sheet Lamination	Paper Plastic sheets Metals sheets	Low chances of warping and internal stresses. Various materials and colours are possible.	Fumes produced during material cutting. Warpage of lamination material.
Vat Photopolymerization	VP photopolymers Monomers Photo-initiator additives	Wide variety of materials High precision, accuracy, and resolution. Low-imaging specific energy	Require support Require post processing & curing

1.4 The oil and industry gas: a potential horizon

Although AM technologies have been around for a long time, they were initially limited to building prototypes since the initial printers were unable to deliver full rigid parts. Due to high underlying potential AM has seen speedy evolution into a production-ready technology. The AM's capability to construct complicated geometries and optimize the topology to control several loading cases is far superior to the other methods. AM permits engineers and designers to create geometries that were previously impossible to achieve using traditional methods.

The prospects of AM for the oil and gas industry (OGI) are still under exploration. AM, like the automobile and aviation industries, can bring a positive impact on the costs, production time and delivery charges of the products. Parts made for OGI are frequently complicated, larger in size and are made-up of hundreds of smaller subcomponents. AM can become a suitable production process as it has proven potential for complex geometries and different sizes. It is a more cost-effective alternative for building prototypes and end-use products. The 3D printer facilities can eliminate different supply chain costs.

An American technology firm, Gartner, has developed the Hype Cycle [17], a time-based graphical representation of a common pattern that arises with each new technology each year. Gartner releases over 90 Hype Cycles in various sectors to monitor the future potential and technological maturity. The Gartner hype curve 2018 pointed out that 3D printing technology for OIG is in the phase of innovation trigger and its plateau of productivity will reach in the next 5-10 years.

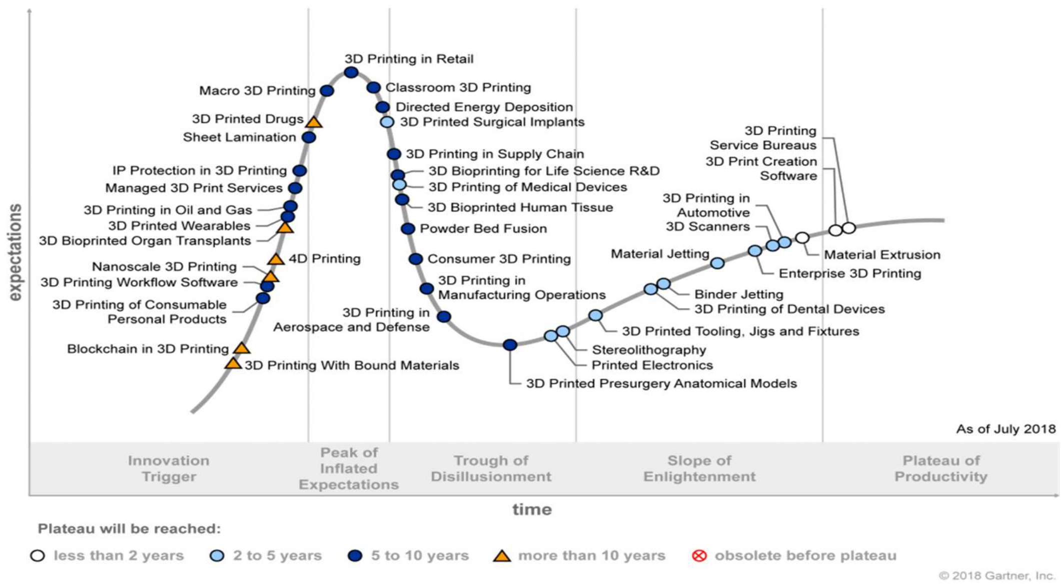


Figure 2 Hype Cycle for 3DP (Source: Gartner)

Today, 3DP/AM is mostly used in the oil and gas industries as a quick prototyping technique. As shown in Figure 2, many sectors have entered a plateau of productivity and have begun to use AM to make operational parts with complex geometries, demonstrating the technology's potential. Many other technologies are also gearing up to enter production levels.

Additive manufacturing and 3D printing show a lot of potential in terms of delivering on-demand and high-performance components to the OGI, which may add a lot of value. Major process equipment innovations for enhanced heat exchanger, reaction vessel, valve, and machine part design are among the near-term oil and gasses of AM and 3DP. Longer time, AM could lead to better catalyst manufacturing and boost process intensification activities in refineries and chemical plants [18].

Another important aspect of the OIG is the management of time. In case of any mishap or part failure, the plant can be compelled to shut down for a certain period which will incur heavy amounts. Time to deliver new tools, parts, and equipment is paramount which can be improved by 3DP. Beyond prototype, AM or 3D printing is a viable approach for production and fabrication. This is in contrast to traditional manufacturing which needs the removal of materials to create the required net shape [18].

The implementation of AM for the fabrication of practically useful parts for use in the oil and gas sectors is just getting started, thanks to the innovative processes that AM can offer to their product development. The characterization of materials used in 3D printing, such as functional metal, ceramics, and polymer, should be studied to describe the properties that can be well suited to the international working standards in oil and gas equipment facilities. This will fend off unexpected equipment failure caused by 3D printed replacement components.

1.4.1 AM/3DP for oil and gas industries

As discussed earlier in the introduction, several large companies have adopted AM/3DP technologies to augment their productivity and benefits. Following the success of 3DP processes in large-scale manufacturing, it can be concluded that OIG can also leverage these advanced methods to create a positive and modern change. AM/3DP will carry a multitude of interests upon successful adoption and integration into OGIs. Some of the main profits are as follows

1.4.1.1 Rapid prototyping of parts

One of the most significant benefits of 3DP is the speed with which new products can be developed. Companies can develop and validate their designs faster due to AM's rapid prototyping capabilities, which speed up the design process and allows them to respond to undesired results. The agility offered by 3D printing can reduce the production time of oil and gas components, resulting in a development time reduction. For example, General Electric reduced its product production and validation process by half by using AM to develop a new burners for the NovaLT16 gas turbine [19].

1.4.1.2 Generation of complex geometries

The machinery used in OGIs is often complex, which should meet stringent work and environmental regulations. AM enables the creation of complex geometries with fewer parts, saving assembly time, enhancing performance, and lowering emissions. 3D printing enables the manufacturing of single-part flow control and other devices. Additive manufacturing, as opposed to investment casting, simplifies the fabrication of turbomachinery, pumps, valves, and other critical components, lowering costs and improving performance.

1.4.1.3 Spare part production

The nature and location of OGIs necessitate the maintenance of spare part stock. Mostly these are low-volume parts that are expensive to produce, store and maintain. Since delivery time of high-quality parts for maintenance operations is crucial, generally operators keep substantial stockpiles of critical spare parts to reduce unscheduled downtime. Because of the wide global spread of operations across continents and oceans, oil and gas producers confront substantial logistical hurdles. The significant expense of downtime simply adds to the parts shortage problem.

1.4.1.4 Cost effective supply chain

A single day of downtime can cost OIG companies hundreds of thousands of dollars in lost income, and spare component's lead times are typically exceedingly long – assuming the parts are even available. To counteract this, businesses keep large stockpiles of different machine parts on hand, sometimes at a high cost. 3D printing is well-positioned to provide the industry with digital inventories and on-demand spare part manufacture, particularly in remote, offshore areas where the capacity to produce components on-demand almost removes supply chain difficulties. Additive manufacturing not only allows for better and more efficient part design, but it may also greatly speed up product development as a rapid prototyping method.

1.5 Case studies

a. DNV

DNV, an international regulator founded in 1864, released a technical standard "DNVGL-SE-0568" [20] that establishes safety and efficiency requirements for 3D printed items, assets, and systems in the OGIs and general energy production industries. Since 2014, DNV has been researching the advantages and disadvantages of additive manufacturing. The first guideline to use additive manufacturing in the maritime and oil and gas industries was released by DNV in 2017. DNV launched a Global AM Center of Excellence to act as an incubator and testbed for 3D printing technology research and development for the oil and gas, offshore, and marine industries. The new standard emphasizes AM's ability to avoid lengthy, costly production shutdowns and reduce supply-chain and carbon footprints.

Table 2 DNV's ongoing projects related to AM/3DP [21]

JOINT INDUSTRY PROJECTS	LOCATION
PILOT PROJECT ON TECHNOLOGY READINESS OF AM FOR REPAIR APPLICATIONS IN MARITIME AND OIL & GAS INDUSTRY SECTORS	Singapore
FEASIBILITY STUDY OF STRUCTURAL SUPPORT NODES USING LASER ASSISTED ADDITIVE MANUFACTURING (LAAM) TECHNOLOGY	Singapore
PROGRAM	Oslo, Norway

b. American Petroleum Institute (API)

The American Petroleum Institute (API) covers all aspects of the oil and gas industry in the USA. API is working on a latest standard to promote the use of 3D printing to enhance component design to reduce lead times and to increase efficiency, safety, and technological advancements throughout the industry [22]. Technical, quality, and certification standards are established in this standard for 3D printed metallic components. It also specifies the requirements for training, inspection, monitoring, and measurement equipment, as well as material testing and quality control.

c. Equinor

Equinor is a multinational energy company with operations in more than 30 countries, including several of the world's most important oil and gas locations. The company has been at the forefront of technological advancements in the oil and gas business. 3D printing and drones have been on the company's radar in recent years to improve production efficiency, reduce CO_2 emissions and promote a digital supply chain.

Recently, Equinor flew a drone for the shipment of a printed spare part made for the lifeboat system from the Mongstad base in the North Sea. This particular element was a diesel nozzle holder, which is a vital part of lifeboats. The product is an obsolete component that is very expensive to produce through conventional machining. Such equipment would normally have to be transported by supply ship or helicopter [23].

Similarly in 2018, an electrical motor fan at Tjeldbergodden broke down which halted different operations. There were no spare parts available in the inventory. Fieldmade, a 3D printing firm, printed the fan at an onsite facility instead of installing a new motor. A new motor is expected to cost NOK 500,000, while the additively made fan would cost NOK 12,000. This is just one example of how AM carries the potential to transform the energy industry in the future by lowering costs, reducing waste, and increasing product delivery speed [23].

Digital storage is a potential solution for spare parts; the part can be in the digital inventory, can be printed by any supplier, and then packed and transported by drone in a matter of hours or days. If a replacement part is required at the Peregrino field in Brazil, the same digital item can be acquired, and 3D printed locally.

Figure 3 3D printed part (L) and drone used to transport the printed part (R) (Source: Equinor)

d. Siemens

Siemens is a well-known international technology organization. The energy industry, infrastructure, transportation, and healthcare are the areas where Siemens concentrates. The company also provides purpose-driven technologies, resource-efficient industries, resilient supply networks, smarter buildings, more comfortable transportation, and improved healthcare. Siemens is a prominent technology provider to the energy and oil and gas industries.

According to Siemens, AM can potentially become a game-changer. It brings up new opportunities in the manufacturing of different components. Therefore, Siemens has a history of investing in this cutting-edge technology and is now leading the way in industrializing and commercializing it. Siemens is an early adopter of AM and employs it for quick prototyping. In addition, the company is currently developing solutions for printing gas turbine burner nozzles and fixing burner heads that are suitable for series production [24].

Figure 4 3-D printed gas burner for a gas turbine (Source: Siemens)

Siemens started printing gas turbine burners with selective laser melting technology in 2017. Conventional methods required 13 different pieces and 18 welds to make a single burner head. Through AM/3DP each burner head is made entirely in one piece. Improvements in design, for example, the pilot-gas supply being part of the burner head rather than the outside fuel pipe, allow for lower operating temperatures, resulting in longer component and, eventually, gas turbine operational lifespan [24]. Siemens' cutting-edge metal AM technology is recognized internationally due to its wide array of applications in the company's business of power generation. Siemens has manufactured hot rotating parts with AM for use in gas turbines for more than 110,000 hours in fully functioning power plants with 3D-printed gas turbine parts [24].

e. Kongsberg Ferrotech

Kongsberg Ferrotech provides robotic services for underwater inspection, repair, and maintenance (IRM) in the energy and maritime industries. The remotely driven robots can perform IRM procedures in a single operation and provide solutions for all subsea services [25]. Several large companies have teamed together with Kongsberg Ferrotech to develop and test 3D printing technology as a seabed rehabilitation solution. The technology, according to Kongsberg Ferrotech, will enable in-situ repairs of subsea components such as flowlines and conductors using additive manufacturing processes. The assets' lifetime is likely to be greatly extended because of this.

Kongsberg Ferrotech's Nautilus robot will have 3D printing technology. Nautilus is a flexible underwater robot with a comprehensive toolkit for inspecting and repairing subsea equipment and its components. Nautilus provides sophisticated robot technology in a dry environment, allowing for advanced seabed repairs without shutting down production. Nautilus is unique in that it can execute repairs and adjustments while entirely underwater in a dry environment. The technology is now ready for commercial applications and operations [25].

Figure 5 Subsea robots (Source: Kongsberg Ferrotech)

Current underwater pipe repair methods are time-consuming, costly, and in many circumstances necessitate production shutdown. By equipping subsea robots with AM technologies, the time and costs of repairs can be diminished. These advanced subsea robot saves the customer money and time while also being environmentally benign and emitting no discharges into the water. According to Kongsberg's plans, the company will begin supplying underwater composite repairs to the different markets during the second quarter of 2022 [25].

2 Chapter II

Product Development

- Product Development Processes
- Product Selection
- Product Design
- Material Selection
- Manufacturing Techniques

2.1 Product development processes

For materials and design, it is the combination of elements of art and science that make it work. Materials are not simply numbers on a datasheet. And design is not a meaningless exercise in styling, and it is not an isolated exploration of technology. What matters is the process of finding solutions that are meaningful to people, that enable new experiences and inspire and create positive impact in society and in our own daily lives. (Mike Ashby & Kara Johnson, Materials and Design 2nd edition)

The product development is a multi-stage process that provides guiding principles for developing a product, from concept to market launch. The development of a whole new product is both a challenging and rewarding task. From concept to research and development, no two product launches happen to be the same. Although, there are many product development models for each industry, and all share a common procedure which is involved with the product development in all industries. This comprises identifying a market need, researching competitors, developing a solution, developing a product roadmap, and building a minimum viable product (MVP) [26].

One of the most important, but difficult, responsibilities that product developers have is the development and introduction of new products which should be competitive and successful. New/upgraded products that are attuned to the voice of the consumers are brought out to offer substantial competitive benefits from a strategic standpoint. Consider Apple's iPod, which replaced cassettes and CDs as a means of purchasing music. This new product entered a mature market dominated by giant corporations that had lost touch with their customers.

Figure 6 iPod vs existing cassette players (Source: David Duffinn)

To increase the success rate of their new product efforts, product developers should master techniques for designing, production, evaluation, and management of necessary competencies for the new product development process (NPD). These measures ensure that the proposed new products will support the company's strategic goals and capitalize on its strategic competencies. The NPD process entails the creation of new product concepts, the formulation of an initial new product, a business feasibility evaluation, product development, market testing, and actual product launch in the marketplace [27], as shown in Table 3.

Product development aids organizations in highlighting the processes that must be followed throughout the procedure at all levels. It takes through the major stages of any future product, from start to finish. Product development is a complex process that can be organized and accelerated. With meticulous planning, company’s product projects can easily avoid any logjams, temporary or permanent. The flowchart developed by Harvard Business Review depicts the project and process management for effective product development [28].

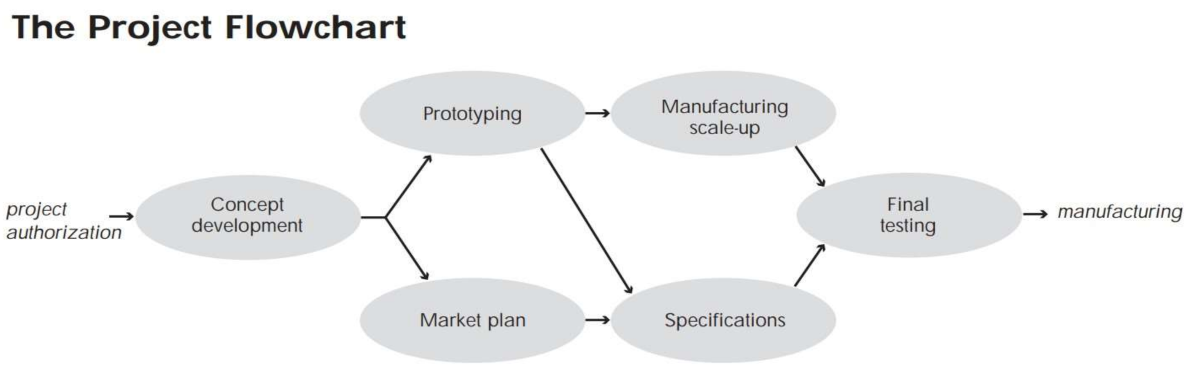


Figure 7 Project flow chart

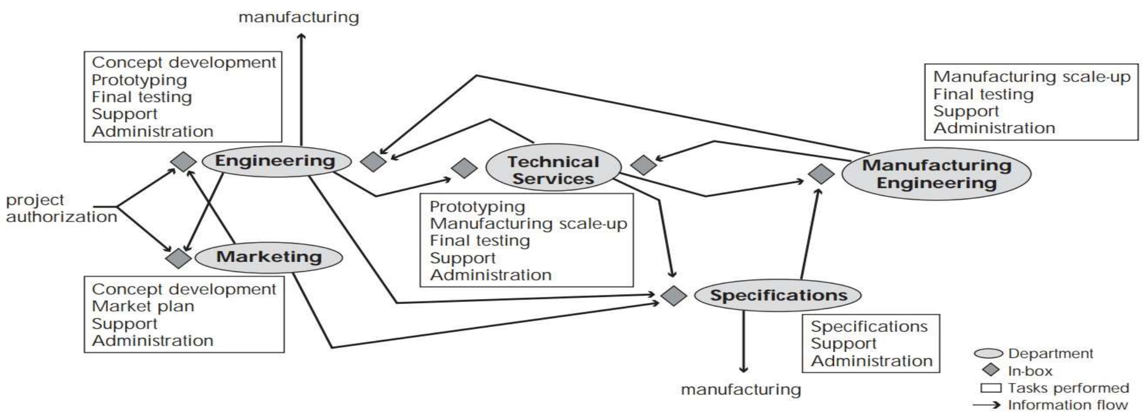
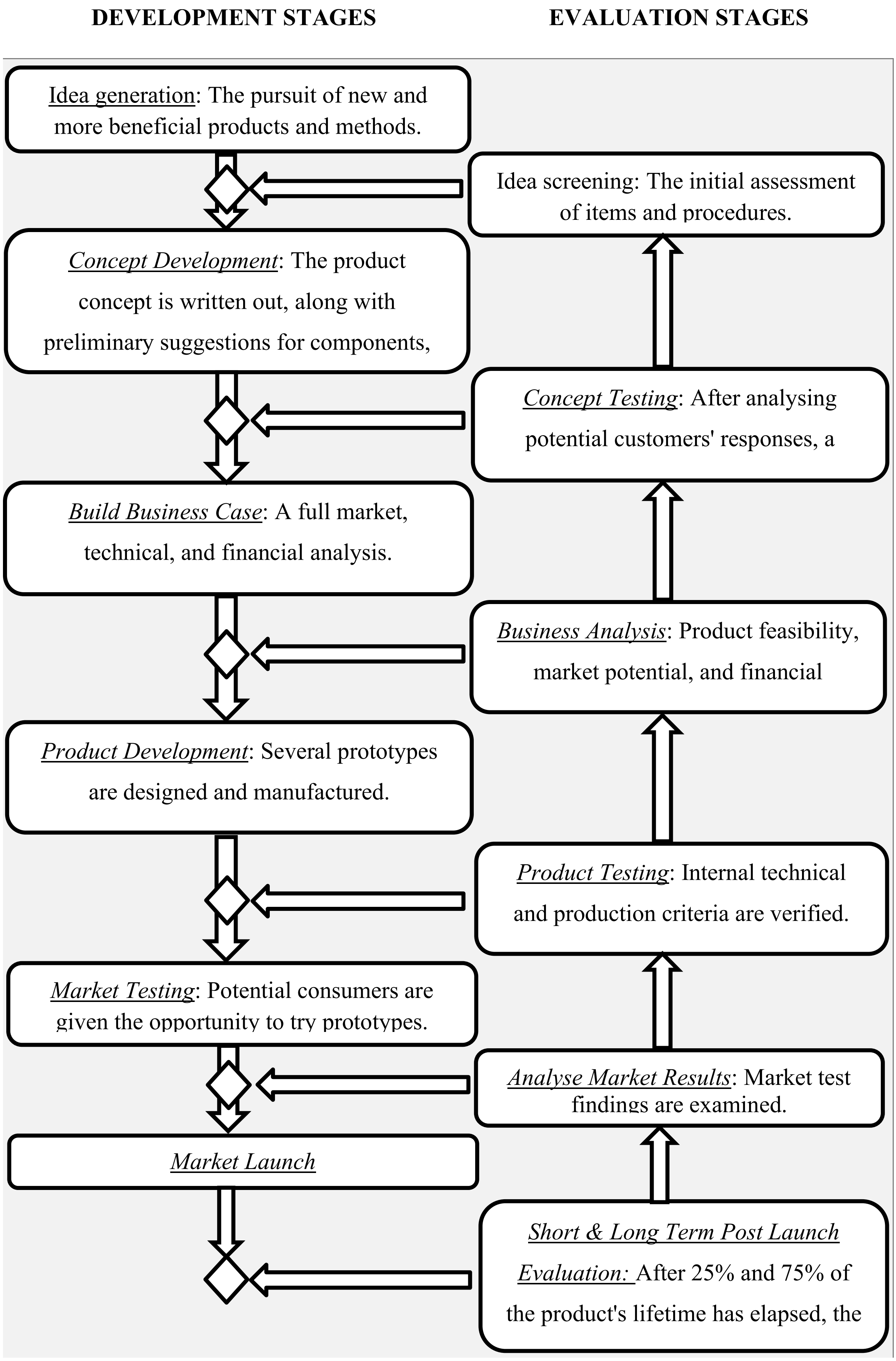


Figure 8 The processing network model

Table 3 Product Development Stages



According to a case study, Table 4, based on a notion proposed by the value engineering department to apply new technological concepts to an existing product to achieve a paradigm shift that may lead to significant innovations [29]. With the rise of competition, businesses have worked to boost the value of products.

PDP	**Department**				**Action**
	VE	**Product Engineering**	**Process Engineering**	**Purchase / Supplier**	
Concept	Target Concept VE	Concept Concept			• Concept development • Target cost • Concept alternatives for cost quality and function • Concept decision
Products and Process	Target-cost Project- VE	Development of Product & Process			• Start of product and process development • Preparatory information • Analytics • Creation • Judgment • Planning
Validation and Production	Strategic Target-	Validation of Product & Process Validation VE			• Prototyping • Manufacturing study • Mass production • Process improvement • Production improvement

Table 4 Flowchart of product development processes

2.2 Product selection

Nothing is static. Today's designer seeks to optimize a design to best meet the needs of today's markets, but before the optimization is complete, the boundary conditions – the forces that influence the design decisions – shift, requiring re-direction and reoptimization. It is helpful to be aware of these forces; they create the context in which design takes place. (Mike Ashby & Kara Johnson, Materials and Design 2nd edition)

The consumers, industries, and masses, have certain expectations of the products. These expectations do not stop with a product that works well and is reasonably priced; but also include several factors such as, robust design, good aesthetics, long life, and high durability. These all are important considerations. According to the designers, these are the most significant influences right now. And, naturally, they frequently clash [26].

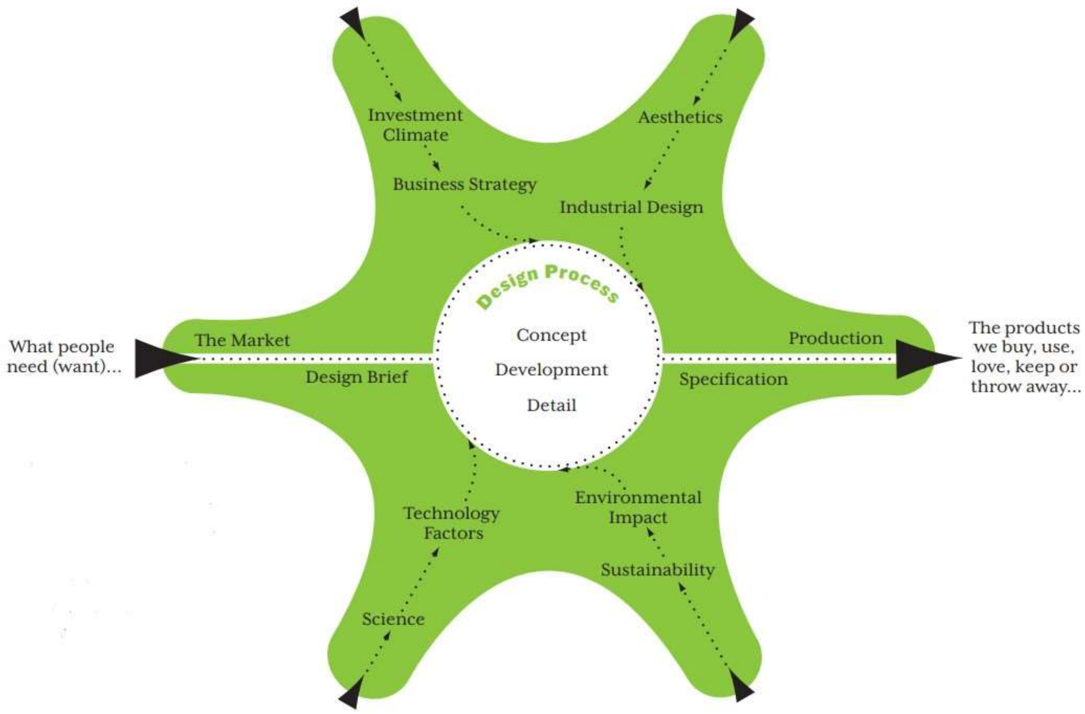


Figure 9 The dominant inputs to product design (Source: Materials and Design 2nd Edition)

The influential factors are all mentioned in Figure 9. It can be observed that the design process, the centre circle, and its workings and dynamics are shaped by the impacts of different factors. The surrounding branches are the external factors that bring changes into existing design processes. A mindful designer has to take all these external factors into consideration to chalk out a successful product development plan.

2.2.1 Market and market trends

Changes in the broader sales environment affect all firms at some point. These shifts have the potential to have a significant impact on the industrial economy. The market is a significant driver in product design because of today's economic developments and wealth, at national and individual levels, and the free-market economies' nature. The market trends examine how the product entered the market, how it has evolved, and where it is likely to go in the future. Many goods in industrialized countries are technically mature and have saturated markets.

All market dynamics are driven by *need*. The "*Need*" pushes companies to make better and latest products that conform to the latest functional and environmental standards. It's vital to be aware of possible improvements so that plans can be adjusted accordingly. A common example is the introduction and evolution of electrical cars. Today's product design is influenced by user want, and one of the changes consumers want is more functionality. [30].

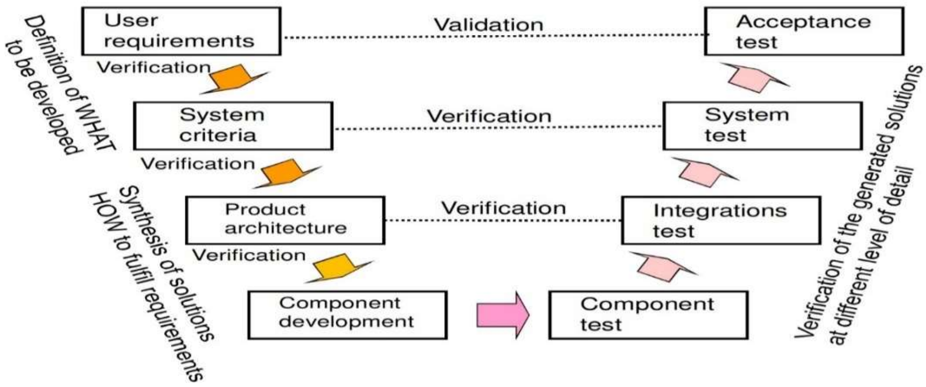


Figure 10 The V-model for specification and verification [30]

2.2.2 Technology factors

New technologies have enabled innovation in materials and processes which continues to expose latest material and process improvements. The need for new technology solutions is greater than ever due to rising demands for better efficiency. The demand for more advanced and novel technologies, materials, and production methods in the aerospace, defense, automotive, oil and gas, and industrial sectors has resulted in the development of a new series of materials with significantly improved performance and capabilities [30].

2.2.3 Industry 4.0

Industry 4.0 refers to the strategic deployment of digital technologies across the production assets of industrial manufacturing enterprises. It has a critical role in assisting oil and gas upstream enterprises in navigating the industry's tough landscape. Capabilities like as autonomous drilling, digital modeling, and predictive maintenance can sharpen the competitive edge for firms battling with ever-changing demand-and-supply cycles and falling margins. [31].

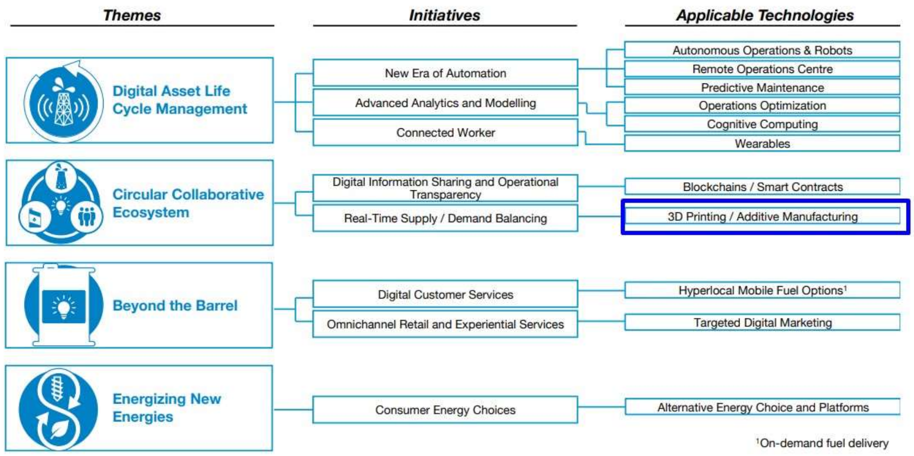


Figure 11 Pillars of Industry 4.0 (Source: World Economic Forum/Accenture analysis)

The future of oil and gas is currently grim due to a variety of factors. The most significant of them are low oil costs, new hydrocarbon supplies, renewable energy, electric vehicles, strict carbon laws, and improved energy storage technology. Most upstream companies have a tendency to invest in Industry 4.0 strategy that includes solutions for project design and evaluation, autonomous drilling, ecosystem reliability, and maintenance forecasts from exploration through production. These skills will help organizations develop profitably while also increasing efficiency [31].

Industry 4.0 has the ability to change how industries design, evaluate and choose different projects. The incorporation of advanced digital technologies, for example 3D printing, cloud storage, and analytics, will create a digital framework that can evaluate and generate results far greater than those of traditional methods. The oil and gas industry has the potential to invest in developing such a value chain which, in return, will reduce costs, save time and increase efficiency [32].

Figure 12 shows the important factors required to successfully implement Industry 4.0. The facilities like 3D printing and cloud storage can lead to production of different tools on-board rather than from other parts of the world. Using these technologies, offshore facilities can rely on their in-house built products for predictive and preventive maintenance. Although, massive research is to be carried out in this regard but it can be predicted that, based on previous case studies, AM technologies will play a huge role in offshore working environments [32]. More information about Industry 4.0 can be found in Appendix I.

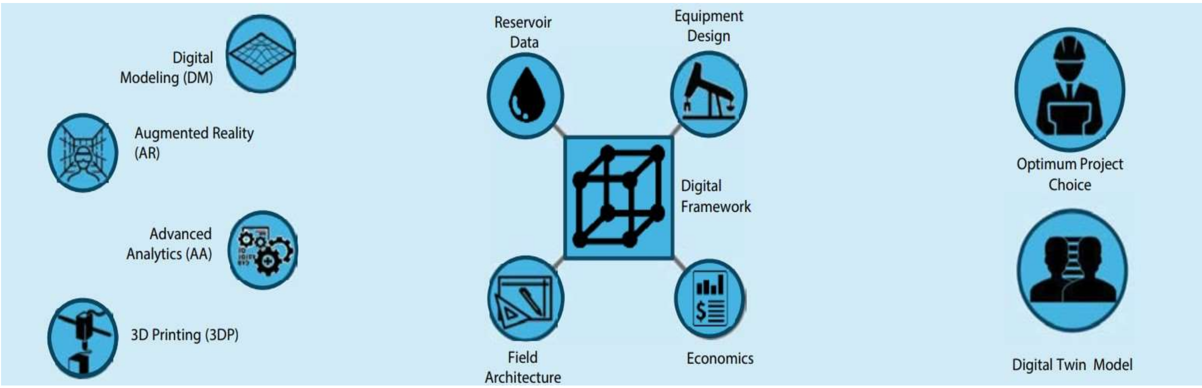


Figure 12 Important factors of industry 4.0 for oil & gas industries [32]

2.2.4 Environmental impact

Almost every industry has experienced different changes at different levels due to market trends. The oil and gas industry are not much different than others and many reservations are raised about the products and processes. The oil and gas industry are currently facing significant challenges. The foremost is to produce more energy with reduced prices and pollution. The world's population is increasing, and after COVID-19, energy consumption would not only recover, but even increase. Consumers are also looking for greener energy, therefore oil and gas companies must deliver it with fewer pollutants.

According to the International Energy Agency (IEA), societies want both energy services and emission reductions at the same time. Oil and gas companies have excelled at providing the fuels that underpin today's energy system; the question now is whether they can also help with climate solutions. As a result, it paves the door for the petroleum business to join the alliance that the IEA thinks necessary to combat climate change, which some corporations are already doing. This initiative would be immensely aided by more firms joining in wholeheartedly. Low-carbon technology development expenditures are an investment in a company's long-term viability [33].

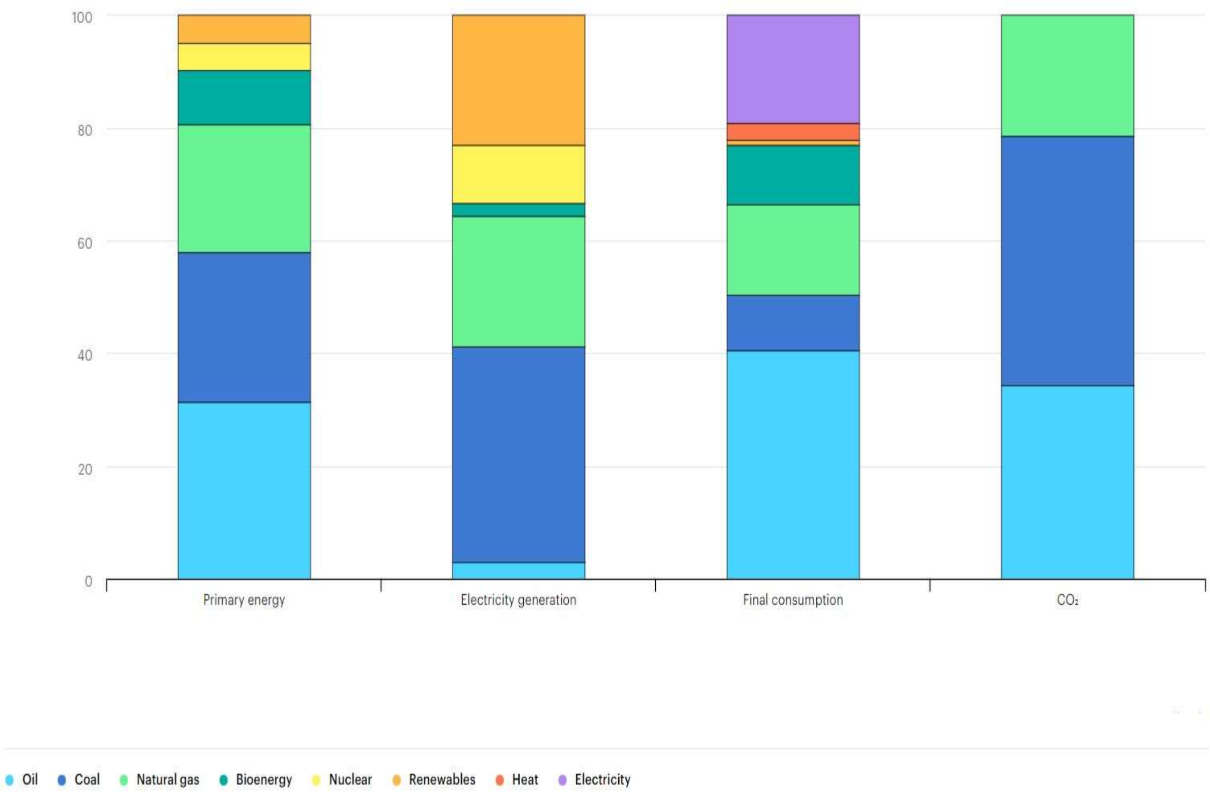


Figure 13 Global primary energy, electricity generation, final consumption and CO2 emissions by fuel, 2018 (Source IEA)

Costs, carbon emissions, and risk are projected to be reduced by oil and gas companies. Bringing costs down necessitates a constant effort to enhance efficiencies across the value chain. Best-in-class operational processes are necessary just to reduce carbon emissions. Moreover, oil and gas companies will need to preserve and strengthen their softer skills of innovation, teamwork, and communication in addition to the hard skills required to deal with the challenges described below.

2.2.5 Production

Crude oil and gas are converted into commercial goods by processing and refining. Once the transformation is complete, gasoline for automobiles, heating oil, jet fuel, and diesel oil are among the items obtained. Oil refining processes include distillation, vacuum distillation, catalytic reforming, catalytic cracking, etc. All of this infrastructure is required to extract oil and gas from the ground and process it into final products that are used in a wide range of industries. Manufacturers must have highly trained personnel with experience in concept design and development who can assist in the creation of unique oil and gas components. The manufacturers must maintain a group of workers with extensive experience in fabricating parts and machinery for all phases of the oil and gas production process.

Similarly, to produce components and parts for oil and gas machinery it is mandatory to have machinery of different kinds. Several operations on single part necessitate the use of multiple machine tools. The parts come in different sizes from ounces in the palm of your hand to tons in a truck. For example, downhole well-completion tools usually have a large length-to-diameter ratio, necessitating long beds and steady-rests on lathes and mill-turn centre [34]. For extended reach and internal machining, these long items frequently necessitate lathes with long projection, and damped boring bars.

An in-depth examination of current oil and gas industry trends, environmental challenges, and production methods will eventually lead to the creation of a system that combines many cutting-edge technologies and processes to usher in a new era of innovation. The benefits of installing a 3D printer should be considered in light of the advancement of additive manufacturing technologies. As a result, this will have a good impact on part manufacture at offshore factories.

While additive printing allows for considerable design alterations, complex superalloy components may also require exceedingly precise post-process machining before assembly. While AM and automation continue to gain popularity in the energy industry, special requirements such as extremely sophisticated thread patterns, massive parts, and superalloys necessitate a deeper understanding of how to manufacture components that work well in severe environments [34].

2.2.6 Product selection criteria

Components used in oil and gas equipment must be meticulously developed to withstand harsh operating conditions. The NORSOK standards specify technical standards for the design, manufacture, assembly, product inspection, installation, and testing of mechanical equipment. The mechanical equipment includes compressors, gas turbines, pumps, steam turbines, combustion engines, lubrication and sealing systems, transmission boxes, expanders, centrifuges, baseplates, cyclones, atmospheric tanks, and pressure retaining equipment. The Norwegian petroleum industry established the NORSOK standards as part of an effort to standardize the petroleum industries. International standards are often referenced in the NORSOK standards. The contents of NORSOK standards are used as input to the international standardization process where appropriate. The international standards used for the centrifugal pumps for fire safety and general refinery service are API 610 which classifies pumps in different sections according to the application area. Standards can be found in Appendix II.

Furthermore, to maintain both efficient operations and safety, the parts must fulfill these hurdles [35].

High Temperatures: In oil and gas applications, temperatures of up to 500 degrees Fahrenheit are usual. Components must be able to withstand prolonged exposure to these temperatures without deforming or impairing performance in any way.

High Pressure: For transportation and a variety of refining operations, both oil and gas are pressured. Components must be able to perform in extremely high-pressure environments.

Caustic Chemicals: Caustic compounds abound in the oil and gas business, from cleaning agents to sulfuric "sour" gas. Components must be able to withstand repeated exposure without compromising performance.

Abrasive Environments: Sand and other abrasive particle matter are frequently present in raw media. Industry components must be able to withstand extensive wear without sacrificing performance or longevity.

Reliability: There are two reasons for the necessity for oil and gas components to be reliable. First and foremost, companies cannot afford parts which might collapse suddenly; such failure carries both financial and real danger. Second, they must limit the amount of maintenance labour required, both to save revenue and because most of these components are buried deep within sophisticated systems that are difficult to maintain.

Cost-Effectiveness: At the scale required by this vast business, certain of the materials utilized in high-pressure/high-temperature settings are just not cost-effective. A component used as a one-off selection in aerospace may withstand the needed circumstances, but in oil/gas, where a single plant or pipeline may require thousands, it is not cost-effective.

Environmental Effect: The offshore industry's operating discharges represent a massive continuous input of pollutants into the waters from many widely dispersed sources. The adverse effects of containments on individuals of key species, as well as the repercussions of drilling waste on benthic populations, should be kept at minimum levels. All records suggest that the consequences of current discharges are limited to within 1–2 kilometers of an outlet source in the seas and on the seabed, and the chances of widespread damage are low.

Case Study: OREDA Database

Companies keep track of all the expenses incurred by various sources. These records play a key role to understand different behaviours of several machines and their parts. It is critical to be able to calculate annual costs. Predicting the life of machine parts and their cost effects have become vitally important as manufacturing companies shift to a sustainable product-service systems. The adequate quality maintenance and operation data from existing facilities are required for reliable findings and future planning. The reliability, availability, maintenance, and safety (RAMS) of industries are some of the major concerns to companies. RAMS analyses act as a handbook for future decisions and operations. In this regard, 2 organizations Sintef and NTNU, a research organization and a leading technology university, respectively, publish the offshore and onshore reliability data (OREDA) in a book form. OREDA is a comprehensive databank of reliability and maintenance data that provides information to evaluate and improve RAMS in the oil and gas industries. Following is a case study of failure modes in pumps and impellers

Compressors

Highest maintainable items versus all failure modes

Unknown	21.46%
Seals	12%
Other	7.66%

Failure mechanism vs failure modes

Leakage	26%
Mechanical failure	11%
Faulty indication	9%

Pumps

Highest maintainable items versus all failure modes

Unknown	32.47%
Instrument, Temperature	8.44%
Anti-surge system	6.87%

Failure mechanism vs failure modes

Unknown	21.46%
Faulty indication	14.90%
Leakage	8.45%

From the results, it is obvious that the "Leakage" is one of the leading problems in compressors and pumps. Other records show that turbines also experience similar problems during the operation. In order to replace parts which fail to provide optimal performance, the operators must have a well-maintained inventory that can replace malfunctioned parts. These parts contain different seals, impellers, and casings. These pump and compressor components must conform to strict NORSOK and API standards in terms of integrity and stress handling. Manufacturing such high-performance components takes a considerably high cost and maintaining an inventory can exacerbate the situation.

Although, there are always some backup pumps in place to counter the adverse effects of any possible failure, but it still adds to the operational costs of the plant. When any pump fails due to any problem, a backup pump starts functioning to avoid and/or reduce downtime. In the meanwhile, the main pump is fixed by technical staff. Since offshore plants do not have a large inventory so in case of unavailability of any certain part the problem can prolong. The unavailable parts can either be brought from onshore or be produced on-site, whereas the latter option is very limited due to absence of right set of machinery which can produce a precise component. The opportunity to manufacture components with varying geometries can be made possible through the introduction of 3D printers on offshore plants.

2.3 Product design

This section describes the detailed drawing process for a component which will be taken as an example to analyse the prospects and suspects of 3D printing. From abovementioned OREDA case study, it can be settled to take an impeller as a potential product. Impeller is a vital component of any centrifugal pump which has complicated geometry, stringent tolerance, and high work efficiency. The 3D printing of a component that has complex shape, accounts for a long production time, requires heavy machinery and high level of skills will definitely accentuate the potential of AM technologies at offshore platforms.

2.3.1 Impeller

A centrifugal pump is made up of an impeller that is attached to the shaft and rotates with it, as well as a casing that surrounds the impeller. Air and/or upstream pressure drives liquid into the input side of the pump casing. As the impeller rotates, liquid flows toward the discharge side of the pump. At the inlet of impeller, a void or low-pressure area is formed. More liquid is forced into the impeller to fill the vacuum because the pump casing inlet pressure is higher than the impeller inlet pressure. An impeller is a revolving disc with vanes that accelerates the flow radially outwards from the centre of rotation. The water pump impeller's velocity is converted to pressure when the fluid's outward movement is limited by the pump casing [36].

The centrifugal pump's impellers are divided into two categories: open and closed. The main distinction is that the vanes are readily visible from the suction side for an open impeller. In case of closed impeller, there is a shroud covering the vanes and hub. The leading edges of the impeller vanes make up the leaking joint for the open impeller [36].

Figure 14 Open (L) and closed (R) impellers (Source: Carver Pump)

The open impeller pumps are typically regarded as a better alternative for liquids containing particles or materials with stringy particles. Open impeller pumps come with an option to alter the impeller axially in the field to adjust the wear effect on the impeller. This wear happens as the liquid flows past the leaking joint on its way from exit to suction, and it's even worse if the liquid contains abrasives. The ability to lower leakage rate by resetting the impeller without disassembling the pump is a major advantage. Few open impellers are known as semi-open or semi-enclosed which features a full or partial shroud on the rear side of the vanes.

A closed impeller pump of the same size and particular speed provides more efficiency than any open impeller. Closed impellers appear to be more efficient since impeller's leakage joint has a smaller area than an open impeller's corresponding annular leakage space. The open impeller design is more effective in several vertically oriented pumps that have both open and closed impeller types. Another distinction is that in an open impeller liquid is exposed on one side to casing’s machined surface, whereas liquid in a closed impeller is exposed on both sides to an as-cast surface. A closed impeller with the same rating and particular speed produces less axial thrust [36].

Closed impeller designs are ideally suited to liquids that are relatively pure and noncorrosive and particularly well-suited to high-temperature environments. On the disadvantage, when made of stainless steel, the axially oriented leaking joint can block due to stringy material, wears rapidly against the erosive particles, and is more likely to fail. Because open impellers do not have a front shroud, they need less machining in the manufacturing process. Machining the vanes' front edges is an interrupted cut that may require slow machine speeds. Because the front side of the vanes is not hidden by the shroud so the easy manual adjustments can improve performance [36].

In conclusion, there are numerous elements that influence the impeller type that is best suited to a specific pump and application. Closed impellers are usually favored because of their better efficiency and lower axial thrust, as long as the liquid is suitably unsoiled and free abrasive particles. If the pumped liquid contains particulates and abrasives, open or closed impellers with radial leakage joints may be preferable. Open impellers are employed in hygienic centrifugal pumps, such as those used in a dairies/biopharmaceuticals. This allows the pump impeller to be hosed down more completely (after the front casing has been removed) to prevent bacteria growth.

2.3.2 Mathematical design

In a centrifugal pump, the impeller is the most vital component. The impeller is responsible for the entire construction of a pump. The most important aspect of pump design is the impeller. The impeller's fundamental equation determines the head created by the impeller about the momentum increase of the flowing fluid.

Suction Speed

Suction specific speed is a non-dimensional number that describes the profile of an impeller's suction side. Suction specific speed is denoted by the letters Ns, and calculated by using

$$N_s = \frac{N \times \sqrt{Q}}{\text{NPSH}_r{}^{3/4}}$$

S values for most designed impellers are typically in the 8000 to 9000 range. N_s values in the 10,000 to 13,000 range are related to a large eye single-suction impeller. High suction specific speed impellers should be utilized with caution since the allowable operation range on the pump curve might be more limited for pumps with higher N_s values.

According to book Rotodynamics, Leonard Euler, a mathematician, provides an elementary one-dimensional theory for centrifugal pump design [36]. His one-dimensional idea is still regarded as the foundation of centrifugal pump design. When the length-to-width ratio of the impeller passage is lowered, the existing 1D theory does not agree with the real results. The research of fluid flow in impellers is carried out using theoretical equations and correction factors discovered through experiments. Basic one-dimensional theory may be successfully utilized to calculate the blade system in impellers where the flow route's length between 2 blades is substantially larger than the width of the passageway [36]. Euler's 1D theory is utilized for impeller design with corrections in real flow cases, e.g., for a specific number of blades with a specific thickness, and it agrees exactly with practical results. T In actual flow with a finite number of blades and finite blade thickness, the velocity at any radius across the flow passage width between two successive blades of the impeller passage is not constant. Because of the surface contact between the fluid and blade, the flow is not axisymmetric. The blade pushes the fluid forward. This is the primary reason that in all rotodynamic machines, all flow tubes must be submerged in the flowing fluid or filled with flowing fluid.

The theoretical head (H_∞) calculated using Eeuler'1D theory for an infinite number of blades will differ from the actual head (H_m) calculated using the finite number of blades condition.

$$H_\infty = (1 + p)\, H_m$$

where, p denotes the correction coefficient for finite blades application. Although, various authors developed different values of p.

<u>Selection of Specific Speed and Suitable Pump Type</u>

Before a pump design or selection can be made, a specification must be created that expresses several needs. Specific speed is a dimensionless measure of discharge performance obtained from a computation including shaft speed, flow rate, and differential head at a pump's Best Efficiency Point (BEP). The value of specific speed is calculated using the following formula

$$n_s = \frac{N \times \sqrt{Q}}{\mathrm{H}_{opt}{}^{\frac{3}{4}}}$$

It's a crucial consideration in pump and impeller design and selection. Traditionally, pumps are classified as mixed flow, axial flow, or radial flow. The axial flow impeller develops the majority of its head through the pushing or lifting action of the vanes on the liquid whereas the radial flow impeller creates pressure by centrifugal force.

<u>Impeller Hub-Ratio and Blade Number Calculation</u>

Based on specific speed, the ratio of impeller hub diameter to the outside diameter, D_h/D_o, can be calculated. Thus, the impeller hub ratio is

$$D_d = 26.8\,(n_s)^{-0.063}$$

<u>Input Power</u>

The following equation can be used to calculate water horsepower.

$$WHP = \rho g Q H$$

The following expression can be used to calculate braking horsepower.

$$BHP = \frac{WHP}{\eta_o}$$

Where η_o is the overall efficiency of an axial flow pump. The shaft power is given by

$$P = \frac{\rho QgH}{\eta_0}$$

Pump's Shaft Diameter

The shaft diameter d_s is

$$d_s = \sqrt[3]{\frac{16T}{\pi \cdot \tau}}$$

Here, the T is the torsional moment, and it's value is given by

$$T = \frac{60\ BHP}{2\pi n}$$

τ represents allowable shear stress of material of shaft.

Determination of Impeller Diameters

We can find the velocity distribution in the impeller blade system by creating triangles at different radii "r" between the input radius r_1 and the outlet radius r_2. The vectorial subtraction of absolute velocity "C" and blade velocity "u" gives out the relative velocity of fluid "w". The direction of blade velocity "u" is always tangential to the circle of radius "r" whereas the direction of relative fluid velocity "w" at any point on the blade is always tangential to the blade curve at radius. With respect to the blade velocity, the relative velocity is inclined at an angle of "β".

The relative velocity vector and blade velocity vector at the radius of the blade in the impeller passage are represented by a parallelogram. A velocity triangle is generated when all 3 velocity vectors are drawn in their proper positions.

The symbols used in velocity triangles are:

u	Vane or blade velocity
C	Absolute velocity of flow of fluid *i.e.,* velocity of the fluid co any non-moving object.
w	Relative velocity with reference to the blade or impeller. The velocity of the fluid inside the blade passage, when the blade velocity is brought to zero

$$\vec{w} = \vec{C} - \vec{u} \; or \; \vec{C} = \vec{w} + \vec{u}$$

α	Absolute angle, the angle between the absolute velocity 'C' and blade velocity 'u'
β	Vane angle or blade angle—the angle between the relative velocity 'w' and vane or blade velocity 'u'

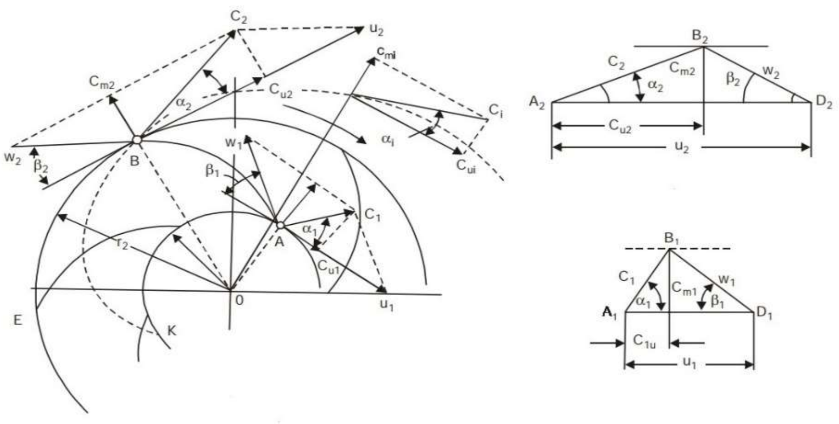


Figure 15 The velocity triangle (Source: Rotodynamic Pumps, 4th chapter)

Suffices marked in the Figure 15 denoted following terms

0	Before the impeller blade entrance edge
1	At the impeller blade entrance edge
2	At the impeller blade outlet edge.
3	After the impeller blade outlet edge.

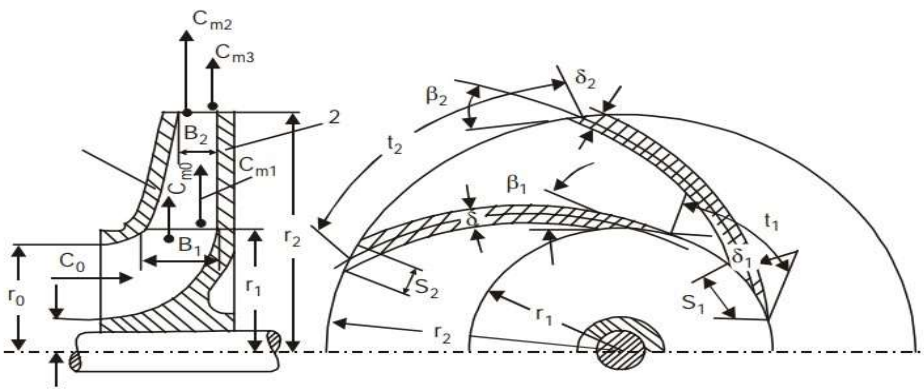


Figure 16 Suffices used in velocity triangles (Source: Rotodynamic Pumps, 4th chapter)

The impeller diameter can be measured using

$$D_{max} = 0.1 \cdot \sqrt{Q \cdot 60}$$

$$D_{min} = 0.08 \cdot \sqrt{Q \cdot 60}$$

The outer diameter D_2 can also be calculated using the head coefficient ψ

$$D_2 = \frac{60}{\pi n} \sqrt{\frac{2gH}{\psi}}$$

$$\psi = \frac{gH}{\frac{U_2^2}{2}}$$

$$U_2 = \frac{\pi D_2 n}{60} = \sqrt{\frac{2gH}{\psi}}$$

Inner Diameter of impeller

$$D_1 = \sqrt{\frac{4Q}{\pi \cdot C_{m0} \cdot \eta_v} + d_h^2}$$

The radial velocity at the inlet is given by

$$C_{m0} = \varepsilon\sqrt{2Y}$$

ε denotes inlet number and Y is lift force. Whereas η_v represents volumetric efficiency.

$$\frac{1}{\eta_v} = 1 + \frac{0.287}{n_s^{2/3}}$$

Impeller blades angle

The blades of centrifugal pumps are commonly curved backwards in the rotational direction. Some pump impellers have straight blades rather than curved blades. The degree of curvature of the blades and the number of vanes, among other factors, affect the shape and qualities of the pump performance curve.

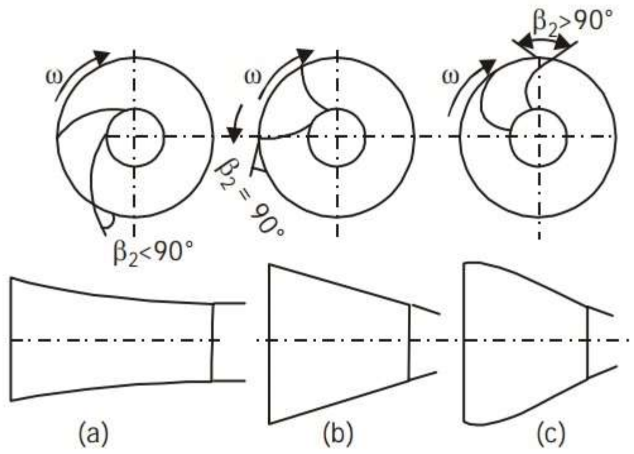


Figure 17 Blade shapes for different β_2 (a) β_2 < 90° (b) β_2 = 90° (c) β_2 > 90° (Source: Rotodynamic Pumps, 4th chapter)

Blade angles are characterized into 3 types: backward curved blades, forward curved blade and radial blades. Inlet and outlet blade angles can be determined using following expressions

$$\beta_1 = \tan^{-1}\left(\frac{C_{m0}}{U_1}\right) = \tan^{-1}\left(\frac{C_{m0}}{\pi D_1 n}\right)$$

$$\beta_2 = \tan^{-1}\left(\frac{C_{m2}}{U_2 - C_{u2}}\right)$$

C_{u2} represents the whirl velocity at the outlet. When β_2 goes from 90° to > 90° for the same impeller rotation direction, the blade shape changes. When β_2 = 90°, the outlet blades are curved backward, radial when β_2 = 90° and curved forward when β_2 = 90°.

As a result, the flow path between the impeller's blades varies. The channel shape and the blade shape when β_2 changes from 90° to > 90° are shown in Figure 17. Blade passage is longer at β_2 < 90°, but the angle of divergence is smaller. There can be no flow separation and the flow can be seamless. The passage length is lowered, and the angle of divergence is raised for β_2 = 90° and β_2 > 90°, resulting in consequent hydraulic losses and flow separation owing to secondary flow. Because the flow path is divergent, β_2 < 90° is typically used for pumps to increase efficiency. For flow through a convergent route in turbines and return guide values, β_2 = 90° is employed.

2.3.3 CAD design of impeller

The use of 3D geometric modeling tools in a CAD system, such as SolidWorks, helped speed up the design process. The complex portion with such components is that defining the blade/passage shape, such as blade angle distribution between the leading and trailing edges, is heavily reliant on the experience of a skilled designer. The model is built on the dimensions [37] presented in Table 5

Table 5 Impeller dimensions

b_2	Impeller inlet width (mm)	14.38
D_1	Impeller outlet diameter (mm)	102
D_2	Impeller diameter (mm)	255
D_3	Volute base circle diameter (mm)	266
D_4	Volute inlet diameter (mm)	65
D_h	Impeller hub diameter (mm)	30
e	Blade thickness (mm)	4
z	Blade number	6
ϕ	Blade wrap angle (°)	97.52
β_1	Inlet blade angle (°)	39
β_2	Outlet blade angle	28.22

2.4 Material Selection

Materials are divided into the five broad classes that are visible in Figure 18: metals, ceramics, glasses, elastomers and polymers. Hybrid materials are the combination of the different materials for example composites, sandwiches, cellular structures, etc.

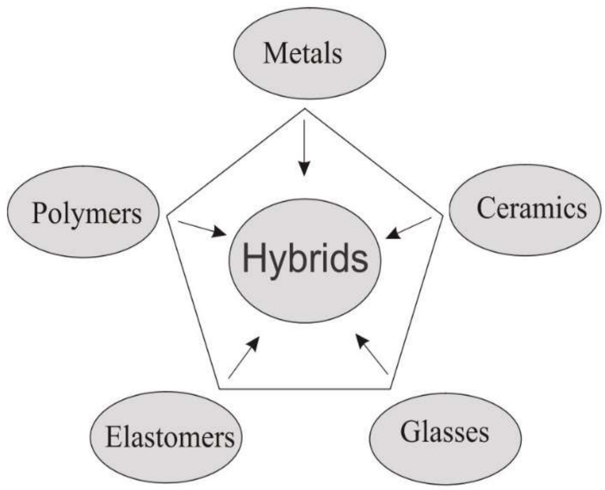


Figure 18 Material classes

2.4.1 Important consideration for impeller materials

Due to the compounds included in the fluid used in various industries, different physical damages take place in the sections of the fluid contact of the centrifugal pumps used for irrigation. Wear, corrosion, and cavitation are the three types of wear that can occur on pumps [38].

Wear or abrasion is defined as the removal of unwanted material caused by contact friction on the object surfaces that move relative to each other. The rate of wear of the revolving and stationary elements of the pump is determined by the materials used. Although material hardness is not the only standard of wear resistance. The wear processes differ. They can be physical or chemical in nature. Mechanical, corrosive, and adhesive factors all have a role. The deforming action of small particles or surface protrusions during friction causes abrasive wear. When one component is harder than the other, the softer material bears the brunt of the effects. Abrasive particles might enter the system through lubricants, the air, or debris from prior wear. In many fields, e.g., oil and gas industries, where these types of microscopic bits may be encountered, abrasive wear is a risk.

Corrosion is caused by chemical and electrochemical reactions in liquid or gaseous environments which causes metals to lose their metallic characteristics. A protection is required to save metallic parts from corrosion. Generally, all kinds of machines have protection against corrosive environments of the oceans. Long interactions with fluids and seawater increase the chance of corrosion. Although bronze, brass, stainless steel, zinc, and aluminum can endure a long time in very slow corrosion circumstances without protection. Structural corrosion of iron and steel can occur quickly if the metal is not properly protected.

The corrosion of a material's interior structure is known as intergranular corrosion. Centrifugal pumps are especially vulnerable to impeller erosion and corrosion. Erosion corrosion happens when metal and liquid are subjected to slip and friction forces. It is a type of corrosion that occurs when a corrosive fluid comes into contact with a metal surface. When two metals are electrically coupled and submerged in a conductive solution, galvanic corrosion or bimetallic corrosion occurs. Cast iron, iron, and graphite are all affected by galvanic corrosion. Graphite corrosion has had a severe impact on the cast impellers that operate in seawater. Cast iron impellers can experience graphite corrosion which causes irreversible deterioration.

Fatigue can also occur in any material that is susceptible to simple corrosion under periodic loading. When selecting material for sections subjected to varying loads, the material's entire variable stress limit must be taken into account. The highest total variable stress value on the material rests without distortion is known as the whole variable stress limit. The material will not deform if the stress magnitude does not exceed the whole variable stress limit. In a corrosive environment, however, the same steel will deteriorate quickly if subjected to full tensile stress of 200 MPa. The shaft carries load at every turn, and its life lifetime is determined by the material's fatigue corrosion resistance and rotating speed. The easiest technique to avoid shaft wear is to use shaft bushings to keep the shaft from coming into touch with the liquid.

Seawater contains moisture, oxygen, and salts, all of which are more destructive to metal than rust. This mixture corrodes the metals, weakening and causing them to fall apart. Metals corrode five times faster in seawater than in freshwater, and ten times faster in ocean humidity than in normal. The material properties of components are determined by the size, shape, and hardness of the particles present in the liquid. The presence of diverse chemicals in the liquid, even at small levels, has a substantial impact on the solution's corrosive action. If the wrong material is used, the effect of seawater might cause excessive wear.

Cavitation occurs when the fast evaporation occurs due to the suction line pressure becoming equal to or lower than the vapor pressure of the fluid. The formation of bubbles at low pressure, and when they reach the wheel, they burst into the high-pressure zone, where they concentrate in a very short time. The pump's effectiveness is diminished by cavitation, and it appears that the impeller is crushing sand. The enormous pressure created due to the eruption of steam bubbles wears down the pump's components, particularly the suction mouth and impeller. The impeller blades are blasted by hammer impulses, and cavities are created on the wheel surface. Aluminum bronze, monel metal, hardened martensitic steel, and titanium alloy steel are the materials with the best cavitation resistance. Using laboratory data and practical experience of cavitation-resistant materials, cast iron, bronze, steel casting, manganese bronze, martensitic steels, austenitic steels, and nickel-aluminum bronze can be used in pumps.

2.4.2 Common materials

The variety of available materials, metallic and non-metallic materials are favored for centrifugal pumps, according to KSB, one of the leading manufacturers of the pumps, however, the specific choice relies on the level of stress involved [39].

Metallic material

Metallic materials include cast materials, forged or rolled materials, and materials in other product forms. Due to the high level of design freedom and wide choice of specific alloys, these are the most commonly used design materials for pump casings and impellers. The cast materials differ depending on the composition of the material.

Plastics

According to the ISO 1043-1 standard, plastics are classified into four classes depending on their mechanical response to temperature. The mechanical characteristics of the 4 groups are described below:

Thermoplastics: These materials can be distorted multiple times when exposed to heat. Polystyrene (PS), polyvinyl chloride (PVC) and polyethylene (PE) are some examples.

Elastomers: Materials with wide-mesh, cross-linked, and high-polymer with rubber-like elastic characteristics in different temperature ranges.

Thermoplastic elastomers: Crosslinked, wide meshed, and high polymer materials with rubber-like elastic characteristics above 20 °C. Polyethylene or high molecular weight polymethyl methacrylate (PMMA) are examples of such materials.

Thermosets: Cured high-polymer materials with close-mesh cross-linked substances such as phenol formaldehyde resins, epoxy, or polyester.

Elastomers are employed for sealing elements or as coating materials, whilst thermoplastics are used as design materials for impellers and diffusers.

Ceramic materials

Ceramic materials are characterized as non-metallic, inorganic, and crystalline materials (more than 30%). Ceramics are increasingly being used for various components, such as impeller wear rings, casing wear rings, and impellers, in addition to being employed as state-of-the-art technical ceramics for sealing and bearing elements.

MATERIAL	CHEMICAL COMPOSITION	SPECIAL FEATURES
SIC, SINTERED	SiC > 96% Si < 0.5%	Excellent heat conductivity
$\mathbf{ZrO_2}$	ZrO_2 > 85% $MgO, CaO, Y_2O_3: 0 - 15\%$	High thermal expansion and high strength

2.5 Manufacturing techniques

Several ways have been used to make centrifugal compressor impellers over the years. With the inception of new materials and the development of machining procedures, the production methods have evolved a lot. Below is a brief introduction of widely employed manufacturing methods for impellers.

2.5.1 Three piece method

The three-piece construction is the most conventional method for making impellers. It is named after the 3 independent components: the hub, blades, and cover. Most impellers were constructed this way before the start of new millennium. Many parts and relatively basic designs made blade shaping, machining, and fabrication easy. Generally used materials were low alloy steels. The thin sections of blades also enabled the usage of a range of product forms, such as plates, sheet, forgings, and bars. Each impeller blade was hot molded or machined to its final shape. The hub and cover components were machined, and the blades were installed before the sections were connected.

While piece-wise production carries many advantages, the disadvantages include being intensely manual and reliant on the technical prowess of employees. For instance, any geometrical errors or improperly positioned blades could have caused major consequences in terms of aerodynamic performance, structural integrity, and vibrational/modal behavior. Fortunately, because the less sophisticated designs of the time were relatively strong and operating needs were less rigorous, the human factor was more than compensated for, and the construction process was able to function for decades [40].

Figure 19 An impeller with separate blades (Source: Metrology News)

2.5.2 Two piece method

In the late 1990s, more sophisticated 3-dimensional impeller designs were introduced which gradually became more preferable. Since such designs had far less room for error in order to produce a high-quality item so they effectively replaced the three-piece fabrication. As a result, the original equipment manufacturers (OEMs) shifted their focus to it, and it is now used in most impellers manufactured today. In contrast to three-piece production, almost all the parts are forgings, and the blades are integrally machined into one of the sections and use separate hub and cover pieces. With the availability of 5-axis CNC machines, complicated blade designs can now be precisely manufactured to strict tolerances. Due to the numerical control, the variability inside and between pathways is considerably decreased, as many of the probable deviations are eliminated. The impeller parts are attached using different kinds of welding which introduce heat deformation and negate some of the benefits of this process [40].


Figure 20 Welded impellers (Source: PTR Welding Services)

2.5.3 One piece method

The single-piece impeller has no joints and is built of a single piece of metal. Because most OEMs are familiar with 5 axis machining of two-piece impellers, using the same method to a one-piece impeller is a natural progression. Impellers of any size are theoretically achievable and can be manufactured because of the 5-axis machines' flexibility. The accessibility and reach of a design determine how far it can be machined. The tools must be appropriate enough to accommodate the flow channel and have to manufacture the profile in terms of accessibility. When it comes to small impellers, tool size is a key stumbling block. Reach is important since the greater the impeller, the longer the supports must be to hold the tools.

The long, thin supports on bigger impellers with small tip holes are frequently not robust to resist the deflection or tool bouncing, which is harmful for both impeller and the tool. The impellers with narrow tip openings effectively have 2 downsides, that normal tools are too large and require extremely thin supports. Because of these variables, the majority of one-piece impellers now on the market are wide and open designs. Milled one-piece impellers waste a lot of material. This might, in theory, limit the materials that can be used to create impellers. Provided the high costs of raw materials and the waste material amount, it would become very difficult to machine an impeller of titanium economically competitive [40].

Figure 21 One-piece machined impeller (Source: Metalex)

2.5.4 Alternative methods

The alternative methods are as follows. These methods are discussed at length in Appendix III

- Electrical discharge machining (EDM)
- Investment Casting
- Hot Isostatic Pressing

2.5.5 Comparative study of manufacturing methods

This case study is presented with the intention to draw a comparison between different manufacturing methods covered earlier. The study is based on the research published in Asia Turbo Machinery & Pump Symposium. The methods included in research are: EDM, Investment Casting (IC) and Additive Manufacturing (AM). The investment casting is done in 2 different ways: impeller with the 3D printed pattern and invested flow path (SLA IC) and using a ceramic core in the mould (Core IC).

The cost of each item is shown in the graph in comparison to a 17-4PH brazed impeller. The precipitation-hardening stainless-steel 17-4 PH is a kind of martensitic stainless-steel which allows designers to improve product reliability while simplifying fabrication and lowering costs. At temperatures up to 600°F (316°C), it delivers an extraordinarily high strength, strong corrosion resistance, and better mechanical qualities. For additive manufacturing, a material of Inconel 718 was printed using direct metal laser sintering (DMLS).

The impeller has a diameter of about 300 mm, a tip opening of less than 6 mm, and 3 blades. The tolerances were for two-piece construction with 5-axis milling tolerances. The impellers were put through a series of tests to assess their structural stability and dimensional accuracy, as well as to characterize the material qualities that resulted [40].

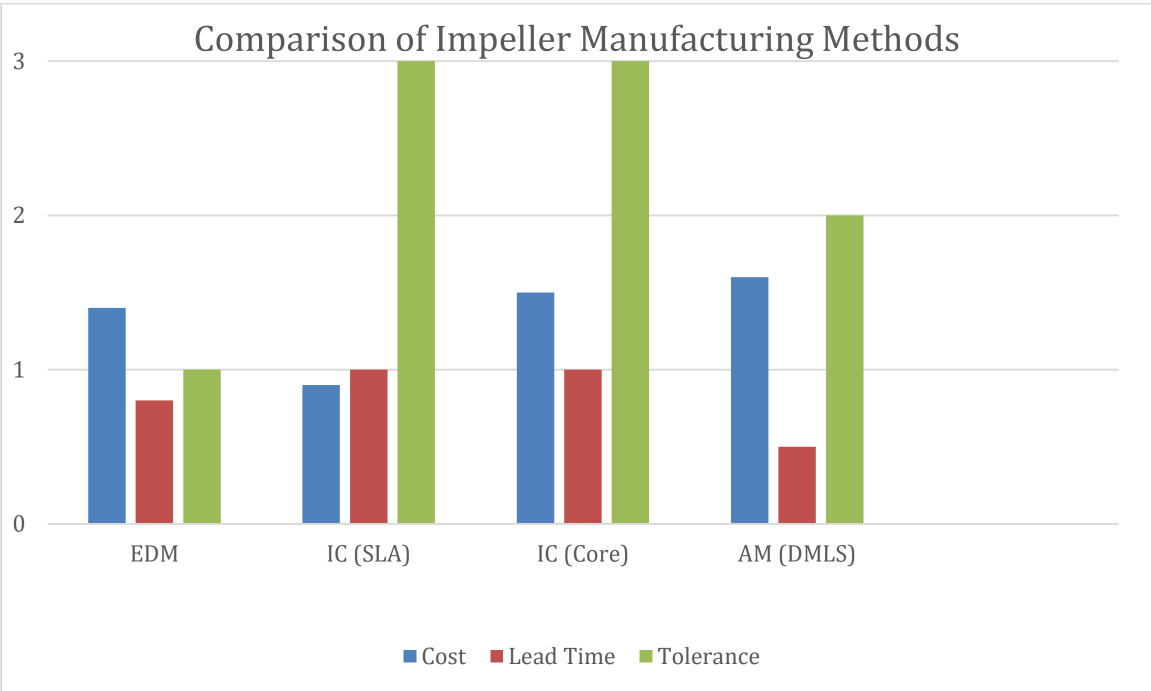


Figure 22 Comparative analysis of different impeller manufacturing techniques

The impeller with 3D printed design and invested flow path (IC SLA) was the least expensive in this comparison. The use of ceramic core in the mould (IC Core) raises the cost by around 50% over the brazed impeller. The DMLS and EDM are roughly 45% and 30% more expensive, respectively. Additionally, the material for DMLS is more expensive and the equipment for these processes is reasonably economical to purchase and build in-house, which can cut expenses.

All methods were as quick as or quicker than the brazed impeller's typical time. In this regard, the DMLS impeller has a significant benefit, taking half the time of the normal impeller. It was noticed that the impeller took just under two days to manufacture. The majority of the cost and the time associated with this technology are determined by the build height rather than the scope of intricacy necessary in the horizontal plane. The EDM took the 2nd shortest time, accounting for 75% of the time consumed by a brazed impeller. EDM and DMLS might be sped up if the machines were in-house, because the majority of the lead time is spent on planning instead of work actually.

While the investment casting has its own scheduling issues, the processing of these impellers takes a long time. The pattern print time is comparable to the DMLS impeller's construction time; however, the investing process, heat treating, and upgrading cycles can all take a week or more. EDM outperformed the others in achieving those criteria. All of the dimensions that are routinely examined in a production impeller were easily met. The impeller made with DMLS was marginally more accurate than the investment cast impellers based on the cited tolerances and preliminary results. While manufacturers might be able to brace the ranges on future impellers, it remains very unlikely to attain the desired tolerance.

In general, all of the methods can produce impellers in this size range. The production method will entirely be relying on the circumstances. If the circumstances were different and the identical impeller design was mass produced, investment casting providers can perfect the requisite tooling, which might be impossible to attain for cost and, perhaps, lead time with others. In contrast, each of them is in a different stage of development when it comes to a custom, one-off application. In this regard, EDM and AM are definitely the most sophisticated and ready for use. The other methods haven't advanced far enough to draw firm judgments, but additive manufacturing and investment casting appear as extremely viable options. Particularly, AM is interesting since it is still relatively latest, and the surface has only been scraped in terms of what it can do [40].

3 Chapter III

3D Printing

- Challenges in printing components
- Solutions to overcome problems
- Finding the right type of printing technology
- Deviations in printed parts
- Manufacturing techniques

3.1 Pre-requisites for 3D printing

Every machining and manufacturing method brings its own set of prerequisites which are necessary to carry out any function. Similarly, 3D printing technology cannot perform without deciding about the prerequisites. Due to large variety of printing technologies and machines it is not possible to explain all prerequisites here, but a general list of prerequisites is as follows:

3.1.1 Materials

It's crucial to remember that 3D printers can produce a wide range of materials. Nonetheless, there is a small group of materials that cannot be printed with 3D printers. The most crucial thing to understand is that parts cannot be printed using materials that cannot be melted. Because some materials burn instead of melting, care should be taken while choosing the element to use. Some of the materials which cannot be, currently, used for 3D printing: are rocks, wood, paper, fabric, and textiles

3.1.2 Component shape

The 3D printers come with ability to produce components of various shapes, from simple geometries to very complex parts. It will not be unrealistic to say that there are not so many shapes that a 3D printer cannot produce these days. However, this does not imply that this approach can produce all shapes. Following are some exclusions in more detail below.

- Shapes with reduced base contact or the objects with thin or sensitive contact with their bases will be challenging for a 3D printer to create. The object with insignificant base-contact has a greater chance of detaching from the printer platform.
- Thin-edge parts or objects that are too thin, such as the thickness of a knife-blade are quite difficult to produce with 3D printing.
- Parts with large overhangs and bridges in 3D model designs might be challenging to print at times.

3.1.3 Long size components

The 3D printers come in different sizes which are still developing. It is not possible to print parts that go beyond the printer dimensions. It is very difficult to print an item that is larger than these dimensions and it becomes complicated to locate equipment capable of printing a massive thing in one go. Another option is to print the object in sections. Extra large-format 3D printers for professional and industrial applications are the solution for massive goods, prototypes, tools and fixtures, and moulds and casts.

3.1.4 Wall thickness

The surface quality and dimensional accuracy of the printed parts are affected by the wall thickness. High extraction temperatures and median wall thickness values enhance both dimensional accuracy and surface roughness, according to the findings, with temperature being the most critical element. The layer thickness and printing plane are most important factors for length and component thickness, respectively.

3.1.5 Complex geometries

Additive techniques have been utilized for decades to create complex geometric structures that are frequently employed as physical models and prototypes for a variety of applications. Provided the capability of latest 3D printers it is not fair to process parts which can easily be made using traditional machines such as lathes or CNCs. Parts with simple geometry and regular operations, drilling, turning, facing etc, are more economic to produce by conventional methods because 3D printing will take more time as well as costs.

3.1.6 Customized and low volume production

According to the Forbes, the technology has numerous advantages, but it also falls short in several key areas [41]. Being too sluggish for many mass-production applications, most experts agree that it will require many years to replace existing mass production technologies like injection moulding. The production speed of 3D printers is limited. To fulfill a large number of product orders, a large fleet of printers should be on hand. The alternative option is to begin with low-demand items and work way up to meet all demands.

Case Study: Printing of Poppet Valve

Poppet valves are used in compressors. They operate in difficult applications with oily and particle-laden gases. The valve body sections are composed of stainless steel, and it can also be made of different materials depending on the application. Whereas the poppets are made of thermoplastic polymers with high performance (e.g., PEEK and polyamide with appropriate fillers). For cryogenic applications and compressing very hostile gases, filled PTFE is used.

Initially, it was decided to print 2 parts of valve assembly, replaceable seat plate and poppets. The decision was based on the findings of the OREDA. Leakage makes up approx. 9% of total failure mechanisms, third only to unknown problems and faulty conditions. The leakage can decrease the efficiency of system and eventually halt the process. The possibility to 3D print sealing components was tested.

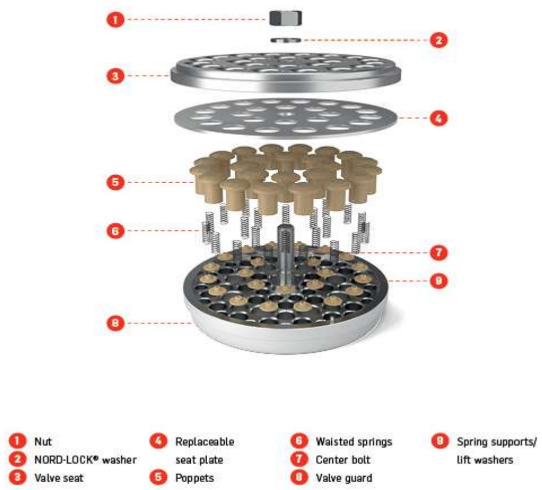


Figure 23 The poppet valve (Source: Buckhardt Compression Poppet Valve)

Based on aforementioned pre-requisites following table was prepared

Pre-requisites	Status (Y/N)	Notes
Material	☑	Plastic and metal material are widely printable.
Component Shape	☒	Poppets have less base contact and overhangs which needs to be supported properly.
Wall Thickness	☑	Wall thicknesses are appropriate
Warping & Curling	☒	There is an imminent chance of warping of seat place.
Low volume production	☒	The part is a mass production of batch production part which will take more time and effort on 3D printers.
Complex geometry	☒	The geometry is simple and can easily be achieved on any 3-axis CNC machine.

In order to proceed further with desired parts, it is necessary to accommodate all prerequisites appropriately. For instance, the geometry should be designed with supports. Simultaneously, the geometry of part is not very complicated, and it can be made on readily available forming machinery. In order to decrease the chances of warping, it is mandatory to set up proper heat exchange system which will add more cost to the product value. Products with simple designs can have counterproductive consequences.

Price matrix for 3D printing the "Skinneprofil" on Lumex 60 Avance					
			Powder cost for the project		
Material cost (stainless steel 630)	1991	nok/kg	2389,2		Printing cost (current setup)
Machine hourly rate	598	nok			21706,2
Manual labour (operator cost)	900	nok			
Build plate	3000	nok			
xXxXxXxXxX	0	nok			
Filter cost per hour	49	nok			Total cost (current setup)
Additional materials	200	nok			26206,2
Printing	Current setup (0.05 mm layer)	Possible setup after update (assumed, 0.1 mm layer)			
Build time (hours)	11	17			
Programming	2	1			
Setup of the machine	4	4			
Part removal and machine cleanup	3	3			
Service while printing (maintenance after 10 hours)	1	2			
Post-process					
Heat treatment	1	0	done while machine cleanup		
Part removal from the build plate	2	0.5			
Post processing (machining the bottom side, treading)	2	3			
xXxXxXxXxXxX	0	1			
xXxXxXxXxXxX	0	1			

Figure 24 Cost analysis of valve plate (Source: Lazar Sibul, Labingeniør, UiT Narvik)

The cost analysis shows that a valve plate can cost around approx. NOK 22,000 which is far too high for such product. The 3D printing might save the material cost but, according to lab engineers, it will take more time and incur high costs. Conclusively, it can be derived that the component selected must show high conformity to the pre-requisites.

3.2 Common challenges in printing components

Like other manufacturing methods, there are some complications connected to the use of 3D printers. It is important to highlight these challenges and find suitable solutions to save time, material, and costs. Common challenges are discussed here briefly.

3.2.1 Shape optimization

Generally, the traditional manufacturing processes create parts with solid interiors. AM has the ability to fill the product's internal space in nearly any way. This design space might comprise both the model's perimeter and its inside [42]. The optimization of the design space has a substantial impact on the printing of the part, reducing time, materials to manufacture, electrical energy, and environmental costs, resulting in lower production costs [43]. The goal is to select the optimal material to fill in the design space while optimizing specific design criteria like as strength, mass, and volume. Even if a suitable allocation is discovered, it may not be compatible with all techniques of 3D printing. Trapped material, poorly made walls, and a lack of support can all cause problems [42].

To determine the best material allocation, there are two ways that are often utilized.

- Structures such as lattices, honeycombs, and other recurring shape elements
- Topological optimization to fill the design area by allocating material in the design space while attempting to meet certain design specifications.

3.2.2 3D printing specific design

The design process must be reconsidered to support designs for 3D printing. The current CAD software have not been created with the 3D printing in mind. Boundary representation and constructive solid geometry are commonly used in the systems which restricts what can be done with 3D printers. Geometric complexity and operations on many features constitute a bottleneck in CAD software [44]. When developing for 3D printing, the system must be aware of the constraints and advantages of the process. Manufacturing materials are one of the most significant impediments. Due to restrictions, this might render few designs that are possible with other modes of printing impossible. The materials must show compatibility with the manufacturing method, which may limit the options available to the designer [45]. Similarly, creating intricate patterns by printing parts in various pieces may necessitate changes to the design and assembly planning. There are a variety of methods for making interlocking components, but none of them work for every type of geometry [44].

3.2.3 Pre and post-processing

3D printing does not provide a perfect printed part immediately after the model is created. Before sending the model to the printer as a set of instructions for building the part, it must be pre-processed. Depending on the technique, further care may be needed to remove supports, increase the surface quality, or finish crucial components after the part has been created. Pre- and postprocessing, both, present unique challenges that influence how designers approach the printing process as a whole. Pre-processing is a process of dividing a model into individual tasks to plan ahead of time for the printing process. The four tasks that make up the planning process [46] are

- Creating STL
- Selection of the ideal orientation
- Slicing the model
- Producing supports (if needed)
- Arranging the tool path

To bring a printed part's accuracy closer to the genuine model, it may require additional care. Nearly all 3D printing technologies involve the removal of support structures, cleaning, and extra curing stages. The secondary curing procedures include coating of surfaces for protection, polishing, and surface roughness improvements. Post-processing can be expensive, especially when done by hand which is time-consuming and inefficient [47]. In large-scale production, it will also become unsustainable. The cost of post-processing can be nearly a third of the cost of producing a 3D printed model. According to the 2018 Wohler's research, post-processing costs can account for 27% of the total costs of making a model [48]. Fortunately, the recent development of a variety of post-processing devices means that the task of finishing 3D printed items can be automated, lowering prices.

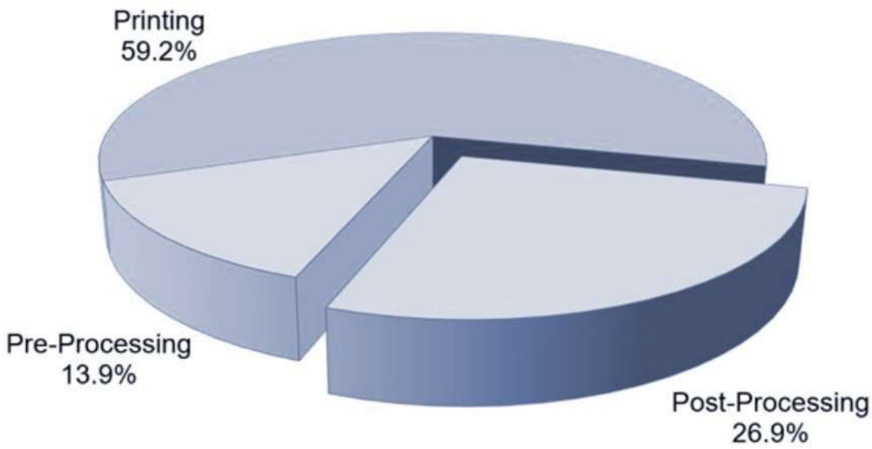


Figure 25 Cost segmentation (Source: Wohlers Associates)

3.2.4 Selection of printing

When it comes to additive manufacturing, there are a number of different methods that may be employed to create items. Other methods are available, but lay-by-layer manufacturing (AM) appears to be the most common and thoroughly researched. Each method, like any other sort of engineering, has advantages and disadvantages. Depending on which manufacturing option is chosen, the part's mechanical or physical properties may be greatly impacted. For example, in order to print a metallic part with high strength values. Figure 26 can be referred to

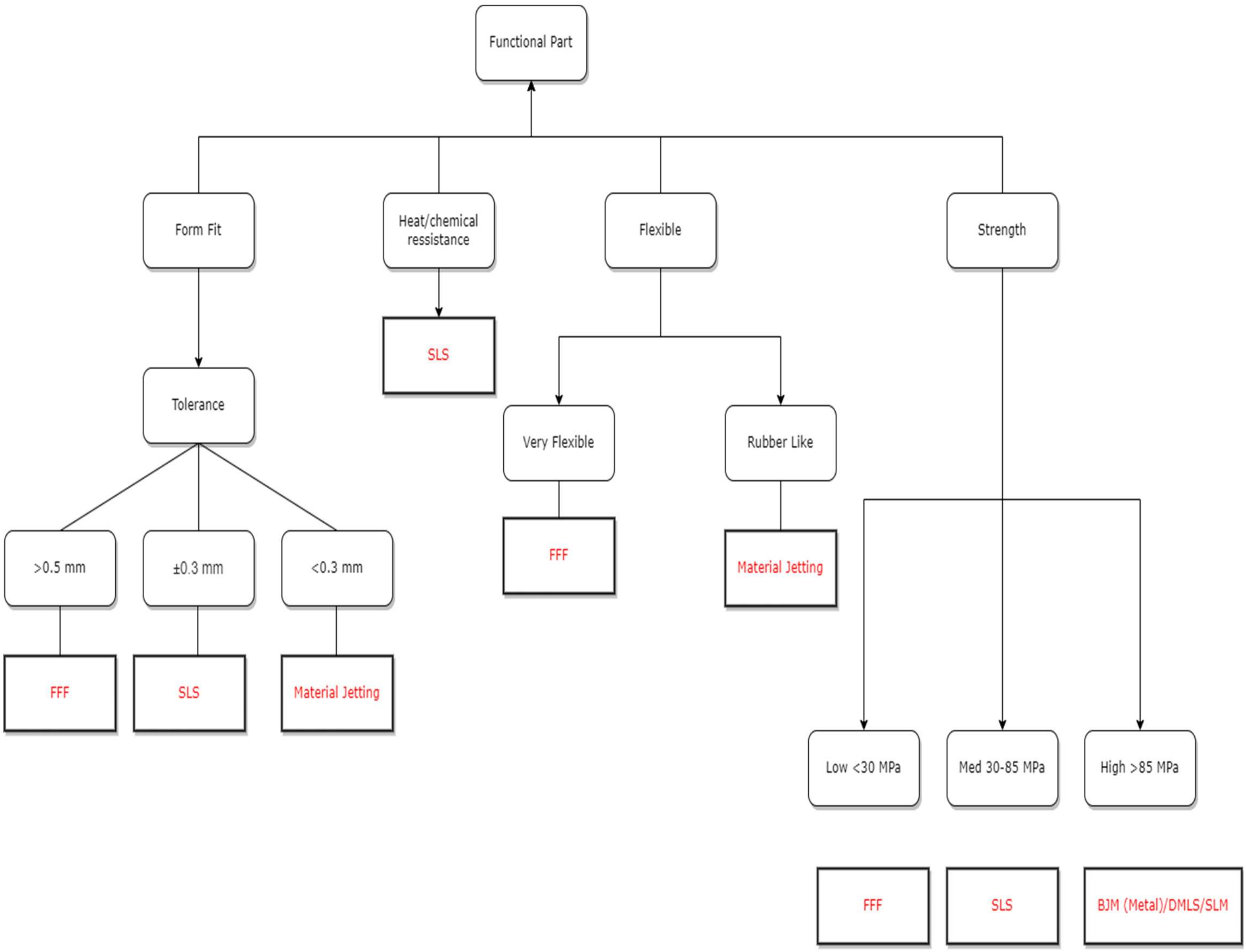


Figure 26 3D printing method selection (Source: The 3D Printing Handbook)

3.2.5 Error control

3D printing, like any other production method, has its drawbacks. The current equipment on the market may not always be the most trustworthy due to a lack of quality control methods [49]. The three categories of 3D printing defects include data preparation, process error, and material error. Error avoidance could be done during the data processing step, however, due to the nature of process material problems, avoidance may not be practicable. The orientation, slicing, path planning, tessellation, and accessibility parameters can all be altered, and errors can be anticipated, but they are still not completely preventable [50].

Deviations in the parts might also be produced by machine tool speed fluctuations or positioning system errors. There is no method of recognizing when an issue has occurred because most current 3D printing systems lack a feedback or process monitoring system. Consequently, the rectification of errors is quite tough. Although research is being conducted over combining subtractive and additive processes to improve error and precision, this will increase the complexity of hardware and planning [44]. Similarly, there are other errors like material errors which should be counted for.

3.2.6 Hardware and maintenance issues

AM machines have their own set of issues with maintenance and performance. Each machine must be set up with the essential specs for a successful build. These criteria include energy constraints, material barriers, and process-specific restrictions. Clean-up activities on the machines are frequently required after a part is completed to keep machines functional. Simultaneously, there are different materials which must be stored in a specific condition and temperature, for example photopolymers. This material handling and maintenance requires special attention and routines which increase the cost and time for using such machines [44].

3.2.7 Part orientation

The manufacturing process is influenced by several factors that are co-related to the build direction. It's also important to remember that there might not be any ideal orientation that fits the design's requirements. Especially, when optimizing numerous criteria at the same time. The number of possible orientations is theoretically limitless [51]. Altering the position of any part to minimize or maximize any manufacturing factors is what the part orientation problem is all about. Certain characteristics may be more crucial than others depending on the part's use or function. In the literature, many alternative methods for determining an ideal part orientation have been utilized.

3.2.8 Slicing

An STL or CAD model must be divided into slices for all layered manufacturing processes. To determine the geometry of the slices, the model is bisected with many horizontal planes. The layer thickness determines the height of the slice. The model is prepared for deposition path planning by the slicing method [52]. Uniform slicing, in which all slices have equal layer thickness regardless of the geometry, is the most prevalent way of slicing employed in today's machinery.

These slices are frequently referred to as 2.5D contours since they have tend to alter the model's original geometry in vertical direction. Because of this, the slicing problem presents major obstacles. One issue is the containment problem which occurs when a slice falls either outside or inside of the original model rather than on the exact geometry [51]. These factors contribute to subgrade surface quality and precision. The slicing method has a direct impact on the part's build time, accuracy, and roughness [53]. The slicing has 3 types: adaptive Slicing, direct slicing and STL slicing.

3.2.9 Speed

Speed is frequently misinterpreted as the height of the manufactured component. The entire process, from pre-process to post-process, should be studied when analysing the pace of 3D printing. The amount of time spent planning is related to the model's and process's complexity. Process planning can be time-consuming and computationally expensive. The post-processing time is determined by the part's accuracy requirements, and it may take longer depending on the part's application and manufacturing technique. It can take additional time to prepare tools, harness material, or relocate the build platform, depending on the procedure employed to accomplish the printing. Regardless of the type of machine or procedure is utilized, the physics of the materials used for manufacture will always limit it [54].

3.3 Part printing

3.3.1 3D model

The model of the impeller is exported from CAD software, Solidworks. An operator can impact the accuracy of AM devices by making decisions about printer calibration, ambient temperature, and printing material storage conditions. In addition, other aspects of the manufacturing workflow, including as the device's geometry and thickness, printing parameters, support parameters, slicer software, and post-processing methods, have an impact on the properties of AM devices.

The 3D printing was done in 2 iterations, model 1 and model 2. Firstly, the model 1 was printed without any pre-processing and consideration towards the printing method. Whereas second iteration, model 2, was carried out using several pre-processing operations. 2 different machines were used to explain the difference between basic at-home-usable 3D printers and superior quality printers. The pre-process included following procedures:

- The best way to model any object for printing purpose is to create the model as a single mesh. By default, certain slicers can integrate many intersecting portions into a single sliced model.
- It should be made certain that all the components in a model are connected. Few slicing software will integrate the parts, while others will cause numerous complications in the connecting area, resulting in unsuccessful or falling apart prints.
- The model should be exported in STL format and quality should be increased as much as possible. High quality STL files will have minimum stair-case effect on the outer boundaries.
- The sharp edges, corners, and spikes should be rounded to ensure best surface structure.
- Thin sections are more likely to fail, and they frequently cause the entire print to fail as well. Furthermore, thin parts may break when being removed from the printer's print bed.
- There should be no gaps in the model. Slicing can fail due to the gaps. There should be no inconsistencies in the model.
- For every model a tolerance, depending on the 3D printer, is recommended for optimal size. This approach is appropriate in the vast majority of scenarios involving connected parts.
- The design should be such that no supports are required or only the bare minimum is required.
- The model can be strategically placed and rotated to reduce the requirement for supports. The rotating might affect the ultimate strength of a product due to the arrangement of layers.
- The optimal print bed positioning for a model is on the flat side of the model so that the first layers can be formed on a firm, robust foundation.

The pre-processing of designs should be carried out with consideration of selected 3D printing types and machine’s characteristics. The design consideration for printing method and machine characteristics are attached in Appendix IV.

Table 6 Printing parameters

VARIABLE	MODEL 1	MODEL 2
PRINTING METHOD	FDM (FFF)	FDM (FFF)
PRINTING MACHINE	Creality Ender 6	MarkForge Onyx Pro (Gen 2)
MATERIALS	PLA	Onyx
INFILL PATTERN	Triangular	Triangular
INFILL PERCENTAGE	25%	30%
LAYER THICKNESS	0.1 mm	0.2 mm
ORIENTATION	Shroud on bed	Shroud on bed
PRINTING TIME	16 hours	13 hours

The printed parts are shown in Figure 27 and more information about infill patterns can be found in Appendix V**.** Model 1 has a very uneven surface which will obviously lead to substandard performance. Furthermore, the inferior print quality of shroud section (base of impeller) allowed for warping. The nozzle did not stop the material feed while moving to other blades which produced a net of thin wires across the whole structure. The amount of post-processing is high and will be difficult to process the pathways between the blades. Whereas the printing quality of model 2 outshined the print quality of model with a very high margin. The aesthetics are easily comparable to those parts made after long hours of CNC operations.

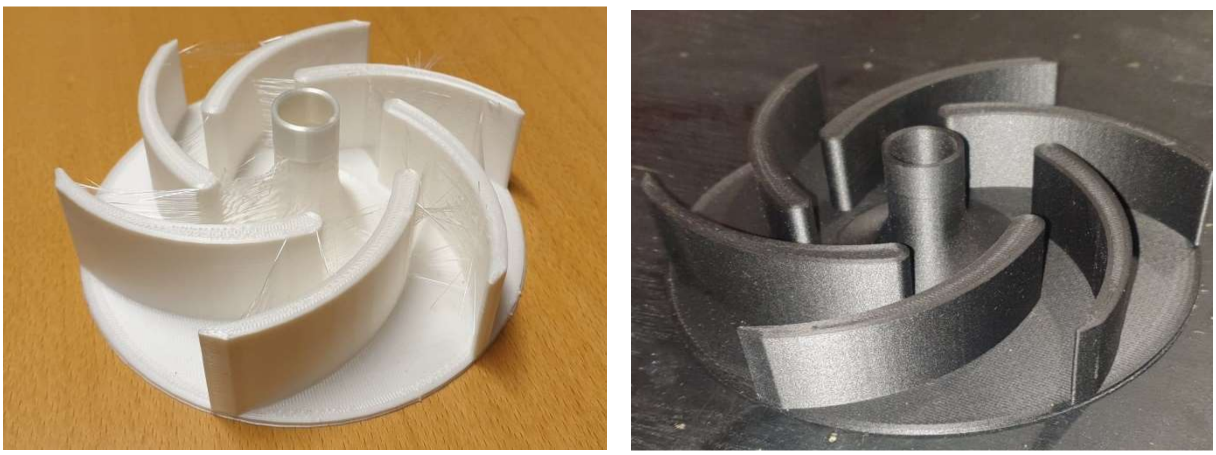


Figure 27 Printed impellers Model 1(L) and Model 2 (R)

The materials used for both models are PLA and Onyx. With the increase in use of plastics for building pump impellers and casing many materials including PLA and PFA are getting attention. Further details for these materials can be found in Appendix IV. The loss of energy in the pump is dependent on relative surface roughness and Reynolds number, both have an impact on pump efficiency. Surface roughness is becoming increasingly significant in boosting pump efficiency. According to a test, different values of surface roughness (0, 1, 10, 20, 40, and 80 μm) were used for the numerical computation of the 5-stage pump to explore the effect of surface roughness on pump performance [55]. As can be observed, as the head (H) and efficiency (η) continue to decline with the increase of μ.

Roughness μ (μm)	0	1	10	20	40	80	Test value
η (%)	41.67	41.13	37.71	35.34	32.46	28.96	40.73
H (m)	41.83	41.62	40.27	39.25	37.83	35.91	41.87

Figure 28 Effect of surface roughness on the pump performance and head [55]

A similar study shows the method to attain best quality surface of stainless-steel impeller made up of AISI 410 material. According to the results, the best-achieved surface roughness is equal to 0.876μm [56]. Correspondingly, the values of surface roughness of printed parts were measured using Mitutoyo Surftest-211. The results are as follows

Table 7 Surface roughness value

MODEL	MATERIAL	MINIMUM VALUE	MAXIMUM VALUE
IMPELLER 1	PLA	1.58	8.37
IMPELLER 2	Onyx	2.45	11.08

The minimum values show the quality of surface in the direction of printing whereas maximum values show the opposite. The maximum values can be brought down using various solutions which are readily available. On the other hand, minimum values prove the fact that 3D printing machines can, without a large machining facility and long set-up time, can deliver optimal results.

3.3.2 Post-processing

As mentioned earlier, every printing technique has its own specific post-processing requirements. Table 8 provides post-processing details for FFF, whereas such details for other techniques which can be used to produce impeller are listed in Appendix V.

Table 8 post processing operations for Material Extrusion (FFF) (Source: The 3D Printing Handbook by Ben Redwood)

TYPE	POST PROCESS	DESCRIPTION
COMPULSORY	Support removal	If a smooth surface is desired, the surface in touch with the support material will usually need to be sanded. Support can be dissolved without losing surface quality in the case of dual extrusion.
SURFACE FINISH	Sanding	Sanding is possible with FFF materials. Because some FFF plastics are soft, light sanding with a high grit sandpaper (600 or higher) is recommended.
	Gap Filling	It's a solution that's applied to the surface of FFF parts to make them smooth and consistent. Epoxy resins are a suitable choice for filling gaps. For larger spaces or surfaces, autobody filler is employed. The surface is sanded after the filler has dried.
CONNECTING	Cold Welding	ABS cold welding is a standard method for joining two pieces together. Acetone is used to melt the components together, resulting in a strong bond. After drying, the joint is sanded.
AESTHETIC	Polishing	After sanding, the surface is polished with a plastic polishing compound. For designs with small intricate details, polishing may not be the best option.

	Vapor smoothing	Vapor smoothing is a process used in the manufacture of ABS products. For a brief period of time, parts are placed in a chamber and subjected to acetone vapor. The vapor dissolves the part's exterior surface, resulting in a smooth, polished surface with considerable detail loss depending on the degree of smoothing.
	Epoxy Coating	The prints are given a firm, smooth exterior layer as a result of this procedure. The most popular way is to employ two-part epoxies. Thin layers of epoxy are applied and built up to the required thickness.
	Priming & Painting	The better the surface is prepped before painting, the better the finished product will look. Before painting, two thin coats of primer are applied. Regular spray paint is suitable for painting and will result in a smooth finish.
	Metal Plating	To produce a metal finish, FFF pieces can be covered with a conductive coating and then subjected to typical metal coating techniques.

Since the parts are printed with other material than ABS so there is no requirement for Acetone processing. Other listed operations can be carried out with general mechanical machinery. The important factor here is to determine whether or not machines are available at the offshore locations.

Chapter IV

Reliability & Lifetime of 3D Printed Parts

- Effect of process parameters on the strength and fatigue behaviour
- Effects of post-processing of 3D printed ABS parts
- Reliability of 3D printed products
- Effect of environmental changes on dimensional stability

4.1 Effects of process parameters on the strength & fatigue behaviour

A study conducted to analyse the lifetime of PLA-graphene filament products printed using FFF technology provides results to predict the lifespan of similar parts. According to the results, the varied sources of temperature and printing rates influence the mechanical function and lifetime of 3D-printed products. The specimens were tested under quasi-static and fatigue loadings to measure the effects of print speed and platform temperature [57].

The mechanical properties are affected by printing parameters such as bed temperature (T_B) and printing speed (S). The findings show that ultimate strength increases with increase in print speed and platform temperature, although print speed carries a greater influence. The printed products did undergo a tension-tension stress-controlled fatigue test at the frequency of 1 Hz. The Wöhler curve demonstrates that the fatigue life period is roughly 100 cycles for large amplitudes (35 MPa), but a change of 15% and then 40% in applied stress results in fatigue life of 5000 and 2104 cycles, respectively. It was determined that the spool material's ductility might result in a long-life cycle despite its low strength.

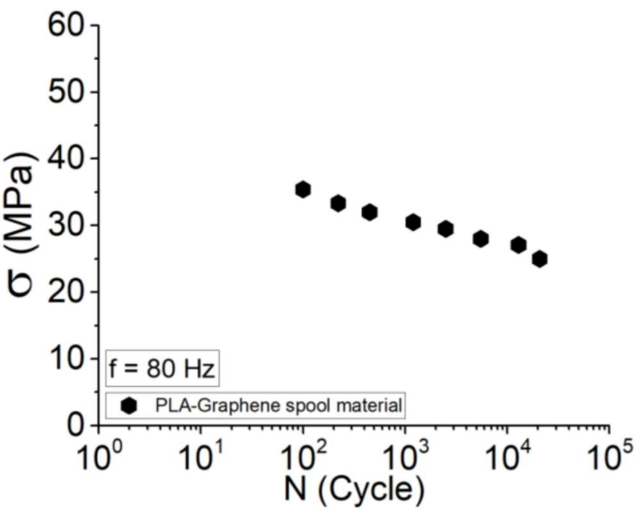


Figure 29 Wöhler curve for PLA-Graphene spool material [57].

The results reveal that there is a fluctuation in the material's life cycle as a function of platform temperature, for both low and high amplitudes. A 20°C difference in platform temperature results in a two-fold increase in fatigue lifetime. The same experiment was carried out on specimens printed under different conditions, although samples' overall fatigue lifetime was increased by ten times. It's worth noting that print speed will always have an impact on these comparisons [57].

4.2 Effects of post-processing on 3D printed parts

A similar study was conducted by University of Siegen, Germany and NTNU, Norway to measure the mechanical specifications of 3D printed parts with ABS material. As already known, the surface quality of FDM 3D-printed parts is often poor. End users are sometimes dissatisfied with the surface quality due to the certain applications. As a result, it is critical to enhance the surface quality of 3D printed objects. The research examined the effects of acetone in the post-processing of 3D-printed ABS components [58].

The acetone was used to enhance the surface quality of printed parts. The tensile stress and water absorption tests were performed on both untreated and treated specimens. Immersion in acetone solution made 3D-printed ABS pieces more ductile. The impacts of the surface modification on the mechanical properties and performance of the evaluated pieces were shown by comparing the results. The fracture load and tensile strength of all 3D-printed ABS specimens were reduced after surface treatment, according to the findings [58]. The results are shown in Table 9

Table 9 Specimen characteristics before and after post-processing

PROPERTIES	SPECIMEN	VALUE
FRACTURE LOAD	Treated	1951.7 N
	Un-treated	2026.1 N
TENSILE STRENGTH	Treated	26.25 MPa
	Un-treated	29.37 MPa
FRACTURE TOUGHNESS	Treated	2.49 MPa
	Un-treated	2.62 MPa

The surface unevenness has practically evaporated following the chemical treatment and reduced from 185.4 μm to 57.6 μm. The treatment also caused softening of material which is basically caused by the absorption of chemical during the treatment, and it is one of the reasons leading towards a decrease in tensile strength [58].

The proposed surface treatment can be thought of as a straightforward way to create a smooth outer layer, which is required for specific structural parts. However, tensile strength must be considered. In this scenario, a decision must be made about how to balance the strength and surface roughness of 3D-printed items.

4.3 Reliability of 3D-printed products

According to a paper published by IEEE, the reliability test of 3D printed sensors was carried out. The old sensor and actuator technologies have been replaced with 3D-printed dynamic structures [59]. These 3D printed sensors are less expensive and much easier to manufacture. A 3D-printed laser scanner that was originally intended for a tiny confocal imaging sensor was put to the test. For 100,000,000 (hundred million) cycles first resonant frequency, the scan-line, and quality factor of three devices were examined. For all the devices under test, the results showed a 6% variance for all scan-lines, quality factor, and resonant frequency over a 108-cycle operation. It was concluded that dynamic structures built using 3D printers are excellent alternatives for a wide range of applications, including opto-medical imaging uses requiring low-cost and disposable scanning technologies. Based on the findings, it was established that 3D printed structures are intriguing possibilities for applications that require frequent disposal of a low-cost dynamic unit [59].

4.4 Effects of environmental changes on dimensional accuracy

A study has looked into the dimensional accuracy of printed parts due to changes in ambient circumstances, such as temperature and humidity. These changes can have an unfavorable effect on dimensional stability. The dimensional stability of SLS-printed 3D objects, with an emphasis on the effects of humidity changes on deformation was taken into account [60]. Humidity cycling was used to determine how humidity affects 3D printed product dimensional stability. The experiment was conducted under maximum and lowest relative humidity (RH) levels of 95 and 15 percent, respectively. The humidity levels in this experiment were adjusted to oscillate between 20% and 90% relative humidity. The ramp up and down duration was 1 hour. At extreme RH levels, the dwell period was set to 12 hours to saturate and dry the samples. Five humidity cycles were carried out, with strain values being monitored in real time [60].

Many part suppliers, such as automotive part suppliers, stipulate the maximum dimensional tolerance for parts to be at 0.5 mm in terms of root mean square (RMS) error with respect to original design. In this case, the influence of humidity fluctuations on 3D printed items by SLS was investigated for quality and reliability investigations.

A shift in humidity from 20% RH to 90% RH resulted in a total percent-strain change of 0.2 percent, according to the test data. For example, a change in humidity could cause dimensional requirements for part design specifications to be violated. From the design stage through field application, 3D printed items must be carefully considered in terms of dimensional stability owing to humidity levels [60].

4.5 Maintenance and process-related reliability issues

Many technologies that are routinely employed in today's 3D printing machines have an impact on the machines' reliability. Lasers are used in almost all stereolithography techniques which allow for exceedingly precise details and geometries to be created, albeit with much higher initial costs. Laser maintenance and upkeep can be costly in these machines because lasers have a working lifetime of anywhere from 4000 to 15,000 hours, depending on the quality of the laser [3]. Lasers must always be fine-tuned for the materials. Unnecessary over-curing or sintering can occur if laser parameters are improper [28].

Processes that deposit materials using extrusion units are less expensive alternatives to laser-based technology. However, because the materials are extracted through a nozzle which can clog and cause prints to fail in the middle of the process [3]. Because the printing heads are fixed in size, the diameter of the nozzle has a direct impact on the part's resolution and building time. Because print heads push material out rather than toggling a power source, they vary how rapidly the material may be prevented from depositing [28].

The chosen 3D printing technology faces its own set of obstacles when it comes to materials. Photopolymers must be stored with care and should not be exposed to light. Materials like photopolymers and various powders must be handled and stored with attention due to health concerns and toxicity. Even solid materials used in fused deposition modeling must be kept in an environment with low-humidity levels [28]. There may be an expiration date on materials that must be followed. After this date has gone, the printing quality may not be guaranteed. Some methods, such as stereolithography and selective laser sintering, allow materials to be reused, although care must be given to sift out and remove any portions impacted by earlier part fabrication. This takes time and failing to do so might lead to discrepancies in subsequent parts made from same material [3].

4.6 Availability of machinery for post-processing at offshore fields

The production of 3D printed parts calls for additional machinery to conduct post-processing operations. The presence of general mechanical machinery allows, to some extent, post-processing of 3D parts. For example, a lathe machine cannot perform all milling operations although by using different attachments the work capacity of lathe machine can be increased. The absence of such machinery will restrict the geometries that can be produced using 3D printers.

According to Dag Ravn Pedersen, an instructor and former offshore engineer, the offshore facilities have a very compact size and the availability of auxiliary machinery to support 3D printing is entirely dependent on the size of platform. The readily available tools are grinders, welding machines, sandpapers, and different hand tools. The possibilities of having large machining set-ups which might include milling, wire-cutter, and/or CNC machines are very slim given the tight space at offshore facilities. Another important factor is the development of unmanned offshore plants. The absence of on-site staff eliminates the chances of any human-controlled machining activity.

To find the details of available machinery at offshore platforms several offshore professionals were contacted and asked to fill a survey. The survey included "Yes/No" questions about the availability of different machines. The survey can be found in Appendix VI. For example, according to a survey, the offshore platform Askepott has following machines on-board

- Lathe
- Milling
- Wire cutters
- Surface grinders
- Small scale CNC
- Welding machines
- Drilling machines
- Heat treatment machines

The accessibility of these machines makes 3D printing on offshore fields a doable task.

5 Chapter V

Discussion

- Result discussion
- Conclusion
- Future work

5.1 Discussion on results

Referring to aforementioned results and cases, 3D printing being a disruptive technology has empowered the development of various customized production methods at a low cost and lead time in comparison to other manufacturing or prototyping technologies. Moreover, 3D printing technologies allowed to unearth new production methods and have served as an innovation catalyst inspiring the development of various solutions. The development of prototypes and functional parts which cover all necessary criteria using the same digital equipment saves precious time and effort. The Model 2 mentioned in the 3D printing section of thesis will be utilized to trace back important constraints and address required adjustments for prototypes that require further research.

This thesis underlines the current status of offshore fields to welcome the 3D printers on board. As mentioned earlier, different offshore platforms are currently using 3D printers for producing simple, plain, and small components. The challenge was to highlight the obstacles which impede the development of convoluted parts and find solutions. The approach employed to answer the identified challenges is described in this thesis work. The approach was based on product development processes which are an essential part of the master's course. The development method was a lens to look through the important steps while developing bespoke tools based on concepts influenced by product development and 3D printing principles. Additionally, various case studies were built to match our aim of being a prototyping and testing work frame, and research methods including brainstorming, ideation, and informal interviews were undertaken. The findings indicate that the supported development strategy has can produce significant advantages.

Serious efforts were made to compile supportive documents which will lead towards the establishment of a knowledgebase which can serve as the bedrock for future studies and plans. The efforts were not only limited to collection of data but also creation of data using available resources in the academia. The models in question were manufactured in different conditions and went through a detailed comparison process. The results indicated the importance of taking into account the specific conditions of 3D printing such as pre- and processes and printing methods.

Furthermore, the mixed communication between industrial and offshore workers led to a conclusive analysis, particularly for the adaptation of the 3D printing station. Due to shortage of time, it was almost impossible to contact all involved parties, e.g., maintenance, fabrication, production etc, together to investigate problems and identify improvement opportunities in current methods. Instead, needs were obtained in collaboration with industrial and academic supervisors utilizing the developed outlined approach.

The entire outcome of the prototypes that were tested is as follows:

- The development technique for the parts received positive feedback, particularly the model 2 showed promising results.
- Machines are available at certain locations which can, potentially, start producing parts and analysis.
- Certain geometries will be worse for 3D machines and hence should be produced using other machinery.
- More iteration cycles and development are required.
- Finally, and maybe most intriguingly, the printed parts are suitable for particular applications.

5.2 Conclusion

The additive manufacturing has a rich landscape of processes and materials to choose from. The current material selection is extensive, ranging from high-performance metals, alloys to various plastics, and it is continually expanding. These technologies offer less-complex production, but they require a fresh product design specifically for AM. 3D printing can unquestionably alter the engineering operations in energy industries, like aerospace and automobile sector. Lightweight and excellent safety are two essential characteristics of this business. 3D printing, with right set of skills and machines, can overtake more traditional production processes in the offshore sector, and it will undoubtedly adapt and evolve. This technology has the capability to modify the way of maintenance and production. It opens up new opportunities for offshore industries to improve their manufacturing competitiveness and streamline old manufacturing processes. The thesis may infer that 3D printers and their technology can be used in the next industrial revolution, Industry 4.0.

The proposed method for generating 3D printed customized tooling was successfully implemented. Furthermore, establishing clear and constructive communication with all involved industrial and academic stakeholders is highly advised during the requirement identification stage of the process. The suggested approach uses 3D printing technology as a cost-effective and time-saving alternative to conventional manufacturing technologies to streamline production and guidance tasks-specific tooling development at the same time. It was a convincing factor that high-quality 3D printers can produce parts very close to the original model. The presence of verstaile mechanical machinery will allow for the furhter treatment of printed parts.

AM in rapid prototyping as well as producing optimal products has the ability to improve the operations at offshore and onshore energy industries; in addition, AM will become increasingly significant for the energy businesses based on case studies of leading energy producers. This document summarizes the current state of AM technologies in the offshore sectors. The following aspects should be prioritized in the future: the 3D printing specific designing, cloud storage of technical drawings, and on-board 3D printing machines. As a result, the dimensionality and reliability of the printed part are critical. FEA & CFD services are a step advance in terms of allowing for numerous engineering simulations which can lead to design alterations and accuracy.

1.2 Future work

The continuous development in the field of additive manufacturing and material engineering brings more and more opportunities. 3D printing is a vast field with countless options in form of printing method, speed, and orientations. The current study focused on few aspects of the process which only provide limited details. In future, it is recommended that more materials and different 3D printing methods should be utilized. More emphasis shall be given to reliability experiments to determine the real potential of printed parts in the field. Then, the engineers should go-ahead from the virtual prototyping and conduct live testing of components in order to completely underline the performance of parts.

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Appendices

Appendix I: Industry 4.0

The four core pillars of Industry 4.0. are Smart Solutions, Smart Innovations, Smart Supply Chain, and Smart Factory. Whereas the smart solutions are composed of smart products and smart services. Industry 4.0 represents a new level of value chain organization and management across the lifecycle of products. The following aims for Industry 4.0 are reported in the literature

- Production must adjust to low, medium, and high demand
- Intelligent machines must track and self-recognize parts and products
- Better interaction between Human Machine Interface (HMI) is required
- Production optimization based on Internet of Things (IoT) connectivity
- Radical change in the business model to changing the forms of value chain interaction.

External factors such as "Digital Infrastructure" and "People Leadership & Change" obstruct Industry 4.0 deployment. Internet technologies are also included in the architecture, such as:

- **Mobile** (wireless) communication is critical for a connected environment in Industry 4.0 for real-time accessibility, object tagging, and internet-to-object communication.
- **Cloud Storage** as part of Industry 4.0 will facilitate borderless data flow.
- **Analytics** will help to assess operational processes and company performance, as well as find and explain inefficiencies and even forecast future events.
- **Machine-to-Machine Contact** is a key component of the 'Internet of Things' (IoT). The entire manufacturing floor may communicate significant information using the interface between the physical and virtual worlds.
- **Community** include complex, enterprise-level services that provide more dynamic, content-rich interactions with collaborators and consumers.
- **3D printing** is the process of creating three-dimensional products from virtual models. Because recent improvements have mitigated several flaws, it's likely that additive manufacturing will largely eliminate the inefficiencies of generating individually designed products. This enables rapid prototyping and highly decentralized production processes: the product model might simply be sent to the next "printing" site, obviating the need for intermediary manufacturing steps, transportation, and warehousing.

- **Robotics** allow robots to fulfil their duty in production as autonomous productive units securely alongside shop-floor employees, thanks to sensors and machine vision, as well as better artificial intelligence.

Appendix II: NORSOK standards

6.2.1.1 Basic Design

All shaft seals on pumps shall be mechanical.

The NPSHR shall be at least 1.0 m less than the NPSH available, for boiler feed pumps at least 3m less. Correction factors for hydrocarbons are not allowed.

Onset of cavitation shall be defined as three (3.0) per cent head drop (first-stage head on multistage pumps) from the horizontal line drawn through the non-cavitating points derived from the head/NPSH plot obtained by holding speed and flow constant, while reducing the suction pressure.

The region of uncertainty is defined as + 5.0% of the NPSHR at the point of incipience and shall be added to the measured NPSHR to define the contract NPSHR value.

The whole pump casing shal have a pressure rating allowing it to be tested at the hydrostatic test pressure of the discharge side by mounting blinds to the suction and discharge nozzles.

The best efficiency point for the pump shall be to the right of the rated point on the head capacity curve.

Fire water pumps shall be designed in accordance with NFPA 20.

6.2.1.2 Critical Speeds

If the first lateral or torsional critical speed of the shaft system for Multi-stage Pumps above 500 kW when coupled to the driver, lies below the minimum operating speed of the pump, vibration calculations are required.

6.2.1.3 Drivers

Drivers shall allow full testing with water.

The nominal motor power rating (kW) shall be selected in accordance with the requirements in API 610.

6.2.1.4 Alignment

Minimum twice the forces and moments in API 610, Table 2 at maximum deck deflection shall apply, but the design's additional capability shall be stated.

6.2.2 Centrifugal Pumps to API 610

Piping

Rating	**PN**	**API-Pumps**
150	20	2 x API 610
300	50	4 x API 610
600	100	6 x API 610
900	150	8 x API 610
1500	250	10 x API 610

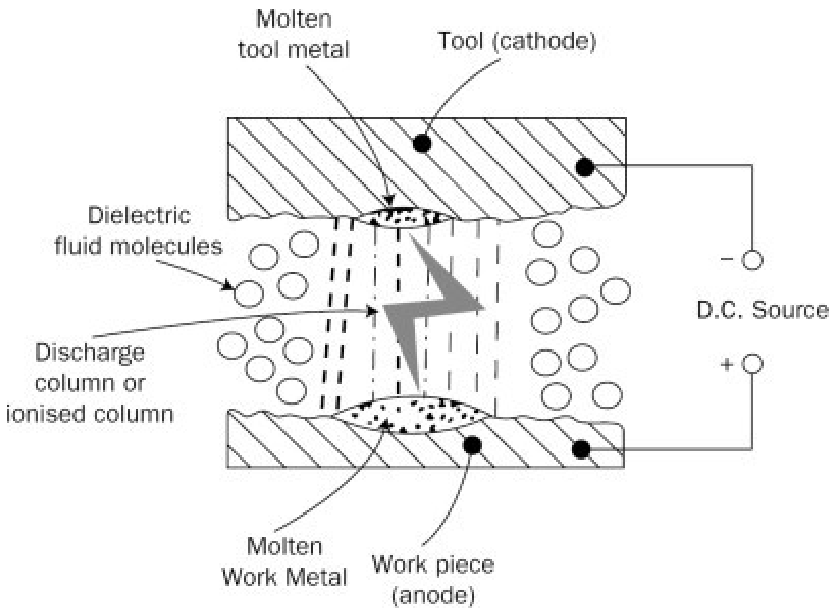
NORSOK Standrads

Appendix III: Alternative manufacturing methods for impellers

EDM

Electrical discharge machining (EDM) is a non-traditional machining technique that has been widely applied to the production of dies and moulds. The method involves removing material using a series of repetitive electrical discharges between an electrode and the work piece in the presence of a dielectric fluid. The electrode is pushed closer to the work piece until the gap is small enough to ionize the dielectric. The substance is eliminated due to the erosive impact of electrical discharges from the tool and workpiece.

During machining, EDM does not create direct contact between the electrode and the work piece, which can reduce mechanical strains, chatter, and vibration. Any hardness of material can be sliced as long as it can conduct electricity [6]. Wire EDM and sinker EDM are the two basic types of EDM techniques. EDM is ideal for machining extremely hard materials that would otherwise be impossible to machine with other methods.

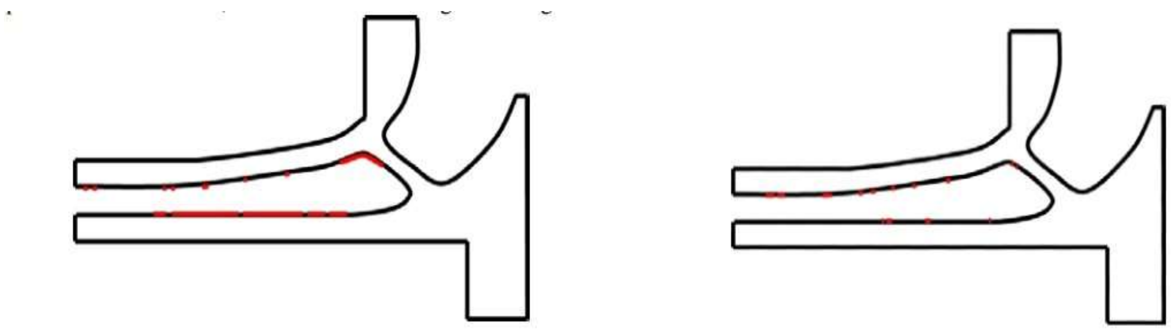


Working principle of EDM

The procedure for making an impeller with EDM is similar to the process for machining an impeller with traditional methods. Since the temperature at either end of the spark is extraordinarily high, and a little amount of material from both the electrode and the component is actually vaporized. The vapor quickly solidifies as a chip, which is washed away by the running dielectric fluid.There are remelted regions on the surface. In fact, EDM's main major flaw is that it leaves remelted material, recast layer, patches on the surface.

However, because of the significant human effort required for various geometries, as well as specific geometric limits in impellers with very small channels and high wrapping angles, the EDM method is only employed in exceptional circumstances. As previously said, the recast layer is often considered to be extremely harmful. It's also crucial to comprehend the worst-case situation in the event that the eradication process fails. The process of driving an abrasive-laden high viscosity fluid through a component is known as abrasive flow machining. The abrasive scrapes down the surface to an extremely fine, mirror-like polish. The other forging was abrasive flow machined and was produced as a whole impeller.

The abrasives are used to achieve an extremely fine surface by removing the recast layer. The recast layer is quite patchy on the EDM surfaces. The recast layer can account for 9% of the flow route surface. Abrasive flow method may not completely remove the recast layer islands but in many cases the thickness of the islands appears to have been reduced. If EDM is to be utilized for impellers, more work may be required to assess whether the remaining recast islands will be an issue or to redo the processing to eliminate them totally.



Impeller flow path showing instances of recast layer (red), (R) recast layer after abrasive flow machining

Investment Casting

Investment casting, sometimes known as lost wax casting, is one of the oldest technologies. Initially, the required component is formed of wax. Wax is plainly simple to work with, resulting in smooth surfaces and fine detail with even the most basic tools. After that, a slurry comprising clay is applied to the wax. The composite structure could then be heated to melt and remove the wax, as well as to fire the clay. As a result, a robust mould was created. The mould was filled with molten metal. The mould was broken off once the metal had cooled, leaving a metal portion with all of the wax pattern's intricacy.

The underlying principle has remained mostly unchanged over time. Permanent dies are usually used to inject mould into the desired shape. The wax pieces are connected to prefabricated gating parts to create routes for molten metal to be fed into the casting. The gates can also be utilized to create multiple-pattern trees, allowing molten metal to be fed to multiple moulds at the same time. During the investing process, very fine slurries/stuccos are employed to form the early layers of the mould in order to accurately replicate the detail of the wax pattern. To create the outer layers quickly and with greater strength, coarser slurries/stuccos are utilized. Investment cast alloys include everything from ordinary copper to superalloys based on nickel.

Schematic of the traditional investment casting process

Since the early 1980s, investment casting has been in use to produce closed centrifugal compressor impellers. At the time, these impellers met all mechanical and dimensional standards. Unfortunately, investment casting's greatest strength is also its greatest shortcoming in this application. The tooling has a substantial upfront capital cost and a significant impact on lead time. Once the tool is in place, a high number of pieces are needed to counterbalance the initial investment. Each design update would require a new tool or a permanent modification of an existing one. In that circumstance, obviously, costs and lead times soar, and investment casting loses its competitive edge. The impeller's tiny flow passageways are also a source of difficulties. Passages in this impeller's size can be difficult to cast appropriately. They can't be any smaller than 1.6mm in diameter or any deeper than 1.5 times that. If the casting design necessitates cores and depending on situation it is not possible to meet these standards, one may need to look for another method.

During casting, the thin, weak regions of the mould can burst. Before enough thickness of molten material is obtained, the material tends to bridge and can seal off portion of the route. This not only damages the part, but it also puts the foundry workers' safety at jeopardy. Despite the risks, a few foundries managed to find ways to produce the flow pathways correctly with care in the investing process, even to the point of physically dipping the impeller. The narrow blades connecting the comparatively massive masses of the hub and cover further complicates the situation. One of these enormous masses may be required to feed molten metal through the blades, depending on the pattern and gating arrangements. The thin blades may stiffen before the mould is filled if caution is not exercised.

Hot Isostatic Pressing

The introduction of Hot Isostatic Pressing, or HIP, by Battelle researchers in 1955 revolutionized the procedure (ASME 1985). The manufacturing process is divided into three steps, starting with the melt and ending with the finished product. Inert gas atomization is used to make powder. The powder is packaged in sheet metal capsules to achieve the appropriate form. The capsules are then heated isostatically pressed to achieve full density under high pressure and temperature. The melt is discharged directly into the atomization chamber where jets of inert gas break up the molten metal, and the atomized melt solidifies into small spherical particles. The powder is kept in hermetically sealed jars that are filled with inert gas. Next step is canning where the powder is canned in mild steel capsules created by sheet metal shaping and welding. The capsule is meant to provide the correct shape to the fully dense end product. Lastly, the capsules are placed in a hot isostatic press and exposed to high pressures and temperatures.

PM HIP products will be heat treated, machined, and subjected to various types of quality control, such as ultrasonic inspection, dye penetrant testing, and mechanical property testing, depending on the type of material and application. After the hot isostatic pressing and heat treatment, the mild steel sheet used in the can remains on the product and is removed by machining or acid pickling. Pressure had to be exerted in discrete directions before this. This resulted in inhomogeneity dis powder consolidation and some anisotropy in material characteristics, limiting the components' complexity. HIP is carried out in a pressure vessel with high-pressure inert gases that apply homogeneous pressure on the surface. This fixed the flaws in prior techniques of applying the required pressure.

Appendix IV: Printer and material characteristics

Printer Characteristics

The Onyx Pro features our unique continuous fiber reinforcement at an affordable price. Built on a durable chassis with precision components, the Onyx Pro prints fiberglass-reinforced thermoplastic parts that are 10x as strong as traditional printing plastics.

Printer Properties	**Process**	Fused filament fabrication, Continuous Filament Fabrication
	Build Volume	320 x 132 x 154 mm (12.6 x 5.2 x 6 in)
	Weight	16 kg (35 lbs)
	Machine Footprint	584 x 330 x 355 mm (23 x 13 x 14 in)
	Print Bed	Kinematic coupling — flat to within 160 µm
	Extrusion System	Second-generation extruder, out-of-plastic detection
	Power	100–240 VAC, 150 W (2 A peak)
	RF Module	Operating Band 2.4 GHz Wi-Fi Standards 802.11 b/g/n
Materials	**Plastics Available**	Onyx
	Fibers Available	Fiberglass
	Tensile Strength	590 MPa (19.0x ABS, 1.9x 6061-T6 Aluminum) *
	Tensile Modulus	21 GPa (9.4x ABS, 0.3x 6061-T6 Aluminum) *
Part Properties	**Layer Height**	100 µm default, 200 µm maximum
	Infill	Closed cell infill: multiple geometries available

MarkForge printer characteristics

Product	Ender 5 PLUS	Ender-6	Ender-5	Ender-5 Pro
Silent operation	N/A	TMC2208 drivers	N/A	TMC2208 drivers
Printing Size	**350*350*400mm**	250*250*400mm	220*220*300mm	
Printing Speed	40-80 mm/s	up to 150mm/s	40-80 mm/s	
Support Filament	PLA/TPU/ABS/PETG	PLA/TPU/ABS/PETG	PLA/TPU/ABS	
Leveling Type	With Bl touch	Manual leveling	Manual leveling	
Printing Platform	Carborundum Glass	Carborundum Glass	Magnetic Plate	
Stepper Drivers	(A4988)	TMC-2208		
Screen	4.3" LCD Touch Screen	4.3" HD Touch Screen	12864LCD Screen	
Power Supply	350W MEANWELL	350W CHENLIANG	Landy	
Z-axis screw	Dual z-axis	Coe-XY	Single z-axis	
Y-axis Motor	42-48	42-48	42-40	
Filament Sensor	yes	yes	no	

Creality printer characteristics

Mechanical properties (*)	Injection molding		3D printing	
	Typical value	Test method	Typical value	Test method
Tensile modulus	-	-	2346.5 MPa	ISO 527 (1 mm/min)
Tensile stress at yield	-	-	49.5 MPa	ISO 527 (50 mm/min)
Tensile stress at break	-	-	45.6 MPa	ISO 527 (50 mm/min)
Elongation at yield	-	-	3.3 %	ISO 527 (50 mm/min)
Elongation at break	-	-	5.2 %	ISO 527 (50 mm/min)
Flexural strength	-	-	103.0 MPa	ISO 178
Flexural modulus	-	-	3150.0 MPa	ISO 178
Izod impact strength, notched (at 23˚C)	-	-	5.1 kJ/m²	ISO 180
Charpy impact strength (at 23˚C)	-	-	-	-
Hardness	-	-	-	-

Thermal properties	Typical value	Test method
Melt mass-flow rate (MFR)	6.09 g/10min	ISO 1133 (210 ˚C, 2.16 kg)
Heat deflection (HDT) at 0.455 MPa	-	-
Heat deflection (HDT) at 1.82 MPa	-	-
Glass transition	~60 ˚C	ISO 11357
Coefficient of thermal expansion (flow)	-	-
Coefficient of thermal expansion (xflow)	-	-
Melting temperature	145-160 ˚C	ISO 11357
Thermal shrinkage	-	-

Other properties	Typical value	Test method
Specific gravity	1.24	ASTM D1505
Flame classification	-	-

PLA Properties

Property	Test Standard	Onyx	Nylon
Tensile Strength (MPa)	ASTM D638	**36**	**54**
Tensile Modulus (GPa)	ASTM D638	**1.4**	**0.94**
Tensile Strain at Break (%)	ASTM D638	**58**	**260**
Flexural Strength (MPa)	ASTM D790*	**81**	**32**
Flexural Modulus (GPa)	ASTM D790*	**2.9**	**0.84**
Flexural Strain at Break (%)	ASTM D790*	**N/A****	**N/A****
Heat Deflection Temperature (°Celcius)	ASTM D648 Method B	**145**	**44-50**
Density (g/cm^3)	N/A	**1.18**	**1.10**

Onyx properties

Appendix V: Pre- & post processing

Designing for FFF

Although FFF is regularly defined as the simplest 3D printing technology, there are several design limitations and rules that must be considered. Most of these centre around the anisotropic behaviour of FFF parts and the need for support material.

Support structures and part orientation

Overhangs are a common element of FFF prints. When the printed layer of materials is only partially supported by the layer below, overhangs form. Overhangs can be found in the form of angled walls or curved surfaces. When a feature has a 45° or less overhang (relative to horizontal), it can drop and requires support material beneath it to keep it in place. Support allows for precise printing of overhanging elements that are less than 45 degrees. The disadvantage of support is that it must be removed, which might cause damage to the part's surface. This difficulty can be solved by using dissolvable support. The part orientation determines the position and amount of support required for a print.

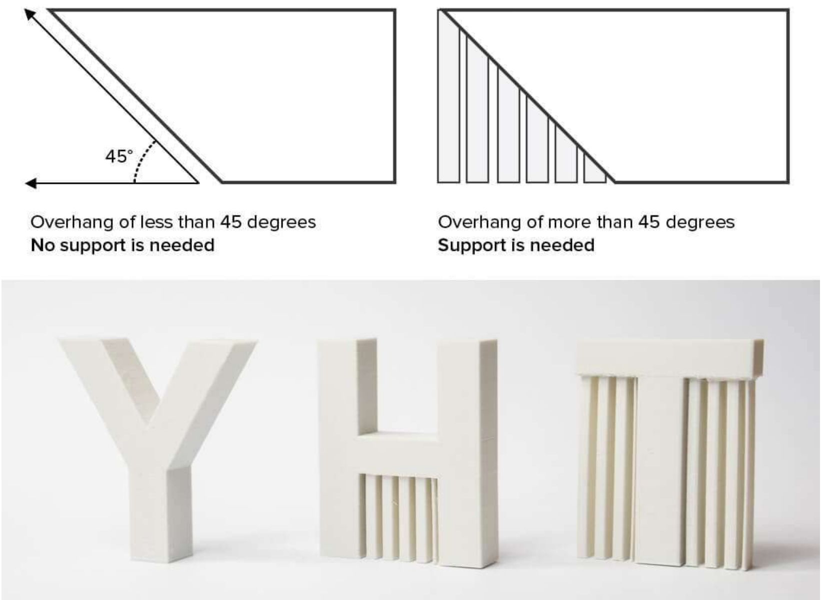


Figure 30 Printing of sample products

Some geometries do not require support along the entire length of a surface; this is particularly common with curved surfaces. The cost and time necessary to create a print can be lowered by strategically providing support only where it is required. To allow the arch depicted in Fig to be printed accurately, only a small quantity of support must be inserted in the correct spot (when the angle drops below 45º).

The most common FFF supports are:

- Dissolvable supports
- Accordian support
- Tree-like support
- Bridging

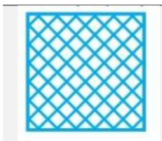
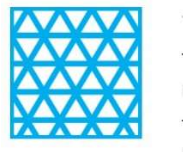
Anisotropy

The anisotropic character of the pieces produced by FFF printing is a significant drawback. The mechanical characteristics of an isotropic material change in different directions. Layers are forced down on top of one another in the FFF printing process to produce mechanical attachment. FFF parts are weak due to the lack of continuous material routes and the stress concentration caused by the join of each layer. Because the layers are printed as rounded rectangles, there are little dips between them. When the part is loaded, these valleys create stress concentrations that could lead to a break.

This behaviour can have a significant impact on a part's performance. When utilizing FFF to create functional parts, it's critical to understand the print orientation to ensure that the part's anisotropic behaviour doesn't degrade performance. The print should be oriented so that the build direction is parallel to the load for components under tension. It's also crucial for a designer to know whether the values in a datasheet apply to the base material or are indicative of a 3D printed object. The strength of the part is often determined by the adhesion between the layers, rather than the material itself. The operator is responsible for layer adhesion, which is based on printer calibration and settings.

Infill

Like most wooden doors are not solid, but have a low-density core, FFF prints are typically printed with a low-density infill. Infill allows a part to be printed faster and more cost effectively with the strength of a design being directly related to infill percentage. Most FFF slicer programs by default print parts with a 20% infill, which is perfectly adequate for the majority of 3D printing applications.

INFILL GEOMETRY	DESCRIPTION
	Many FDM 3D printers use a rectangular infill pattern by default. It enforces strength in all directions while being rapid to print thanks to its block structure and perpendicular layers. When employing this infill type, there isn't a lot of bridging across the pattern.
	When trying to increase strength in the direction of the part's walls, triangular infill, also known as diagonal infill, is utilized. Because the lines that make up the pattern apply force at a 45° angle, the pattern achieves more strength. Printing this form of infill takes a little longer than normal rectangular infill.
	Honeycomb infill, also known as hexagonal infill, is a common infill style that, like rectangular infill, gives strength in all directions. It takes a little longer to print, but it's worth it for things like carbon fiber parts that require more strength than rectangle can provide.
	The wiggle infill pattern varies from the other three on this list in that it adds support without using intersecting lines. The wiggle infill, on the other hand, resembles wavy or zigzag lines. This pattern is most commonly employed with flexible filaments, such as softer nylon or other rubbery filaments, when sections must twist or compress and have a rebound force. Perpendicular walls can still be supported by this filling.

Infill geometries

Holes

Vertical axis holes are frequently printed at a smaller diameter than the desired design diameter using FFF. The following explains why there is a reduction in diameter. As the nozzle prints the perimeter of a vertical axis hole, it compresses the newly printed layer down onto the existing build layers to aid adhesion. The compressing force from the nozzle deforms the extruded round layer shaped from a circle into a wider and flatter shape, increasing the area of contact with the previously printed layer (improving adhesion), but also increasing the width of the extruded segment.

This is especially problematic when printing small diameter holes, when the effect is amplified by the hole diameter to nozzle diameter ratio. The slicing program accounts for the reduction in diameter of vertical axis holes, but accuracy can be a challenge, and numerous test prints may be required to attain the appropriate accuracy. Drilling the hole after printing is the ideal approach if a high level of accuracy is required. When printing horizontal holes with FFF, there are several constraints; if the holes are large enough, support material is frequently necessary. The top of the hole will typically begin to sag or have a poor surface finish if no support is present. Generally, it is recommended to have a clearance of 0.5 mm to create adequate space between parts.

Infill Patterns

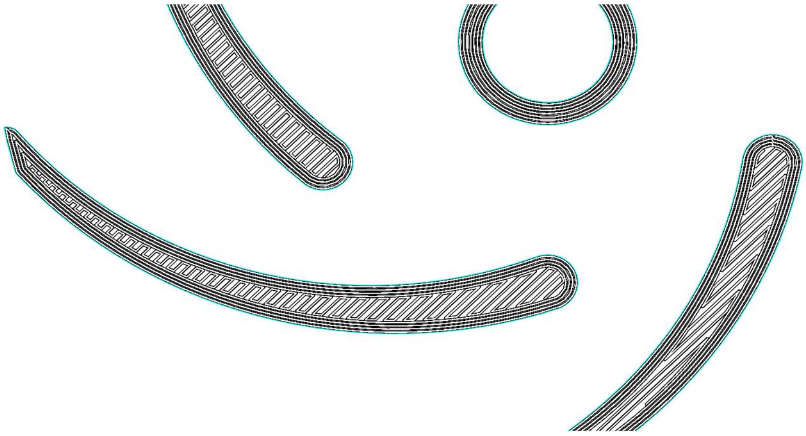


Figure 31 Rectangular infill

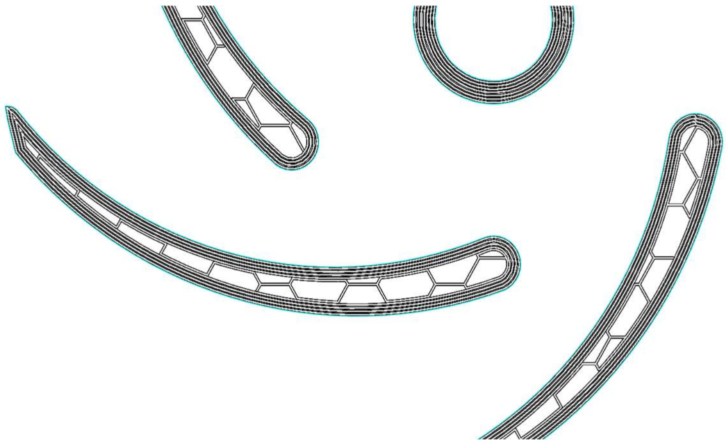


Figure 32 Hexagonal pattern

Type	Post Process	Description
Compulsory	Loose powder removal	Parts are removed from the build chamber and all powder is removed from the part with compressed air. The surface is also cleaned via plastic bead blasting to remove any un-sintered powder sticking to the surface. This finish is inherently rough.
Surface finish	Media Polishing	For a smoother surface texture, parts can be polished in media tumblers or vibro machines. A tumbler contains small ceramic chips that vibrate against the object equally eroding the outer surface down to a polished finish. This process does have a small effect on part dimensions and results in rounding sharp edges. It is not recommended to tumble those parts with fine details and intricate features.
Aesthetics	Dyeing	The fasted method and most economic SLS printed parts are via dye process. The porosity of SLS parts make them ideal for dyeing. The part is immersed in the hot dye colour bath. Using a colour bath ensures full coverage of all internal and external surfaces.
	Painting & lacquering	SLS parts can be spray painted and/or coated with a lacquer. Via lacquering it is possible to obtain various finishes. Lacquer coating can also increase wear resistance, surface roughness and limits marks and smudges on the surface of part. Due to porous nature of SLS parts it is recommended that 4-5 very thin coats are applied.
Functional	Watertightness	A correctly sintered SLS part will have some inherent water tightness. Coating can be applied to further enhance this. Silicon and vinyl-acrylates have shown best results. Polyurethane (PU) is not recommended for SLS parts.
	Metal plating	SLS parts can be electroplated. Stainless steel, copper, nickel, gold and chrome can be deposited on the surface to increase the strength or electrical conductivity. Parts are cleaned and conductive layer is applied to the surface. The parts then go through traditional metal coating procedures. The plastics can be retained as structural support or burnt out to create ting walled parts 25 to 125 micron thick.

Post processing operations for SLS

Type	Post Process	Description
Compulsory	Heat treatment	Heat treatment is used to relieve internal stresses and to alter the properties of some materials such as hardness. The technology and processes are identical to those used in traditional metal manufacturing. The process involves control heating and cooling to specific temperatures. The techniques typically aim to reduce porosity and improve other properties. Heat treatment also helps to reduce microscopic voids or fissures and to achieve a grain structure that is similar to wrought parts made from subtractive manufacturing.
	Support removal	Removal of support material greatly increases the cost of metal printed part. Unlike FFF or SLA where support can be broken away by hand, often DMLS/SLM support must be cut away. The surface where support was attached often needs significant post processing with a file or grinder.
	Loose powder removal	Like all powder bed fusion technologies, all loose powder must be cleaned from a print after it is removed from the powder bin.
	Machining	Machine tools found in modern shops are capable of processing parts before or after heat treating operations. Work-holding can be an issue with complex shaped and should be addressed in this design phase. Although cutting tools like saws can be used, wire EDMs are ideal to remove parts from the build plate before further processing. Machine tools, such as CNC milling machines and lathes, will allow extraneous material to be removed from the parts and to take them from near-net to the final shape. Additionally, the machine tools can prepare surfaces for additional finishing as required.
	Media blating	Media blasting allows operators to improve the uniformity of horizontal and vertical surfaces. This can be an intermediate step for the other surface treatment. After media blasting surface finish can improve to 2-4 RA micrometre.
	Metal plating	Plating of metals is desirable to augment the characteristics of the part. Improvements could include corrosion and heat resistance, increased strength and hardness, conduction and aesthetics.
	Polishing	Electro or hand polishing can be used to achieve a final surface finish. Caution needs to exercise to not induce any surface stresses that make lead to fine cracks.

Post processing operations for SLS

Appendix VI: Questionnaire

Information regarding auxiliary machinery at offshore platforms

Dear reader, this question paper seeks information about the availability of general mechanical machinery. The information is required to facilitate master's thesis, which analyses the opportunities to place 3D printers on offshore facilities. The introduction of 3D printers on offshore platforms is in connection with the implementation of "Industry 4.0", digitalization and reliability of printed components. After every printing operation, the components must undergo post-processing operations which are necessary for optimal performance. It is unknown what kind of machinery can be anticipated on offshore platforms to support such printing operations. So, the professional offshore workers can assist to complete a little survey which will provide a basis for deriving conclusions about the placement of 3D printers on offshore facilities.

Please answer the following questions:

Name of offshore facilities:	Askepott
Lathe machines	(Yes)
Milling machines	Yes
Wire cutters	Yes
CNC machines	Yes
Surface grinders	Yes
Welding machines	Yes
Drilling machines	Yes
Heat treatment machines	Yes
Portable drilling machine	Yes
Portable grinder	Yes

Additional comments:

Majortiy of offshore platforms are fully functional specialized floating/stationary factories with specialised electrical/mechanical/welding workshops since the equipment used in a variety of operations is required to fullfill industry standards. (Reference : API/NORSOK standards for international/domestic requirements e.g tool strength, Integrity, corrosivness, Explosive proof etc.
*https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standards/#.Ym06ytpBxPY
*https://www.api.org/products-and-services/standards

Questionnaire