

**TECHNICAL UNIVERSITY OF LIBEREC**

**Faculty of Mechanical Engineering**



**DESIGN OF THE PRINTING HEAD FOR 3D PRINTING  
FROM THE CONCRETE**

**MASTER THESIS**

**Liberec 2017**

**Machris Ruben John Dias**



# Design of the printing head for 3D printing from the concrete

## Diplomová práce

*Studijní program:* N2301 – Mechanical Engineering  
*Studijní obor:* 2302T010 – Machines and Equipment Design  
*Autor práce:* **Machris Ruben John Dias**  
*Vedoucí práce:* Ing. Petr Zelený, Ph.D.





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## Master thesis

*Study programme:* N2301 – Mechanical Engineering  
*Study branch:* 2302T010 – Machines and Equipment Design  
*Author:* **Machris Ruben John Dias**  
*Supervisor:* Ing. Petr Zelený, Ph.D.



## DIPLOMA THESIS ASSIGNMENT

(PROJECT, ART WORK, ART PERFORMANCE)

First name and surname: **Machris Ruben John Dias**  
Study program: **N2301 Mechanical Engineering**  
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Topic name: **Design of the printing head for 3D printing from the concrete**  
Assigning department: **Department of Manufacturing Systems and Automation**

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2. Design of the special printing head (the possibility of a modular concept).
3. The necessary analysis and calculations.
4. Solution of the functional 3D printing head for the concrete.

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[2] **JACOBS, P. F. Stereolithography and other RP and M technologies: from rapid prototyping to rapid tooling. ASME Press, 1996, ISBN 0-87263-467-1**

[3] **GIBSON, I. ROSEN, D. W., STUCKER, B. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. Springer, 2010, ISBN 978-1-4419-1119-3**

Tutor for dissertation:

**Ing. Petr Zelený, Ph.D.**

Department of Manufacturing Systems and Automation

Dissertation Counsellor:

**Ing. Petr Keller, Ph.D.**

Department of Manufacturing Systems and Automation

Date of dissertation assignment: **1 November 2016**

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prof. Dr. Ing. Petr Lenfeld  
Dean



Ing. Petr Zelený, Ph.D.  
Head of Department

Liberec, dated: 1 November 2016

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Ruben

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## **Abstract**

The main goal of this thesis work is to describe and document the process of designing a printing head for 3D Printing Concrete, from analysing current trends in construction to building a model of the printing head.

The work begins with a study of literature sources followed by a description of the design process. In the middle of the thesis, there is some information about concrete mixes, additives and a few properties of concrete for printing. Towards the end, there is a brief description of the prototyping and testing and a few results and recommendations for future development of the work.

In conclusion, this work gives a clear understanding of the state-of-the-art construction technologies and its future scope and describes an attempt to design an optimised printing head for concrete printing

**Keywords: 3D Printing, Construction, Concrete, Printing Head**

## **Abstrakt**

Hlavním cílem této práce je provést návrh tiskové hlavy pro 3D tisk objektů z betonu. Návrh vychází z analýzy současných trendů ve stavebnictví.

Úvod práce se věnuje studiu zdrojů a literatury, z této studie vychází samotný návrh tiskové hlavy. Práce obsahuje informace o betonových směsích, přísadách a popisuje potřebné vlastnosti betonu pro tisk. Je zde popsán způsob výroby zmenšených modelů hlav, testování a výsledky experimentů. Na základě výsledků experimentů jsou definována doporučení pro budoucí vývoj práce a návrh optimalizované tiskové hlavy pro tisk z betonu.

Tato práce dává jasnou představu o nejmodernějších konstrukčních technologiích 3D tisku ve stavebnictví a jejich budoucím rozsahu.

**Klíčová slova: 3D tisk, konstrukce, beton, tisková hlav**



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## **LIST OF ABBREVIATIONS**

**3DP**, 3-Dimensional Printing

**CAD**, Computer-Aided Design

**AM**, Additive Manufacturing

**CC**, Contour Crafting

**FDM**, Fused Deposition Modelling

**PA**, Polyamide

**PC**, Polycarbonate

**PLA**, Polylactic acid

**PS**, Polystyrene

**RP**, Rapid Prototyping

**SLA/STL**, Stereolithography

**SLS**, Selective Laser Sintering

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## **1.INTRODUCTION**

Creating objects from imagination is the core idea that 3DP and AM have brought to the world of manufacturing. These modes of manufacturing have seen colossal growth over the past few years, thanks to the number of applications these two have. As the needs of the industry grow, so does the applicability of AM. The manufacturing sector has seen its technologies shift toward the concept of Industry 4,0 and AM is at the very crux of this notion.

For example, AM technologies like 3DP can be used to produce structures as big as hotels or villas, and objects as complex as human organs, such as livers and kidneys [65],[5]. It can also be used to print bone tissue scaffolds, with features in a range of a few micrometres [2]. More recently, it was seen that the use of meta-materials in printing enables printing of complex mechanisms, such as pliers and door handles without the need for screws, nuts and bolts. With 3DP growing at the speed it is now, it can be said without a doubt that the technology can change the world of manufacturing forever. One of the industries that have recently received a helping hand from technology is the construction industry, which has, for long, been behind in catching up with recent developments in technology.

3DP has been developed to be used in construction, by printing structures using computer controls. At the moment, the idea is being adapted and developed for commercial construction the world over.

This work is also part of a project by the Technical University of Liberec to build and develop a 3D printer for concrete printing, with the collaboration of the departments of Architecture, Production Machines and Mechatronics from the university. With the department of architecture producing the concrete and the department of mechatronics designing the controller, the printing head is to be designed by the department of Production systems and automation.

The printing head is a key component of any 3D Printer because the actual printing or extrusion takes place from here. The head can be best described as the end effector of a

printing device. The printing head is also known as the extruder in some cases, especially in concrete printing.

## 1.1 DIPLOMA THESIS

The topic for this Master's Diploma Thesis is **“Design of the Printing Head for 3D Printing from Concrete”**. As the initial stage of the proposed university project, the central aim of this thesis work is to collect more information about 3D printing applications in construction, and also design a printing head for such a printer/extruder. This project interested me most because this project had a lot of future potentials and much space for creative work and imagination.

The thesis work is composed of two parts:

- Research/Literature survey
- Design and Prototyping of the Printing Head

The initial few chapters of the thesis work describe the theoretical part of the work, composed of the literature study and research from sources. The current trends in the field and the state-of-the-art of 3DP concrete structures are seen in this part of this work. This can be used to trace the current state of development of the technology and the applicability of this technology at the present moment. A major portion of the work done would be theoretical as the literature survey forms the base of the project.

This theoretical part also consists of studying printing methods being used in various parts of the world, as case studies. The goal of this part would be to get a clear idea of the trends in 3DP concrete structures, and what functions are required to be fulfilled by the head. It would also be useful to analyse existing designs of printing heads and get an idea of the different parts to be used in the head to help improve its function of extrusion.

The latter part of this book deals with the design of the 3DP head and my own idea for a good printing head design. This part begins where the literature review ends, with the

different models of printing heads used, and figuring out the functions and trying to get some ideas that can perhaps be applied to our need.

From here, the next steps are prioritising the most important needs of the head and actually designing the head, testing it and making possible design changes to it. At the end, there is a description of the final steps of the design process, and the creation of the prototypes, selection of an alternative etc.

At the end, there is a summary of the processes that come after the design, namely building the prototype, testing it and investigating the merits and demerits of the designs. There are a few details about what I understood about the design, what I see as an ideal approach to the future development of the design and a few recommendations from my side, in the results and discussions section, with a summary of the work in the concluding chapter.

The ideal outcome of the work would be to design and create a prototype and possibly test it with an ideal concrete mix. This head design can be optimised and developed in the future, and these results would be helpful for future research in the field, and possibly extending the possibility of 3D printing concrete for commercial applications.



### **2.3-D PRINTING**

3D Printing is a technology that has been vital in bringing manufacturing from factory floors to homes. The term has been generally associated with many processes creating objects with computer controls, even though this terminology defines a rather limited array of technologies. 3DP has been used in general relation to similar terms such as Rapid Prototyping (RP) and Additive Manufacturing (AM).

RP is described in the industry as a method of producing a part or system rapidly before it is commercially applied or released to the masses. This means that this part can be used to serve as the prototype or a primitive representation of the final product that could be manufactured in the future. Its emphasis is on the ease and speed with which the part is manufactured [1].

AM, on the other hand, is another mode of manufacturing in which material is laid out layer-by-layer successively, creating a 3-Dimensional object. It produces parts that are larger than the starting material and is the bottom-up approach to manufacturing, where the process begins with nothing and makes its way up to create the final product from scratch. Conventional methods of manufacturing are generally top-down, beginning with a larger raw material, and machining it down to the required size and creating the required product.

Rapid Prototyping was the term that was used in the past to describe all these technologies as a whole but lost its significance after it was debated that these technologies were creating products that were much closer to the final part, than the contextual ‘prototype’. The ISO ASTM Joint Group recently recommended the use of the term AM instead though the topic is still widely debated. The term AM encompasses a broad array of technologies such as 3D Printing, Direct Digital Manufacturing (DDM), layered manufacturing, additive fabrication etc., which all express the same or very similar methods of laying out material to make something. The usage of these terms varies according to context.

3D Printing was first established as an abstract idea and gained momentum after the early 1980s. The invention of stereolithography in 1983 [3] and the development of the world’s first 3D printer prototype in 1984 added impetus to the idea. The technology has

since exploded, with an innumerable number of 3D Printers available and sold all over the world today.

The list of standard process types in AM and their definitions have been given by the ISO/ASTM Joint Group on Terminology in the ISO/ASTM 52900 standard for AM technologies [19]. According to these standards, the classification of processes and names are:

- **Material Extrusion:** AM process where the print material is dispensed through a nozzle or orifice
- **Material Jetting:** AM process where droplets of build material are selectively dispensed over an area
- **Binder Jetting:** AM process where a liquid binder is dispensed selectively to join powder materials
- **Sheet Lamination:** AM process where sheets of print material are bonded together form the final product
- **Vat Polymerization:** AM process of selectively curing liquid photopolymers in a vat is by photopolymerization or light activation
- **Powder Bed Fusion:** AM process of selectively fusing regions of powder beds with thermal energy
- **Directed Energy Deposition:** AM process of converging thermal energy to melt and fuse materials as they are deposited on the bed

## 2.1 The 3D Printing Process

In 3DP, the ‘print’ material is deposited in pre-determined steps creating the required product, facilitated by a computer control with the aid of specialised software packages for processing models. The following is the order in which the 3D printing processes are generally carried out:

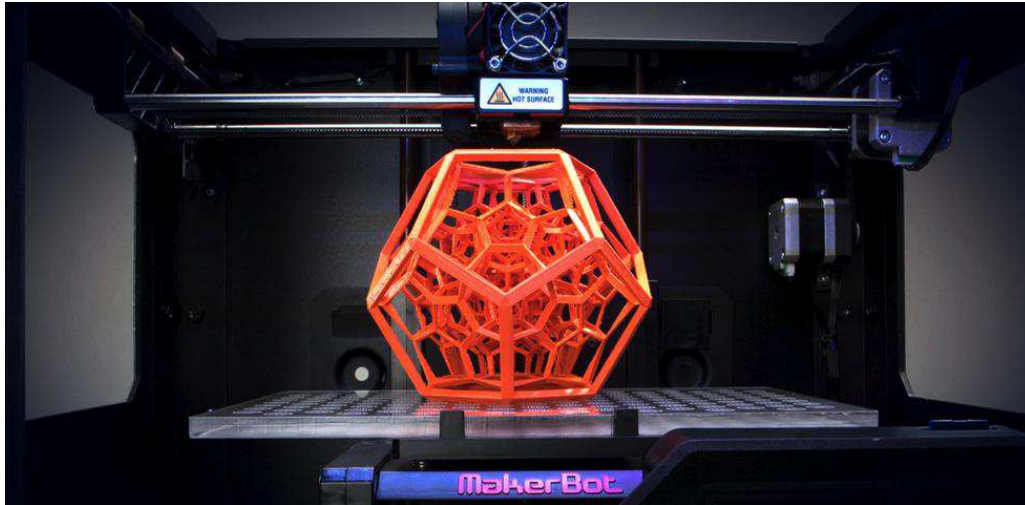
**Modelling:** Computer-Aided-Design (CAD) software are used to create virtual models of these objects, or they could be digitally scanned with 3D scanners which process the shape data and creates a digital model from it. In some cases, cameras and photogrammetric software can also be used for modelling the objects.

**Conversion/Repair:** 3D printing can be carried out only from an.STL file, and for this the CAD data has to be converted to STL format. These output STL files can contain errors such as holes and intersections, caused during conversion and these have to be repaired before the model can be used as the printing data.

**Slicing:** This completed STL file must be processed by a ‘slicer’, which is a software package that slices or processes the 3D data, and creates thin layers that the printer can deposit material according to. Thereby 2D layers are created in this step, and G-codes are generated for the shapes and locations of these layers according to the type of 3D printer being used.

**Printing:** The G-codes are instructions to the printer, through a client software that instructs the printer to move in a certain manner and deposit material at specified points. The printer head has a material dispensing system and the software directs the flow of the material being laid out. The thickness of layers depends on the slicing and the resolution of the printer, which can be expressed in terms of dots per inch (dpi) or micrometres ( $\mu\text{m}$ ). This is also a measure of how accurate the printer is.

**Finishing:** Often, the finished product from the 3D printer is the final product but in a few cases, some amount of finish is required. In such cases, the size of the finished part is larger than required and machined down to the final size. Most metal deposition methods require finishing. Some structures that are complex, have added support structures within the printed model. In these cases, these supports are dissolved in solvents to reveal the final product.



**Figure 1. Printing complex parts with the 3D Printer MakerBot [66]**

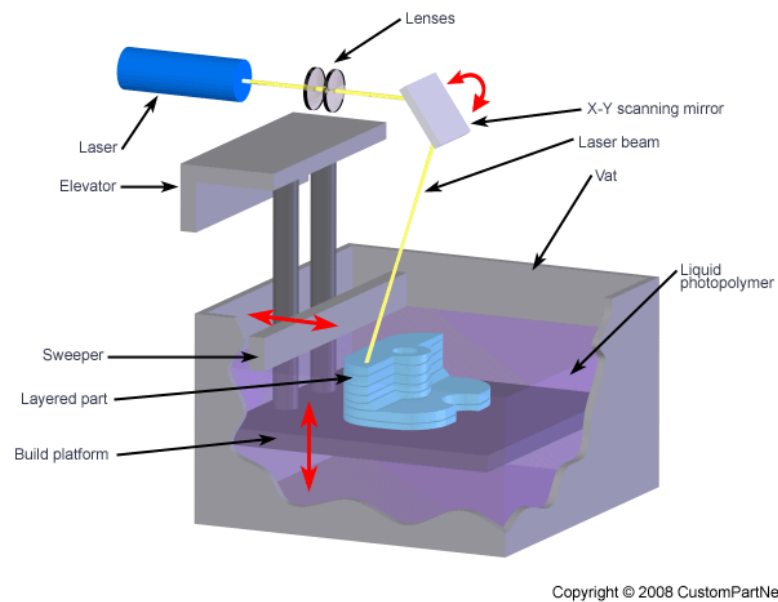
## **2.2 3D Printing Processes**

3DP is an efficient process that has minimum wastage, as it only takes up as much material as required by the build. It is widely applicable to a range of uses and is very flexible to the needs of the user. It has many applications based on print material and mode of use. For example, ABS as the print material can be used to print objects for everyday use, for example, small parts of home appliances. Recently, the possibility of printing human organs such as livers and kidneys from human tissues and cells was discovered. Similarly, by changing the material to fit the needs, 3DP can be used for almost anything in the modern world.

### **2.2.1 STEREOLITHOGRAPHY:**

Charles .W. Hull, the inventor of Stereolithography, [2] tried hardening layers of photosensitive material with Ultraviolet (UV) light to create an object. Stereolithography is used to create objects in a layer-by-layer fashion by the method of photopolymerization, by which layers of materials, typically liquid, radiation-curable resins link to each other to form polymers that make up the solid object [16]. This was seen as one of the first technologies in Rapid Prototyping (RP) that paved the way for the development of similar

3D printing processes in the future [17]. It is generally referred to as SLA or in some cases, as STL. The extension .stl used for 3DP is a simple abbreviation of Stereolithography.



**Figure 2. Stereolithography [71]**

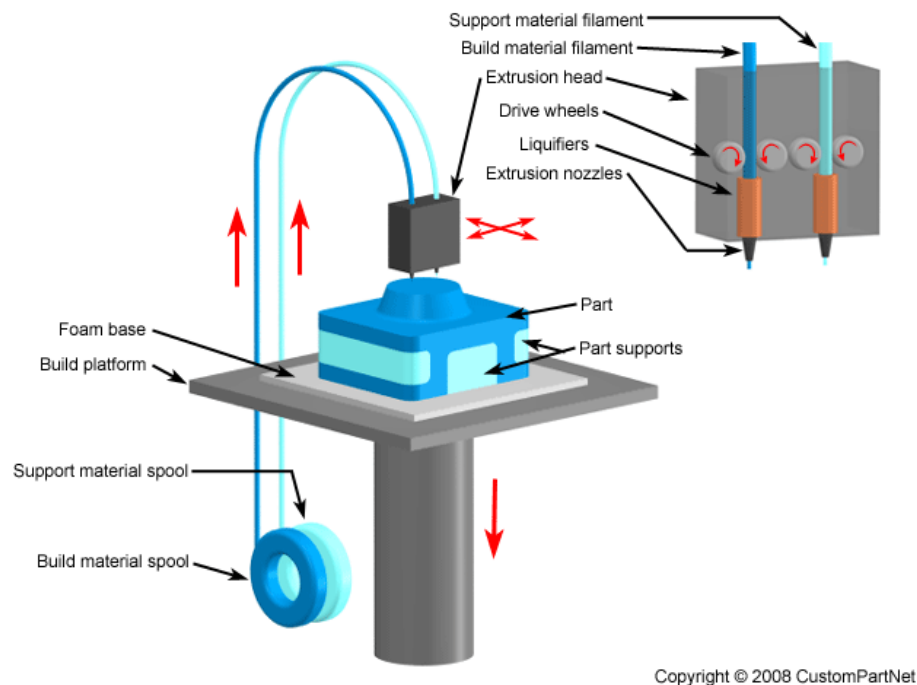
### **2.2.2 FDM:**

FDM or Fused Deposition Modelling, the most popular 3DP method was invented in 1988 by Scott .S. Crump [2]. It uses two different types of materials, one for the model itself and the other for creating support structures that hold the model and is contained within gaps in the model or at specific points in order to adequately support the model.

The support material and the build material are extruded out of a printing head and deposited at specific points, in accordance with a digitised model in a .stl format in successive layers. This is carried out with the help of specialised software. The supports are soluble in solutions and can be removed after completion of the printing.

FDM is commonly used with rolls of thermoplastic, generally, Acrylonitrile Butadiene Styrene (ABS) to build models. Other materials which may be used are PC, PA, PS, lignin and rubber. PLA is a biodegradable material that could be made from corn-starch, and in

some cases, wood, bronze and sandstone or milled chalk can also be used as materials for FDM [2].



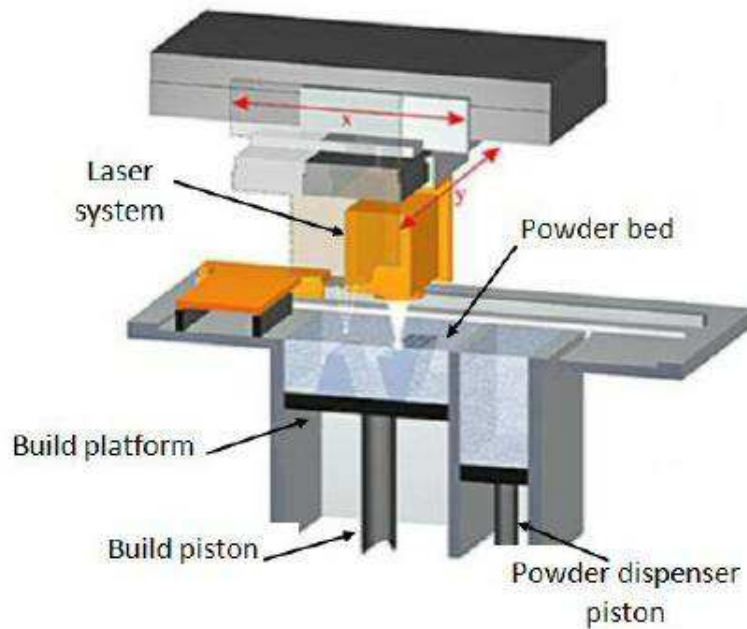
**Figure 3. Fused Deposition Modelling [71]**

### 2.2.3 SLS:

Sintering is a method of partial melting or compacting powdered materials with heat or pressure, without melting it to its liquid [20]. Selective Laser Sintering (SLS) is an AM process that was invented along the lines of SLA. SLS involves sintering materials, mostly metals with a laser. The laser is aimed at specific points or coordinates in the space that is given by a 3D model. This sintered metal forms the finished part [18].

There is another process that is very similar to SLS, direct metal laser sintering (DMLS) also uses the exact same technology but with changes in minor technical details. Sometimes these two can be referred to as the same process. Also, Selective Laser Melting (SLM) is another process with a similar name but it involves complete melting of the material.

SLS can also be carried out with other materials such as Nylon or Polystyrene.

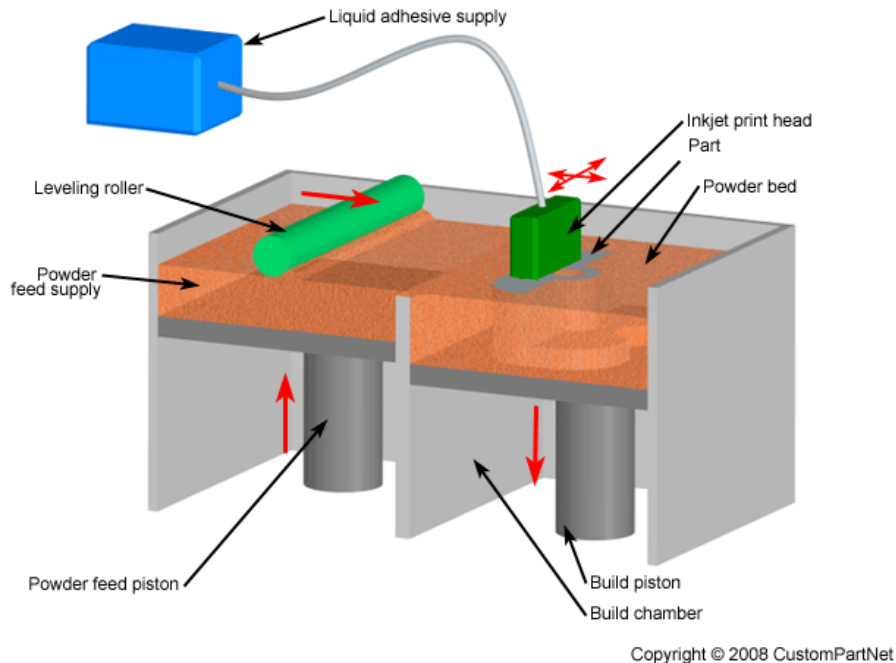


**Figure 4. Selective Laser Sintering [71]**

#### **2.2.4 INKJET POWDER PRINTING:**

The inkjet printing technology was developed in 1993 at the Massachusetts Institute of Technology and patented as '3DP' at the same time. But the term is now being used as a general reference to most AM processes. It is also known as Binder Jetting or Drop-on Powder and is built up from digital design data, as thin cross-sectional layers of the model.

A print head or inkjet head moves above a powder bed depositing a liquid binder on specific parts of the powder, hardening it. Then a layer of powder is deposited on this section and this process of binding is repeated until the final part is obtained. Then the unused powder is separated from the finished part by a process known as 'de-powdering'. This finished part could then be subjected to different treatments to bring out different properties of the part [2].



**Figure 5. Inkjet Powder Printing [71]**

### **2.3 CONCRETE PRINTING PROCESSES: CONCRETE PRINTING**

The use of a 3D printer or its scaled version in construction with concrete to build structures is termed concrete printing. Another compatible term referring to the same is Construction 3D printing first coined by James B Gardiner in 2011 [28]. The processes may involve additive, subtractive and formative processes of manufacturing in order to reach the final desired shape of the product. 3D printing Construction is said to be done in 3 different methods:

- Extrusion
- Powder Bonding
- 3D Welding



Concrete printing has been under research for a very long time, and the progress has been slow and steady, with its roots in computer controlled brick-laying, which was conceptualised during the 1960s when it was first derived and then has come a long way since then [28]. Since the 2000s there has been another surge in this area, with a handful of companies adopting the 3D construction methods, including Winsun (China) and DUS (Netherlands). These companies have already started construction, with Winsun completing some projects and DUS has an ongoing construction of a Canal house in Amsterdam's central region [2].

Concrete is generally laid out with the help of structural formwork that in addition to the foundation, helps in the structural stability of the building. This process has many advantages and just one of them is the elimination of these requirements. Below is an example of a structure built with concrete without formwork.

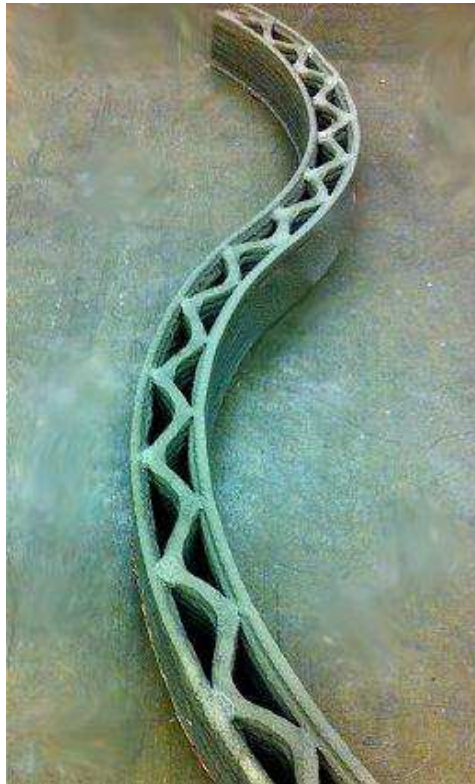


**Figure 6. 3D Printed Castle by Andrew Rudenko [27]**

### 2.3.1 CONTOUR CRAFTING

Contour crafting refers to a method with a special pattern using angled trowels to shape and craft the concrete. Contour Crafting (CC) was first established by researcher Dr.Behrokh Khoshnevis, who explained it as the process of laying down material in a specific pattern, for example, concrete using automated processes with robotic control and supervision [6].

It involves laying two parallel straight lines and a reinforcing pattern in the centre, all of the same material such as concrete in order to create a support-less structure formed in successive layers, as in all processes of AM. This process predominantly uses 2 trowels to craft and flatten the material at the sides to create planar surfaces. Other features are the use of smart materials for construction, automated reinforcement or the use of robotic modular embedding of steel mesh reinforcements [2].



**Figure 7. Contour Crafting pattern [72]**

The concept of CC has been widely used and improved upon, extending it to commercial applications of construction, such as large-scale constructions of residential apartments. The process can be seen in the construction of the 3D Printed Canal House in Amsterdam, carried out by DUS Architects, using a 3D Printer scaled up to create large blocks for construction.[10]

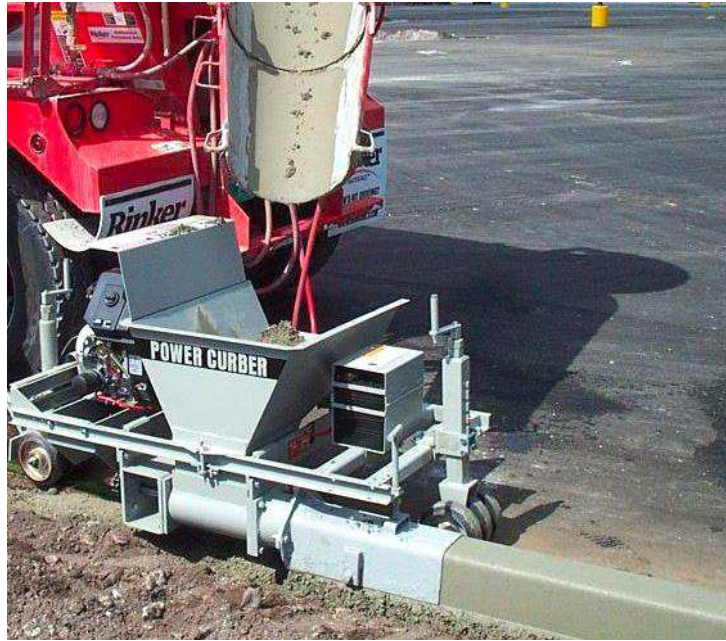
Another commercial application of CC can be seen in the construction of homes in China by Winsun which has completed many homes and other buildings. This was carried out with the help of pre-manufactured walls and by assembling them at the site [9].

These examples are seen as the first commercial successes of the CC process which has been the forerunner of automated construction processes, whose development has been slow because

- Automated fabrication techniques are not suited for large-scale applications such as the construction of buildings.
- Automation cannot be carried out with the help of conventional design approaches and traditional construction methods.
- Materials' limitations in being used by automated methods
- Higher costs of application and initial investment.

### **2.3.2 CONCRETE EXTRUSION**

The extrusion of concrete through a shaped nozzle to produce a continuous concrete extrusion or filament is the principle behind this method, which is used in machines used to lay concrete pavements and sidewalks. These machines, also known as curb extruders take in the raw material, mostly concrete or clay, and process it to the shape to be extruded, forming the curb or pavements.



**Figure 8. Curb extruders [35]**

The above picture is of a curb extruder, which is used with a concrete mixing truck to lay pavements, by taking in the prepared concrete mix; compressing it and shaping it to the desired shape of the pavement.

### **3. LITERATURE REVIEW**

The literature search is the first stage of the thesis, beginning with studying the process and its requirements, and in knowing the current state of the process. It is also possible to analyse existing designs of printing heads currently in use by companies, researchers and universities. The amount of material available is extremely limited as the process of CC is a small part of AM, and is a niche industry with huge potential for growth, as when this potential for growth is tapped can be applied to a variety of applications such as commercial construction and lunar or Martian constructions, which can be a huge market in itself, with mankind looking to expand horizons and create inhabitable colonies in outer space.

The search can begin with studying research papers from journals, and the available designs of a few universities and commercial construction companies. There cannot exist an ideal design of head because each application varies, with some companies using concrete while others use recycled plastics. The design for the 3D printing head was difficult to begin because there were little or no sources of inspiration because there are very few developed concepts available and only some of these concepts are open to access. Also, because there are no proved designs or models of concrete printing heads, and all of them are either university prototypes or projects carried out by researchers.

The following is a summary of the literature review, partly based on the trends in the construction industry, with the onset of the introduction of concrete printing technologies and the other part, studying and analysing the various 3D concrete printers/extruders available throughout the world, and some detailed studies on them.

#### **Construction Industry**

The trend of automation and robotic control has taken over almost all of the major industries and revolutionised them, while the construction industry has been very slow to adapt to these changes. This was solely due to the fact that the construction industry has been considered a very manual industry that cannot be automated. Hence in the race for increased automation and improved efficiencies, the construction industry has been slow in

catching up with the other industries. But increased pressure on resources and the need for sustainable processes has in a way forced the industry to look for alternatives.

### **3.1 Recent Trends in Concrete Printing**

Recently, there is a lot of emphasis on using recycled waste materials and bio-waste in the construction as fillers and reinforcement, and in order to make it more eco-friendly. Also, there are ideas of green houses and energy efficient buildings being integrated into this construction, with developments made in the materials used and the construction processes, with more buildings built with ‘breathing walls’ and other such concepts.

Other developments are the increased importance of the development of ‘Lunar’ and ‘Martian’ constructions on the Moon and on Mars, which would otherwise be impossible to build with the human workforce. This could make way for the idea of human colonies in outer space or for buildings that serve specific purposes such as research, energy provision etc. in space. For example, the construction of labs, storage facilities and even housing on Mars are being researched in order to accommodate the future ideas of humans visiting Mars and other bodies in outer space.

There is more emphasis on the need of the extensive use of ‘in-situ’ materials in the construction of these bodies or those available on-site at these bodies, for example, the materials available on the moon can be used for constructions on it. This can help reduce the cost of these constructions and the need for human labour.

The constructions, as far as they’ve been completed have many benefits and are known to reduce the many problems in the traditional construction industry, such as low labour efficiency, higher time consumption, high costs and reduced accuracy and complexity. The advantages of using a 3D printing system are the exact opposites such as:

- Improved labour efficiency
- Increased accuracy
- Higher complexity of constructions

- Lesser wastes and losses
- Lesser time for construction

And results include the reduced overall cost of construction and improved finish quality in construction. These indicate the future prospect of using a completely automated construction system.

But the construction industry is the industry that can be seen as one that has a huge potential for improvement, due to the fact that it is considered one that consumes a substantial portion of resources, while also causing a sizable amount of environmental pollution. This is seen as there is a lot of particulate matter and fly ash taken up into the air from construction sites. According to a study, the American construction industry accounted for 36% of all energy consumption in the nation. Also, 30% of all raw materials and 12% of drinkable water in the US were utilised for construction purposes [7]. On the whole, this has led the industry to be blamed for its poor productivity considering the portion of natural resources it consumes. In this chunk of consumed resources, there is also a considerable percentage of wastage.

Another point of concern is the decline of the workforce, or the poor availability of skilled workers for construction, as construction is an industry that relies heavily on the skills of workers. When this is something to worry about, it then results in compromising on the quality of the finished product or consuming far too much time than it actually requires.

These could point to the lack of innovation in the industry and its hesitation in incorporating new technologies into construction processes. But recently, it has taken to hosting new techniques in its processes, for example, the inclusion of smart materials in buildings, green building concepts and so on. Another key inclusion probably has to be its hosting 3DP processes, such as contour crafting. Given the basic similarities of these two processes, it was only a matter of time before these two were combined into one. With the onset of contour crafting, this combination was established. From there, more such processes were invented and have marked the beginning of a new era in construction.

Apart from attempting to reduce waste and improve efficiency, there is also some emphasis on the increase in customization of buildings, without compromising on construction time, costs or efficient material use. 3DP has its biggest advantage in the ease of use and the ability to customise the end product with little effort and is only fair that this feature also is available in construction with more or less similar processes.

### 3.2 WINSUN

Yingchuang Building Technique (Shanghai) Co. Ltd, also known as Winsun, is a construction firm from China has been one of the few companies to have first adopted the 3DP technologies to their business. In 2005, they developed a spray nozzle, with was used to experiment with materials such as cement. This spray nozzle thus became one of the key components of Winsun's 3D Printer used widely, even to this day [9].

In 2008, they developed their first continuous 3D Printer with integrated input systems, material analysis and output control systems, after refining and improving the system developed previously. Their 3D Printer is currently the world's largest 3D Printer (used for construction) and measures 150m long, 10m wide and 6,6m high. This 3D printer uses high-grade cement, sand and glass fibres, along with a binder [2]. This inclusion of binders and fibres is said to improve the strength and lifetime of the construction.



**Figure 9. The 3D Printed Villa [9]**



In 2013, they constructed a series of 10 one-storey houses, each 200 m<sup>2</sup> within 24 hours in Shanghai, all with the use of a 3D Printer. The majority of the walls for these buildings, though, were printed elsewhere and brought to the site and assembled on conventional foundations. These walls can be hollowed to accommodate wiring and pipes and can be customised according to customer needs. Winsun also printed a 6-storey apartment building in China and a standalone villa after that. More recently, in 2016 they collaborated in constructing the world's first 3D printed office in Dubai. It was said that these processes required the presence of only 3 people at the site. The time for construction was greatly reduced. For example, the villa took about 1 day of printing and 2 days of assembly. Moreover, up to 50% of these printing materials are said to have been derived from demolition waste. Another impressive feature is that these constructions produce zero waste [8].



**Figure 10. The 6-storey Apartments by Winsun [9]**

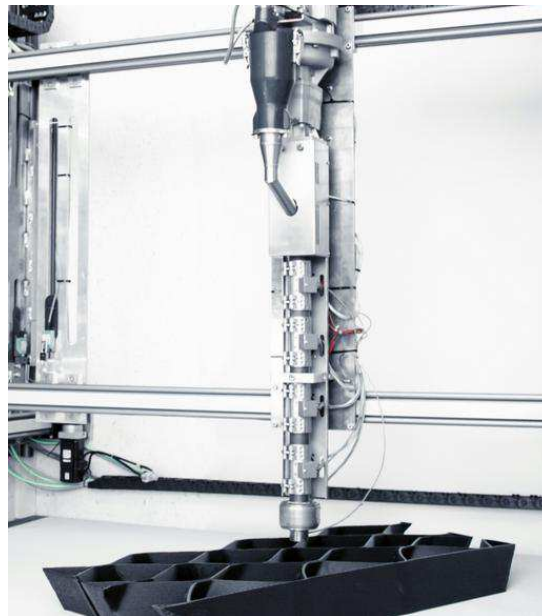
Winsun has estimated that the construction of a standard house will cost about \$30,000. On the Dubai office project, the process is said to have saved about 80% on construction costs, 60% on labour costs and 60% on waste, compared to traditional building processes. If this could prove true on every construction, it can be predicted that these technologies can soon replace traditional methods. Winsun has already gone beyond the concept phase and has

already sold more than 100 houses [9]. The printing head used by Winsun is kept mostly closed, but the extrusion is seen to be in a rectangular shape. But the printing pattern is similar to the contour crafting method, which is one way of printing concrete.

### 3.2 DUS ARCHITECTS

DUS Architects is another architecture firm, based in the Netherlands who have implemented the use of a 3D Printer known as the ‘KamerMaker’ or the ‘Roombuilder’ in Dutch. This 3D Printer is being used to construct the first 3D printed canal house in Amsterdam. The project started in 2014 and is now in the completion stage. It is open to the public as an exhibition of its 13 rooms, each explaining a different stage of design and development of the project [11],[10].

The KamerMaker is a scaled-up FDM printer and has printed the house block by block. The machine itself being 6m high can print elements 2m x 2m x 3,5m, out of a mixture known as ‘hotmelt’, containing bio-plastic and about 75% plant oil. These elements or blocks can be stacked up like toy bricks according to customer needs and completed. These blocks contain few hollow areas that need to be filled with concrete and completed.



**Figure 11. KamerMaker [70]**

DUS has completed another project known as the 3D Print Urban Cabin, which is an 8 m<sup>2</sup> micro-housing in Amsterdam, which provides an insight into what can be expected from the 3D Printed Canal House. This serves as a demonstration of the possibilities of additive manufacturing in creating temporary housing or disaster relief structures, during times of emergency [69]. This cabin can be shredded and its materials reused in printing, after the period of use. It uses a black filament, consisting of linseed oil for printing. The patterns of the walls have angular projections forming a stable support structure. The floors of the cabin with some parts of the walls have been filled with concrete for structural strength.



**Figure 12. The 3D Printed Urban Cabin [69]**

### **3.3 D-SHAPE PRINTER**

The D-Shape stone and concrete 3D Printer is a large sized binder jetting 3D printer that was developed by Enrico Dini of D-Shape Enterprises from the USA. It binds sand to inorganic seawater using a magnesium-based binder to form a sandstone-like material in 24 hours [24]. The printer consists of a 4m square frame, a flat print bed and a wide print head holding up to 300 nozzles over its entire area, that deposit drops of binder on the print bed. The machine is driven by a software control and scans the entire print area to locate the point of deposition [23]. Their patented method for building conglomerate structures and printing head comprises of shells being created from a given CAD file layer-by-layer in

fixed vertical pitches [21]. The first layer of granulated material is laid out, binder material sprayed and then the second layer and so on, according to the predetermined structure of filled and blank areas [22]. This method was patented along with the head between the years 2006 and 2008. The head is carried on a crane in a Cartesian gantry support and can print up to 6 x 6 x 6 m structures with a layer depth of 4-6 mm. This smaller resolution allows greater geometry control.

Under ideal conditions, the company claims, the D-Shape printer would be able to print 1 house of 70 m<sup>2</sup> per 4 days, for under a fourth of the cost of building a house by conventional methods. The printer costs about \$250,000 [24]. D-Shape is currently the first company to obtain a permit for 3DP construction from the United States. They have collaborated with the European Space Agency and have successfully used moon regolith from the moon surface for construction. They are currently working on bridges and other structures that can withstand natural calamities, and other structures such as military bunkers, and estates. They are also currently working on a mixture of cement and metal for printing purposes [25].

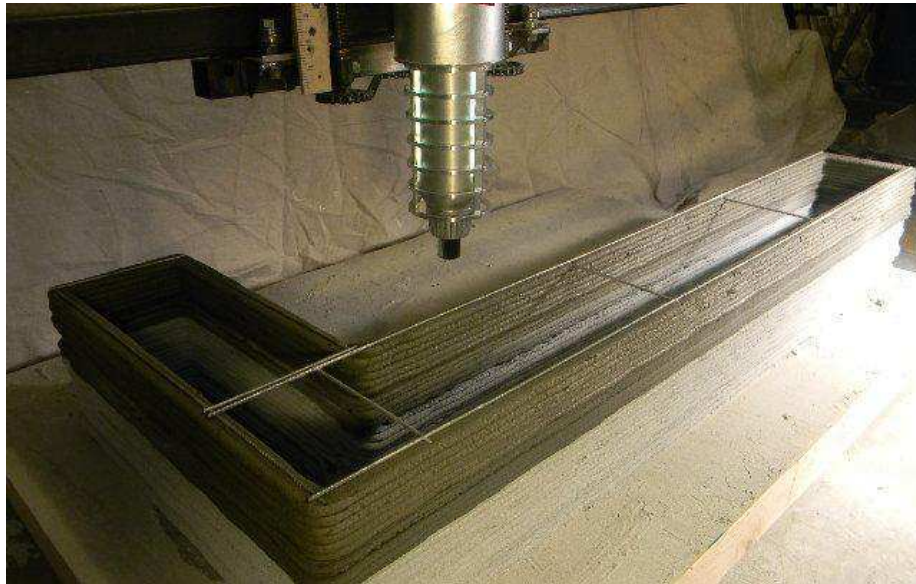


**Figure 13. The D-Shape Printer [25]**

### 3.4 TOTAL KUSTOM/RUDENKO 3D PRINTER

Total Kustom is a 3DP company led by inventor-contractor Andrey Rudenko, who printed the popular 3D Printed Castle, in order to demonstrate the capabilities of his 3D Printer known as Stroybot. It took approximately 6 months of construction and the entire project was in development for about 2 years. The printer used a very viscous concrete mix to print layers 30 mm wide and 10 mm thick [27]. The printer at its fastest was able to create 50 cm high walls in about 8 hours [26]. More recently, the Lewis Grand Hotel in the Philippines had an entire suite 3D Printed using the Total Kustom Printer.

The printer was further developed in order to better optimise the process, quicken the printing and make it more user-friendly. It was made out of a Carbon-Kevlar composite for lightness and portability [27]. The current printer Stroybot 2 was developed with the aim of promoting it as a commercially-available 3DP construction system.



**Figure 14. Total Kustom's Printer Head [68]**

Recently, Total Kustom has started selling prototypes of its models for construction and has developed a number of models for varied applications. In addition to the StroyBot, there are other models like **the** LAByrinth that is a robotic arm printer designed especially

for building in hilly regions, SEVEReBot which is sold as an 'All Season' 3D Printer, for housing and prints even in extreme weather conditions and MegaTowerBot, which is for building oversized towers such as cooling towers [27].

### **3.5 APIS COR**

Apis Cor is another building company that is at the forefront of the 3DP technology. They also recently revealed the first on-site 3D Printed house in Russia. This, they do with the help of a mobile 3D Concrete Printer that they transport to the site. The building envelope is closed off with shelters to protect the deposited concrete, and the process takes place within a few days sometimes within a day. The printer requires only about 30 minutes for installation and has a print envelope of 132 m<sup>2</sup>. According to Apis Cor, there are some other components of the proprietary printing setup in addition to the Construction 3D printer which are the Mobile Automated concrete mix and supply Unit (MAU), their proprietary software and control program and the Dry mixture storage silo.

The printer is about 4 m long, 1,6m wide and 1,5m high and weighs about 2 tonnes. The printer has a manipulator at the end of its telescopic arm that rotates on a circular central platform extends to reach the point of deposition, and prints these structures from within the house. It has a software system to control its accuracy and has a positioning precision of about  $\pm 0,5$  mm. The machine prints a foundation with supports to be filled with concrete. The walls are printed with accuracy and a finish similar to a finished wall. All this reduces costs to a large extent, in addition, to save labour costs and material and transport costs. Their constructions also comply with international safety, energy efficiency, and environmental performance standards. Its output is about 100 m<sup>2</sup> and the company says that a house can be built in about 24 hours, with the help of 2 people who would operate the machine and install it. Apis Cor promises a lifetime of about 175 years for these houses. Compared to using traditional hollow blocks, printing is 2,8 times less expensive. Also, the material used for printing an equivalent area is only about 0,26 m<sup>3</sup> of print material. The printing speed is also estimated to be 6 times faster than producing a hollow block [13].



**Figure 15. ApisCor's 3D Printed house at Stupino and the ApisCor 3D Printer [13]**

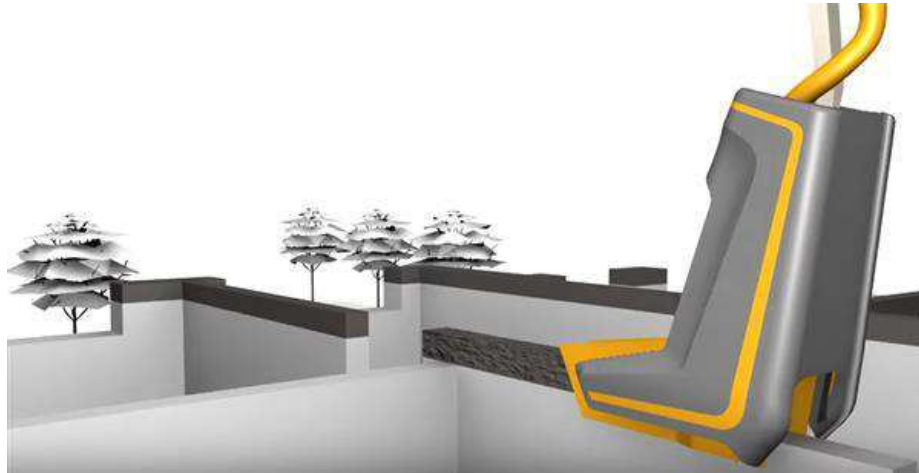
Stupino is a city in Russia that houses the 3D printed house by Apis Cor. The house was completed within a day and has an area of 37 m<sup>2</sup>. It has an unconventional design and the estimated price for this Apis Cor formula is about \$103-\$155 per m<sup>3</sup> and becomes cheaper with increased consumption. The additive manufacturing system works with a special compound, with a special mortar mix with a concrete base with special additives and reinforcing materials. Apis Cor recommends construction of buildings up to 3 storeys high with its proprietary formula [13].

### **3.6 CONPrint 3D**

CONPrint is a recent project that was recognised at a construction fair in Germany for being very innovative and having great potential. It was developed at the Technical University of Dresden by a group of scientists for the prime purpose of reducing costs of construction by eliminating the need for formwork which they claim takes up about a quarter of the cost, and moreover, cannot be reused after usage [14],[15].

The method consists of a robotically controlled print head directly supplied with material from a reservoir depositing and shaping the layers of the building, based on constructional

data. The team claims that this method uses more of the conventional machinery and still eliminates costs of formwork and labour, achieving geometrical precision.



**Figure 16. CONPrint 3D printing head [14]**

### **3.7 MARTIAN AND LUNAR CONSTRUCTIONS**

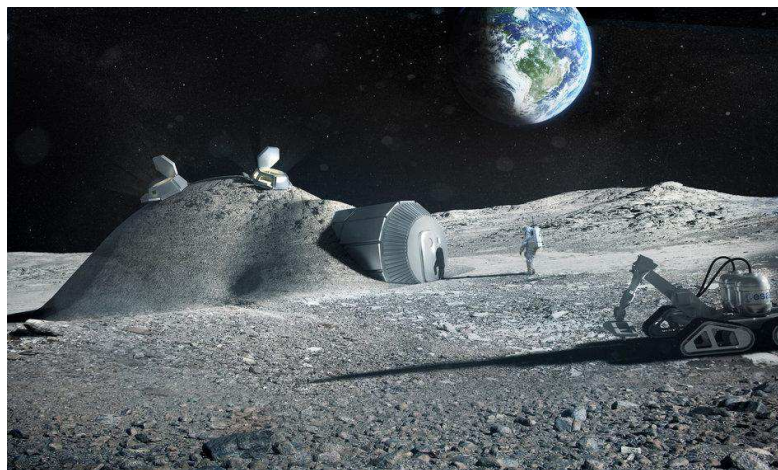
The possibility of human colonies in space has been fascinating to the human race. This idea is soon about to be realised by the few proposed Mars expeditions and missions. The idea has been strengthened by the discovery of the possibility of construction of lunar and Martian bases using in-situ materials from the surface of the moon and Mars [30].

Lunar construction has already been demonstrated by the European Space Agency (ESA) along with companies such as Foster + Partners and D-Shape enterprises, through its display of construction using lunar regolith, a type of soil found on the moon's surface. They have successfully shown the possibility of using this material to build structures, by using a simulated moon dust and an atmosphere artificially created to mimic the moon atmosphere [32]. The demonstrated structure for these moon bases were inflatable dome structures that are resistant to micro-meteoroids and radiations [31]. These dome walls have a self-supporting catenary structure with a cell arrangement that is light and at the same time has a good strength-weight ratio.



The proposed mission of colonising mars would be done in two steps:

- The first step of the mission would be to construct bases suitable for people to live inside by carrying an automated construction machine with them. The main advantage of this is that it is enough to carry only the printer, and the materials can be used from the surface of the moon or Mars.
- The second step would be to inhabit these structures and to demonstrate the possibility of living in space. In the initial stages, enough food and other needs for the length of the stay will be carried along. Also, hydroponic plants and a few seeds would be carried and planted in special structures suitable for plant growth in a special agricultural dome close to the base [33].



**Figure 17. The demonstrated structure and proposed moon base [31]**

### **3.8 RELATED PATENTS**

Next, we were to begin searching for patents and intellectual property in the focused realm of concrete printing from patent offices and databases all over. The Indian, Czech, European, American and International patent databases and search engines were searched and there were a few patents relating to our area of interest, and a very few that specifically met the criteria. From the European patent search, there was a patent for a 3DP method for creating objects from sprayed mortar inside a curing chamber, after an accelerator would be added to the mix [37]. Another method of constructing 3D structures using concrete using 3D moulds is also given, with the help of a robotic arm [38]. The contour crafting method [39] was patented in the year 1996 even though the process has also been in continuous development since then [40]. The D-Shape method of extrusion from a number of nozzles was also patented by its inventor Enrico Dini by 2006 [21],[22].

Also, there were a number of related patents that were interesting from a constructional perspective such as a method of using materials for building that increased strength of building by 70% compared to concrete [41], and others that could be taken into account for future development.

## **4. DESIGN OF PRINTING HEAD**

Being the central theme of the project, designing the printing head was going to be the decisive part of the thesis. This section of the thesis is about designing the printing head, the ideas, the needs and considerations and other factors of the design.

### **4.1 BEGINNING THE DESIGN**

The printing head is the essential component of any printing head, and this importance demands that the design is carried out thoroughly. The printing head is the part of the printer from which the extrusion or deposition takes place, and the scope of these functions can vary with the type of 3D Printers. For example, in 3DP with plastic or ABS, the printing head has a more complex task; that is, the printing head is required not only to deposit the plastic but also to melt, maintain the temperature of the material and so on [36]. So, the functions of the head must be defined at the beginning along with the scope that the head is set out for.

From reading the literature earlier, a few raw ideas had popped up. These ideas were only about basic tweaks to the previous designs that I had seen before in videos and pictures. But without practical experience, these appeared only as abstract ideas.

Before commencing the design, I started with a vision of what I wanted to build, and with how the design needed to carry the tweaks to models I had seen previously. For an initial idea, I wrote down some samples of parts that I should add to the design such as the housing, or the main body of the head; Replaceable shaping nozzles, that can be removed and replaced after each printing process, or according to the shape required; Open/close systems, to allow or restrict the material during printing; Mixing systems, to mix the additives into the concrete mix; Motor holders; Trowels, to shape the extruded concrete; Containments, to hold the additives and add them to the material whenever required by the process

The functions to be carried out by the printing head have to be fixed at the start so that the corresponding functional parts can be added to the head. For this project, the printing head needed a straightforward design at the beginning and then we could consider adding the more complex parts as the design and testing progress.

The idea was to start out with these goals in mind and then design a very basic prototype and then test this out for future additions to the design. Hence from the scope of my thesis work, it was decided to keep the working simple, only fulfilling essential tasks; and so, from the last list of requirements, I excluded a few functions that needed electronic controls and complex structuring.

A few of the primary requirements set at the beginning were that the head has to

- Act as the nozzle for extrusion
- Mix the concrete and push it for extrusion
- Maintain a constant flow of the concrete mixture
- Shape the concrete
- Be the secondary reservoir of the concrete mix

Once finished, this design can be prototyped and tested with concrete to see what other components can be accommodated for fulfilling other secondary needs.

## **4.2 LOOKING FOR INSPIRATION**

The design seemed like a distant dream at the beginning, because there was no clue where to begin the design and how to carry on with it. All I had for designing the head were some very primitive design ideas, some parts that I designed at random and some potential sources of inspiration that my supervisor had shown me during our meetings, prior to beginning the work. For an additional incentive, I started looking for some other designs for printing heads of various 3D printers.

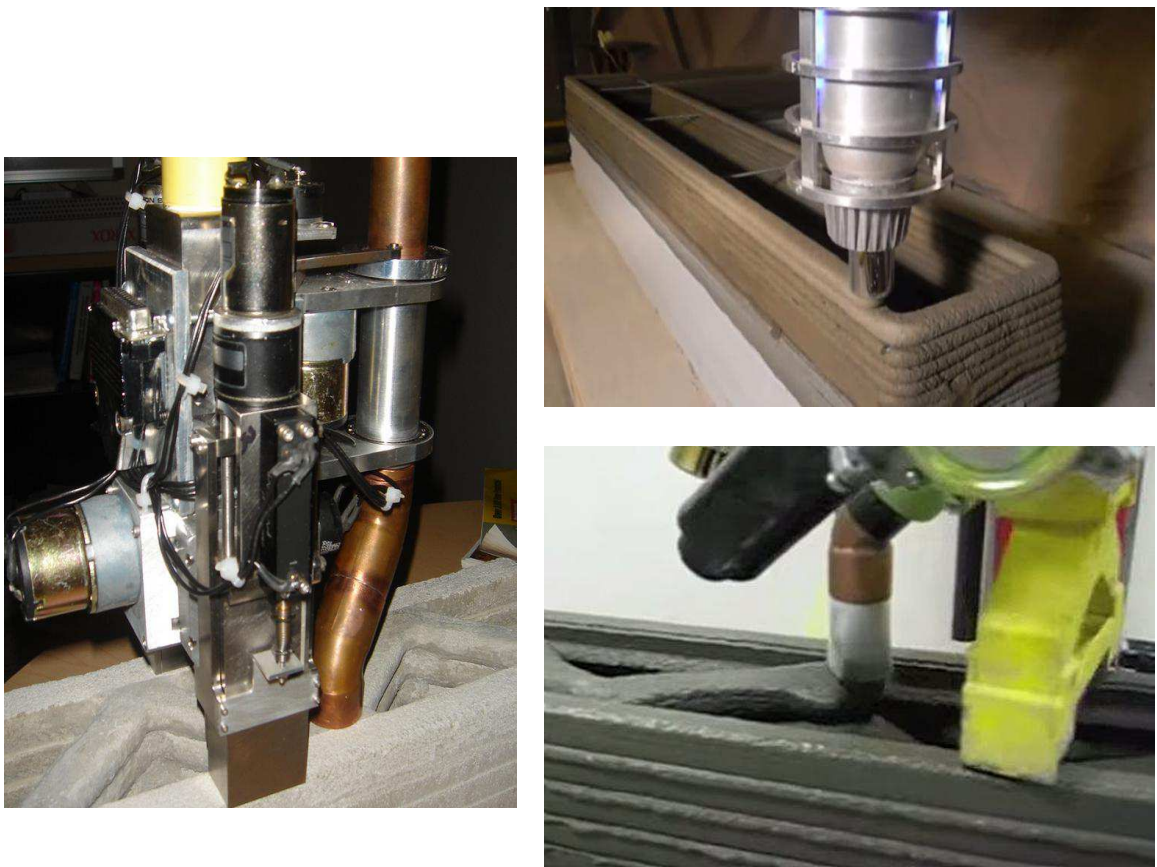
The available options for concrete printing heads were very limited, because the extent of development in the field is small and the companies that developed these processes wish to keep them fairly secret or as proprietary information. This was a challenge that I had to overcome at the initial stages because these designs were only recognised by me through my seeing the pictures or videos of these heads at work. At most times, these heads were kept closed or covered throughout the videos. Nevertheless, some designs we obtained through persistent searching.

Most direct designs of printing heads were mainly from universities or researchers, for example, designs from the Universities of Loughborough, Eindhoven, and Lund were particularly informative [43],[44],[45]. I tried to find out some working videos and descriptions or pictures from these works, and from this, I formed an initial framework of the design that I had in mind.



**Figure 18. The Printing head designs from (clockwise) Lund University, University of Loughborough and TU Eindhoven [66],[70]**

Researchers like Andrey Rudenko and Behrokh Khoshnevis, who are pioneers in the field, had developed some of their own printing head designs. Both these people have already applied their designs to commercial applications through their companies or research groups. After a while, I contacted Mr.Rudenko through e-mail, asking for his suggestions and advice for printing head design. He replied with the suggestion, to begin with, a design that is as simple as possible for example, a plastic hose of 20 mm for the nozzle. Dr.Khoshnevis was the inventor and developer of the processes and technologies for Contour Crafting.



**Figure 19. Printing heads designed by (anti-clockwise) Khoshnevis and Andrey Rudenko [66],[67]**

These designs gave an insight into what the head should look like, and the shape and size of the head. Apart from being one of the few limited resources, these were already in an advanced phase of development and testing and hence would be reliable sources of inspiration.

After the phase looking for design ideas for 3D printing concrete, the next step was an idea to seek out processes and operations that were similar to extruding or depositing concrete, such as ones that extrude semi-solid material onto a surface. During this time, inspiration often came from very unusual places, outside usual modes of literature. There were some fascinating ideas such as the ice-cream maker or softy machine, that are used commercially; then there were the curb extruders used during road laying. There was another interesting project called the hand-held concrete extruder. These were discovered when I was simply browsing the internet for other information.

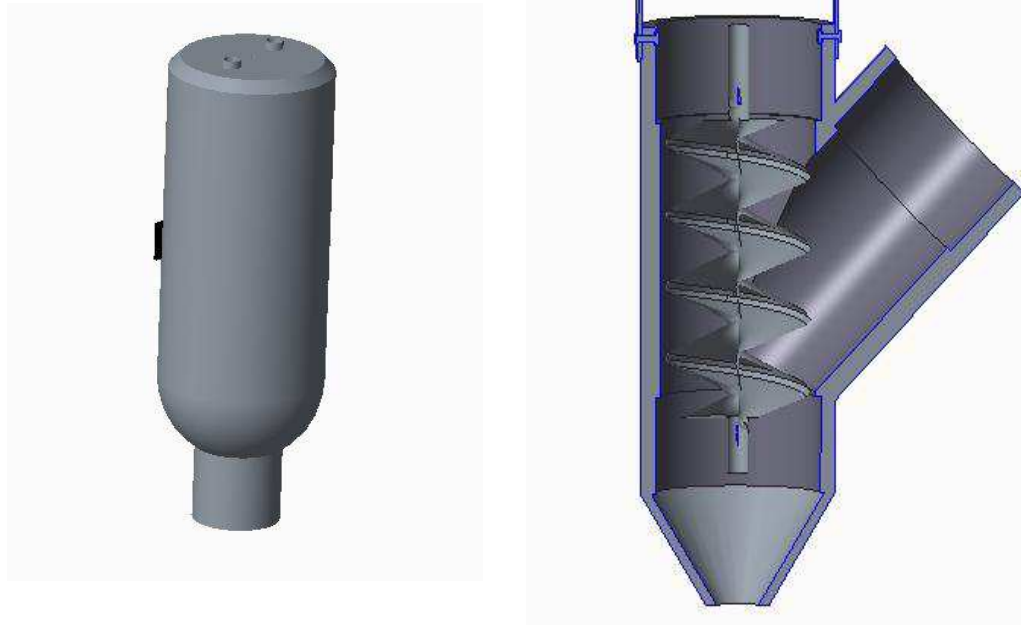
Each of these sources had something to offer to the project: the ice-cream maker can accurately shape a swirl. The curb extruder can perfectly form a rectangular curb, and the handheld extruder had a very simple design. It was true that these objects were unconventional, but these could be interesting given the analogies these held with the subject of interest. Some features of these mechanisms can be considered, and some ideas can be incorporated into our new design based on our need and what can be done with the idea in hand. The softy maker produces patterns with the ice-cream it extrudes, mixing air and ice-cream to a critical ratio to extrude the mixture in a specific shape to a container [49]. The hand-held concrete extruder is another university project from the University of Virginia in the USA [48], where the students tried different combinations for the extrusion head for depositing concrete onto a plane. This device consists of only a handheld tube, with a system to push the concrete inside it to be extruded to the shape of the nozzle, or the hole at the end of the tube. They try various methods to pump concrete in and out of the extruder, including air pressure, manual loading and electric components.

Then there is the concrete extruder, also called hollow-block extruder or curb extruder, which is a machine widely used to lay pavements, platforms or continuous blocks of concrete in a faster way [35].

### 4.3 THE DESIGNS

For printing concrete, our scope will be limited by the needs given at the beginning of this chapter. The printer will need to include the parts for these tasks. At first, with the more complex tasks in mind, I began to design a more complex head design that was going to consist of functional modules for each specific task. The design was possible but was very time-consuming, because of the idea of including many additional features. The initial design was made with provisions for attachment at the back, a separate mixing chamber within the tube, modular containers for additives.

While going through the design, my supervisor advised me to start off with a simpler concept without any attachments. It was to only realise the extrusion process and after this was completed, we could start thinking about adding more features to the design. That is when I designed a simpler design using basic parts, available at hardware stores.



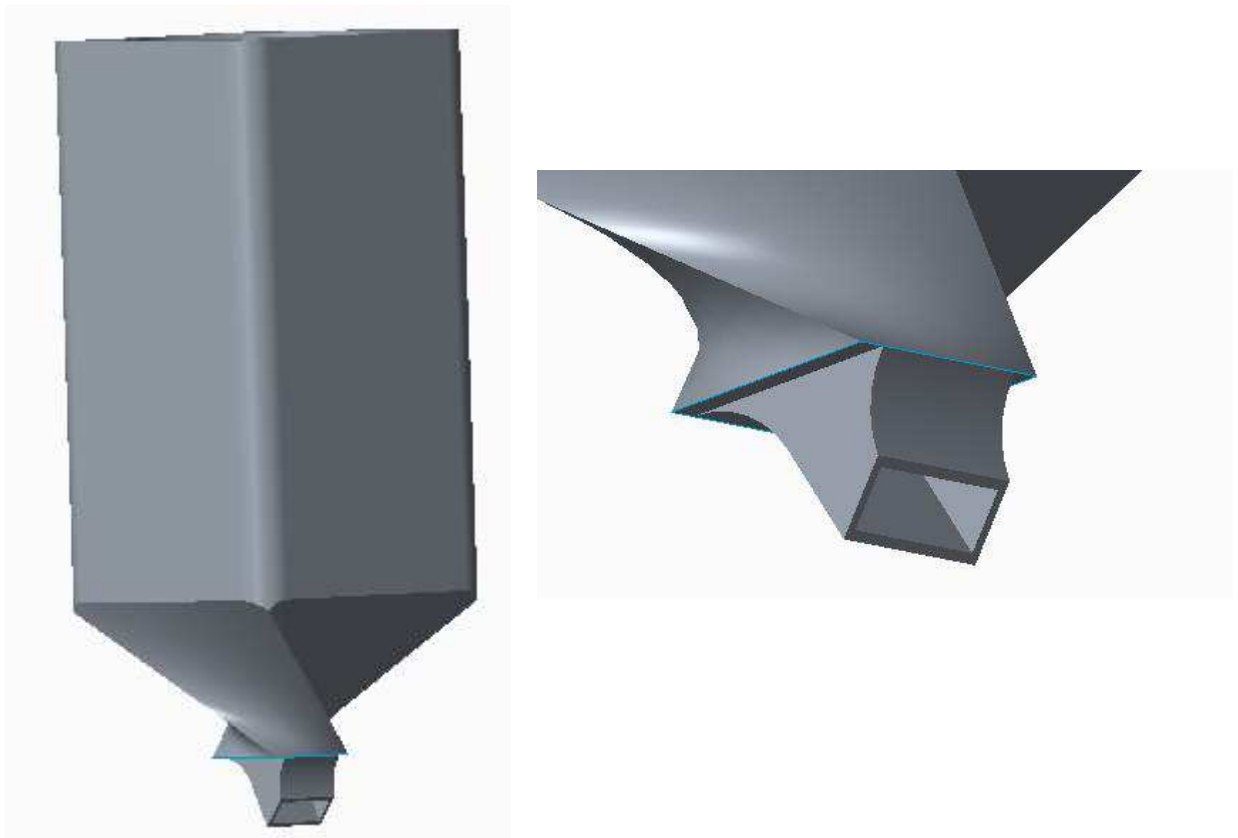
**Figure 20. The basic shape of the initial design and the pipe Design**

The components of the pipe design, which will be designated as Design 1 were a standard PVC Wye pipe of 160 mm diameter, an auger drill bit of diameter 150 mm and a mounting



bracket, that holds the pipe and can be attached to the motor components. The funnel at the end of the pipe can be 3D Printed to customise it to our requirements.

Another variation of the model was also in my mind, which I thought could be done as another separate design. In the future, these two designs can be clubbed to create a design that shares the common merits of both the designs. Its main feature was its curved and projecting nozzle, that would also do the job of shaping the concrete.



**Figure 21. Design 2 and its feature, the projecting nozzle**

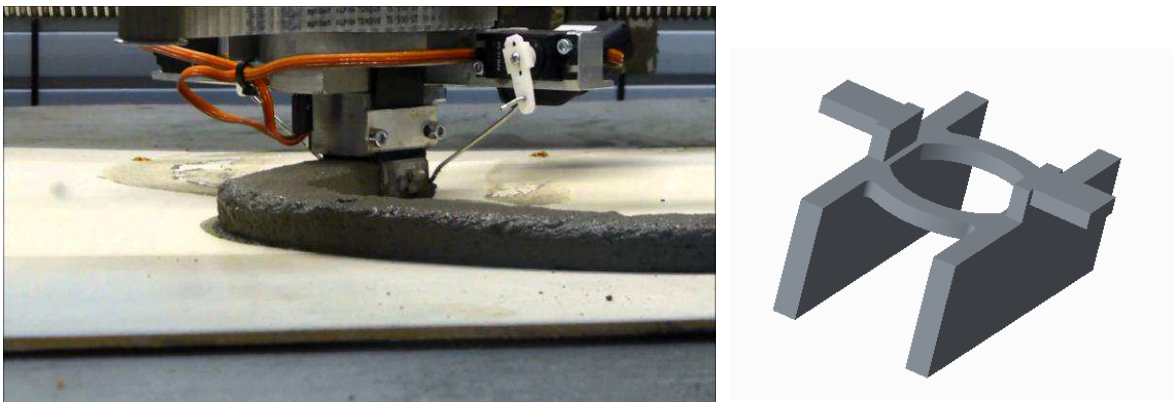
The next step was to draw these parts into CAD software and possibly make prototypes and test their printing capabilities. It was designed in CAD software Creo 3.0 so that there would be possibilities to 3D Print the prototypes in cases when manufacturing the parts would not be possible.

#### 4.4 PART-BY-PART

Before getting to the basic designs above, it was first analysed which parts were essential and which needed to be added to the design. Some of the parts that were considered and the reasons for their selection are given as below:

##### TROWELS/SHAPERS

Some printing heads used a system of trowels to direct and shape the concrete or materials. But from a few videos of those printing heads working, it was seen that although trowels are useful in the shaping and guiding of the material, they always disturbed or deformed the deposited concrete as they moved [52]. Moreover, the attachment of these trowels to the head would need the presence of a control system and other complex mechanisms in the head. Thus it would be better to design the nozzle in such a way as to integrate the function of a shaper or trowel within the design of the head.



**Figure 22. The trowel mechanism used in the printing head from Aalto University and the shaper first designed as an attachment [42]**

## **NOZZLE**

For 3D printing concrete, the nozzle is a critical part that needs to be strategically placed in order to guide and place the concrete in the specified locations. The nozzle selected for the first and second designs were a funnel-shaped nozzle and a shaping nozzle respectively. Because of the fact that both these nozzle shapes would be 3D Printed, they gave a lot of options for customizability.

The second can be contextually called a nozzle but not in the exact sense because its design is peculiar. The unique design came to me as a result of thinking about extrusion machines for concrete pavements and clay curbs. The function of the nozzle has been integrated into the end of the pipes in both the designs.

## **MIXING/GUIDING**

This was an important function of the print head when it comes to concrete because it is a denser material, and needs to be guided and placed till the last minute. This requires that the guiding system has to be extended until the end of the nozzle so that its influence is felt when depositing the concrete onto a surface.

There is another factor in the point that the concrete deposited has to be in the form of a single continuous filament and does not separate out as individual blocks, or as lumps. In order to be a continuous filament, the concrete must be carried throughout the pipe and sent to the nozzle successively.



**Figure 23. 3D printed auger drill (Archimedes screw)**

For this reason, using a mixer would not be an appropriate solution, because though it helps mix the concrete well, it breaks up the concrete. Hence instead of a mixing mechanism, it was a good idea to use the Archimedes screw [53], in the form of an auger drill bit in the design. Since I felt the Archimedes screw was more suited for this job, it was taken as a feature for both the designs

#### **4.5 A BRIEF ABOUT THE DESIGNS**

##### **DESIGN 1:**

This design was my second alternative for the solution and it was an idea derived after going through some designs, inspired by the simplicity. It has the advantages of easy manufacturing and standard parts. The working mechanism is extremely simple in this case. The Wye or Y-Pipe aids in the loading of concrete through its other opening and this comes in as a handy feature. It can be said that this one is a rather conventional design because of the circular sections and its relative simplicity. According to me, this printing head would do the job well, but the shaping and extrusion would be problematic.

##### **DESIGN 2:**

This design was derived a long time after the first one, based on predicting where the first one might go wrong. Its key feature can be described as the nozzle and the bottom part which has a swirled pattern. The overall shape of the design resembles a rectangular block but it has a circular cross-section in order to accommodate an auger drill bit. Its rounded edges can be safe for use in an industrial environment. The uniquely shaped nozzle can shape and dispense at the same time. The nozzle was shaped in such a way in order to minimise the effects of disturbing the previously dispensed concrete. A place that this may go wrong is the placement of an additional space for loading concrete.

## LAYOUT:

The layout of the printing head in accordance with concrete construction would be somewhat similar to what is shown below. A hose or a pipe would carry concrete from the reservoir or tank to the print head through its opening. The head would be supported on a mounting bracket fixed to a gantry crane that moves in a cartesian configuration. A servo motor could be used to turn the shaft of the auger inside the pipe.



**Figure 24. A possible layout of the mechanism**

## 5. CONCRETE

The main advantage of 3D concrete printing is the design freedom that comes with it. This is attributed to the ability to perform freeform construction without the need for structural supports or framework. Although some cases might require the use of structural supports, it can be done without in most of the cases because the concrete itself carries itself as a support system. This requires that special attention is given to the cement being used in these applications.

Cement is the primary raw material for constructional processes. When cement is mixed with water, aggregate, and admixture, it is known as a concrete mix. A concrete mix is to be specially created for these purposes making use of some additives in order to improve certain characteristics of the concrete that are helpful in holding these structures and in forming the required object.

Earlier, when the need arose to use concrete that did not need formwork, there were two novel concepts that allowed this: self-compaction and sprayed concrete. Once laid, self-compacting concrete would harden and strengthen itself, and sprayed concrete needed to be sprayed as thick layers onto existing supports. These methods, however, had some demerits because of which more importance was given to additives for cement.

### 5.1 PROPERTIES OF CONCRETE

Some of the parameters of concrete that are critical to printing are Extrudability, Buildability, Workability and drying time which are influenced by the proportions of the additives in the mix [53]. The first two of these parameters have an important correlation with the latter two.

These parameters and their implications on the finished concrete mix are given below:

- **BUILDABILITY:** The ability of the concrete to be laid down in place correctly, or its ability to remain stiffly in its set position without deforming. Reduction or lack of this property could mean that the concrete structure cannot be stiff and will deform with time [53]

- **EXTRUDABILITY:** The concrete's ability or capacity to pass through small pipes and nozzles at the head. This could imply the ability of the concrete to be shaped and sized to fit the requirement. The principles of self-compaction and sprayed concrete can prove useful in improving extrudability [53].
- **WORKABILITY:** Workability refers to the ability of the concrete to be moved, transported, compacted and finished without separation of its constituents [54]. Workability is referred to in relation to the consistency and lubricating nature of the mixture [54]. The consistency is influenced by the presence and amount of cementitious binders/ aggregates and their ratio. Also, the ratio of water to the binder and the use of admixtures.
- **DRYING TIME:** Drying time is the time taken by the mixture to dry to its final position and shape. Open time or Air time of the concrete mix can, in some cases, be used to refer to this from another perspective. Open time is the time it can be exposed to outside conditions before drying.

## 5.2 ADDITIVES/CONCRETE ADMIXTURES

Some important primary additives and admixtures to be added to concrete to improve its various properties are given below:

- Water
- Aggregates
- Retarders
- Accelerators
- Superplasticizers
- Polypropylene fibres

Water has an important effect on the consistency of the mixture and leads to binding of the cement particles to form a viscous mix; aggregates are fillers that are used in the mixture with cement, and these generally take up 60-80% of the volume of the concrete mix and 70-85% weight [46]. Fillers, though they are passive constituents, have important effects on the stability and the elastic and thermal properties of the structure. Aggregates can be separated as coarse and fine according to their size. Typical aggregates are natural sand, gravel, and crushed stone.

Retarders can help adjust the open time, by retarding the chemical process and delaying the reaction time. Also, retarders have an effect on the hardening time and hence are useful in controlling the flow characteristics [46] amino-tris and Lignosulfonates are examples of retarders. Accelerators on the other hand help speed up the setting time of concrete, making it three times as fast. calcium nitrate, sodium nitrate, and Calcium chloride are typical examples of accelerators. Superplasticizers are additives that improve flow characteristics of concrete and adjust setting time while also reducing the water content of the concrete. They are also known to increase workability and strength of the mixture.

Fibres are used to improve other characters of the concrete mix such as chemical resistance, abrasion resistance, weathering protection and cracking

An example concrete mix more suitably designed for printing consists of 70% Cement such as CEM Type I 52,5, 20% Fly ash, 10% Undensified silica or silica fumes, Binders and Sand in the ratio of 40:60, 1,2 kg/m<sup>3</sup> micro propylene fibres, 1% superplasticizers and 0,5% retarder [53].

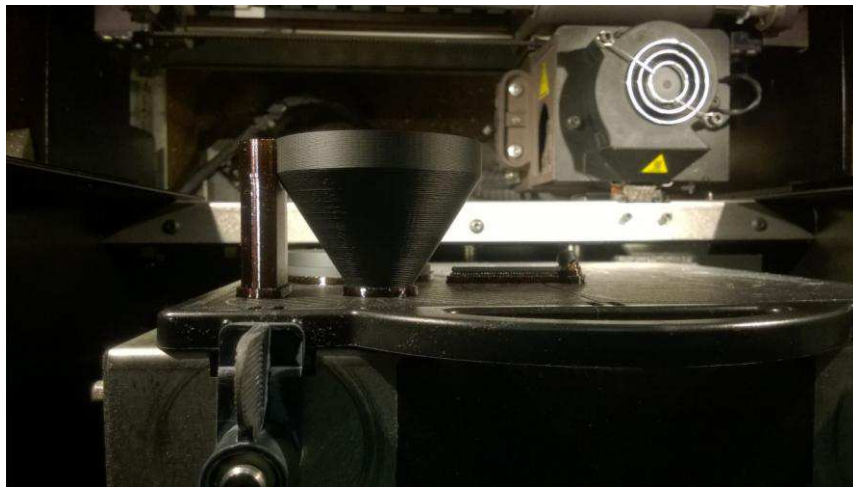


## 6. APPLYING THE DESIGN

After designing the printing heads, it was necessary to manufacture them and test them out for use with a concrete mixture. With results from these tests, it would be possible to obtain a clear picture of the needs of these heads whilst being applied to the real-world of concrete printing. But since the other components of the project, such as the mechatronic system and the developed concrete mix were not available for testing, it was decided to first test it out roughly using a scaled-down prototypical model.

### 6.1 PRINTING THE PROTOTYPES

This model of the prototype was going to be 3D Printed in the digital prototyping laboratory in the university using the **Stratasys Dimension SST 768** FDM Printer out of ABS. The scale of all components of these models was going to be **0,33** as any changes in scale would affect the way they would be assembled or how they would fit inside each other. The parts would be printed from .stl files after being scaled down and converted from the original CAD parts to a printable format.



**Figure 25. Printing the first design using the Stratasys Dimension FDM Printer**

The printing of parts was completed without any glitches in about 50 hours altogether and the print accuracy was satisfactory. The bore and pipe components of the first design were designed with very little tolerance and initially, it was required to put a considerable amount of effort to turn the bore inside the pipe. But with time, the turning became easy with friction between the parts possibly smoothening the surface.



**Figure 26. Printed prototypes of the first and second designs**

There were initial concerns about the possible errors that could take place during the printing of the second design because of the complexity of the design. The design had more sharp edges and complex curves in comparison to the first design. But the printing of the second design also went along smoothly with these curves and edges printed with excellent accuracy.

Some parts were designed especially for the testing, like the cap and a small cylindrical piece at the end of the pipe to act as the nozzle to closely guide the concrete onto the surface to be extruded. These parts would not necessarily be part of the final models. Parts

such as the bore were usable with both the designs as they both have similar dimensions so that all possibilities of using these designs can be reviewed.



**Figure 27. Nozzles from the two designs**

The distinctive features that are shown above, like the conical nozzle, the twisted end, and the shaper, from each design, were what needed to be reviewed principally because these could affect the manner of printing the concrete considerably. After the trial was completed, from the pattern of concrete deposition it would be possible to get some feedback on these features.

## **6.2 CONCRETE FOR TESTING**

A concrete mix, comparable to what is being used in the real world had to be zeroed-in on for being used with the printing heads. It was planned that a plaster mixture would be used, after being prepared with a thick consistency resembling concrete. But later, concrete was used at the time of experimentation.

The cement of type **VK-01** from **Quick-mix** was used for this trial [57], and some of its relevant properties are as given below:

**Particle size: 0 – 4 mm**

**Drying time: 2 hrs**

**Water requirement per kg: 0,13 l/kg**

**Compressive strength ~ 5 N / mm<sup>2</sup>**

**Working temperature: 5-30 C**

A batch of concrete was first made with 1 kg of cement and 0,13 l of water to form a rather dry mix. This batch was moistened with a very small amount of water which also helped bind the particles together. This was particularly useful because this was key to forming the concrete as a cohesive filament. Otherwise, if the cement does not form a viscous mixture, it often happens that concrete is poured out as irregular chunks.

### **6.3 PRINTING TRIAL**

The tests were conducted in the laboratory of digital prototyping in the university with the help of my supervisor, who arranged all the equipment needed in order to test out these models. At first, the material was mixed inside the laboratory by weighing out the exact amount of cement and water required for the mix. After preparing the concrete mixture with the prescribed composition and consistency for printing, we set out to set the models up for the trial. A vice was used to hold up the models of the head, and a plastic base was to be moved as the head extruded out concrete.

This was the other way round from the actual practice where the head would move with a gantry and print along the base. To rotate the bore drill model, a hand drill was used to achieve the necessary torque and rotation speed. The models were used in the trials one by one to see the results of each design, and based on a few parameters some comparisons between the two models can be made.



**Figure 28. The setup for the trials and the printing**

The trial began and the mixed concrete was inserted into the model by hand, and initially, there was some trouble in getting the concrete to the end of the nozzle and after loading enough material to fill the entire model, the extrusion was better than before.

Sometimes, the drill torque needed to be increased to turn the bore because the concrete prevented the bore from turning inside the pipe, and sometimes even when the concrete weight was more.

The trials with the models lasted a few hours and were only very basic tests of how these two designs fared when testing them out over their real interactions with concrete. It was rather surprising to see that these initial tests also went along very well.

#### 6.4 CALCULATION OF PARAMETERS FROM TEST:

Below are the calculations of a few important parameters, using data from the testing and pertaining to the model of scale 0,33.

Torque for turning the bore  $T = 30 \text{ Nm}$  for  $\sim 0,2 \text{ kg}$  of material inside

(Taken from the BOSCH catalogue for the hand drill used)

From the calculations for concrete transport using screw conveyor [58],[59],

$$\text{Volumetric capacity } Q_v = \frac{3600}{4} (\pi D^2) \cdot s \cdot n \cdot \Psi \quad (1)$$

where  $D$  = nominal diameter in m,

$s$  = pitch in m,

$n$  = rotational speed in rps

$\Psi$  = filling factor = 0,7 in our case

$$\text{Volumetric Capacity } Q_v = \frac{3600}{4} (\pi(0,05)^2) \cdot 0,02 \cdot \frac{20}{60} \cdot 1 \cdot 0,7$$

$$= 0,033 \text{ m}^3/\text{h}$$

$$\text{Velocity } v = s \cdot n = 0,053 \cdot 0,3 \quad (2)$$

$$= 0,01749 \text{ m/s}$$

$$\text{Capacity } Q = Q_v \cdot \gamma = 0,033 \cdot 2400 \quad (3)$$

$$= 79,17 \text{ kg/h}$$

where  $\gamma$  = density of concrete in  $\text{kg/m}^3 = 2400 \text{ kg/m}^3$  for concrete

$$\text{Power } P = T \cdot \frac{2 \pi \cdot n}{60} \quad (4)$$

$$P = 30 \cdot \frac{2 \pi \cdot 20}{60} = 62,83 \text{ W}$$

$$\text{Axial force } F_a = \frac{Mk}{R_s \cdot \text{tg}(\alpha + \varphi)}, \quad (5)$$

where  $R_s = 0,4D = 0,0212 \text{ m}$

$$\text{tg} \alpha = \frac{s}{2\pi R_s} = \frac{0,053}{2\pi \cdot 0,0212}$$

$$\alpha = 17^\circ 42'$$

$$\varphi = \tan^{-1}(f_m) = \tan^{-1}(0,9)$$

$$\varphi = 41^\circ 59'$$

$$\text{Axial Force } F_a = \frac{30}{0,0212 \cdot \text{tg}(59^\circ 41')}$$

$$F_a = 850,27 \text{ N}$$

## 7. RESULTS AND DISCUSSIONS

The printing with both designs went along and provided some points of concern for the further improvement of these designs. The trial print using these two designs was useful in understanding more about each design, weigh out their pros and cons based on this experimentation. This was necessary because till now all designs and ideas that were generated had purely been based on theoretical knowledge and this testing was giving some practical know-how on some properties of concrete for printing, the importance of consistency and other factors. During the printing, the consistency was vital for the concrete to maintain its shape and ensure good quality extrusion.

### 7.1 INFERENCES FROM TESTING

There were a few inferences regarding the individual designs and below a comparison has been made between the designs, on certain characteristics pertaining to the trials and certain characteristics of the designs. These characteristics listed below are only a reflection of my understanding of the requirements of an ideal printing head.

**Table 1. Comparing the two designs**

| <b>PARAMETER</b>          | <b>DESIGN 1</b> | <b>DESIGN 2</b> |
|---------------------------|-----------------|-----------------|
| <b>Extrudability</b>      | ✓               | ✓               |
| <b>Shaping capability</b> |                 | ✓               |
| <b>Flow maintenance</b>   | ✓               |                 |
| <b>Form/Continuity</b>    |                 | ✓               |
| <b>Extrusion Quality</b>  | ✓               | ✓               |
| <b>Construction</b>       | ✓               |                 |
| <b>Material Loading</b>   | ✓               |                 |
| <b>Design Flexibility</b> |                 | ✓               |
| <b>Material mixing</b>    | ✓               | ✓               |



Even though these tests were not very elaborate, it was decisive from the fact that both the models had good extrusion capabilities. From the comparison of the above characteristics, it can be seen that both these designs have enough reasons to be selected, though with the disadvantages that these two have. So, an idea that I had for the future development of this project was that the two designs could be combined so that these both contribute to eliminating each other's weaknesses and can help greatly improve the working style and efficiency of the design.



**Figure 29. Extrusions of Designs 1 and 2 respectively**

As far as the final extrusion goes, there were some differences in the end shape. There are separate solid chunks in the first picture whereas, in the second, the formation is seen to be smoother and in accordance with the width of the nozzle.

The extrusions shown above might convince us that both these designs may have to be used with their own special mixture of concrete, and this could be true because, in the case of the second design, the mixture while being extruded out was found to be less consistent and watery. This could prove troublesome when it is required to hold its shape after being extruded out. For the first design, it was seen that the mixture was not formed as solid filaments but kept falling out as chunks. Though this was the case, it was seen that the viscosity of the concrete mixture was consistent with the requirement.

Some general points that could prove useful for improving the design:

- Length of bore drill must be as close as possible to the complete length of the pipe, possible guiding the concrete into the nozzle area
- The nozzle area can be as small as possible because some amount of material was always found to be stagnated around this area
- The unpenetrable area of the pipe and nozzle areas must be minimised because this might mean more material would be trapped inside the head
- The diameter of the bore must be as close as possible to the inner diameter of the pipe that is, the fitting must be snug in order to ensure that material does not get stuck in between the two surfaces
- It was sometimes difficult to turn the drill, the torque being a reason; the other reason was due to the weak shaft of the bore
- A better mechanism to turn the shaft and hold it in place was required
- It was difficult to clean the models after the trial because the concrete stuck to the surface and some stagnated in between due to the clearances

## **7.2 SELECTION OF DESIGN**

Deciding between the two alternatives based on these results of the trial would not be very accurate, as the tests were not extensive enough to choose one and eliminate the other. Even if it were true, coming to a conclusion would be exhausting because both of these designs were equally good in their form and function.

From the three design alternatives, and the two feasible alternatives I would prefer choosing the nozzle of the second design because I feel that apart from being a unique design, it has more potential to be developed and customised. The shaping and extrusion capabilities of this design have been commendable, in spite of the boring drill being smaller. But it is also felt that the first design is very efficient, and given the ease of its construction can be regarded as an alternative that would be chosen in a majority of the cases. Nevertheless, some features from this design were impressive and this would convince us of the possibility of using these features together with the final design alternative. When the salient features of both the designs are used together, they would

complement each other and eliminate the weaker points of individual solutions; this would improve the efficiency of the final design.

My recommendation for the final design would be to use a design that is somewhat like an alternative hybrid between the two designs, using the basic design of the first design with the wye pipe and the 3D Printed nozzle, which can be borrowed from the design of the second alternative. Together with the first design alternative, the second alternative can be a very efficient solution, eliminating most of the aforementioned errors. This way the combination works best because the nozzle would be customizable and the overall mechanism would still be very easy to construct.

### **7.3 SCOPE FOR IMPROVEMENT**

Even though the design is complete, there always is some room for improvement. There are some features that can be further improved or added to the design. There is a need for a mechanism that attaches itself to the shaft of the auger and acts as a cap and housing for the motor. The idea of using other modules as attachments to the design is there, and it is something that can be realised in the future with specific modules for drive units, additives, replaceable nozzles etc. The nozzle design can be further improved for applications in printing through further testing and optimisation.

## 8. CONCLUSION

AM and 3DP technologies have refashioned the way we manufacture by opening up boundless new possibilities in manufacturing, doing things that were once considered unachievable with conventional manufacturing processes. AM technologies are thus taking manufacturing towards another revolution are setting the industry up for the leap to Industry 4.0. This work explores the various possibilities and the current state of the technology from the construction perspective.

Coming to the end of the work, it is important to pause and review the goals that had been set for me at the beginning of the work, and how far along the way I had come towards the end. The key objectives of the thesis work were to:

- Study literature sources
- Analyse existing designs
- Come up with solutions for Printing Heads
- Design alternatives
- Prototyping and testing

The goals set during the initial stages have been met, though to an extent dictated by the limits of time and possibilities. 3DP has been vital throughout the project; being the topic that was being studied, it was particularly a largess during the final stages when creating the prototype. I started reading about the topic from the internet and from journals and books. This gave some fundamental knowledge about the subject and helped start out with the design; this was due to the fact that reviewing existing solutions presented many novel ideas, many on how to go about the design and what all errors may be avoided during the design.

After entering the design phase, I started out with a few rough ideas and then proceeded to design the first alternative which was a concept that was too far-fetched and complicated for beginning work on. The idea was focussed in the right direction but it was better, to begin with simpler models when starting something that we had no prior experience with. Thus I proceeded to work on relatively simpler models such as the next two designs which

were relatively straightforward and clean designs. These two remaining alternatives were then discussed and analysed; following this, these two solutions were modelled in 3D CAD software.

Creating a prototype was the next step in the work, considering that these designs have to be tested in order to be validated. The benefits of AM were felt strongly during this phase of creating the prototype because 3DP made it that much easier to create customised models. The prototypes were scaled down to a third of their original size and were printed in the laboratory using an FDM Printer.

After this, a few trials were conducted on the two models with a concrete mix resembling the mixes used in concrete print construction. A kilogramme of concrete material was mixed and used to test the functionality of the two designs, which were made to print a small sample volume. From these tests, it was concluded that a combination of the first and second design alternatives would be the best solution at present, and also for future development. These conclusions are based on my understanding of the problem and priorities of requirements of each feature.

The thesis work has given me an opportunity to work on 3DP, an idea that I was fascinated about for a long time, and helped me gain some in-depth knowledge about the subject and implement a few of my own ideas to the project. I hope I have been able to fulfil all that was expected of me through this work.

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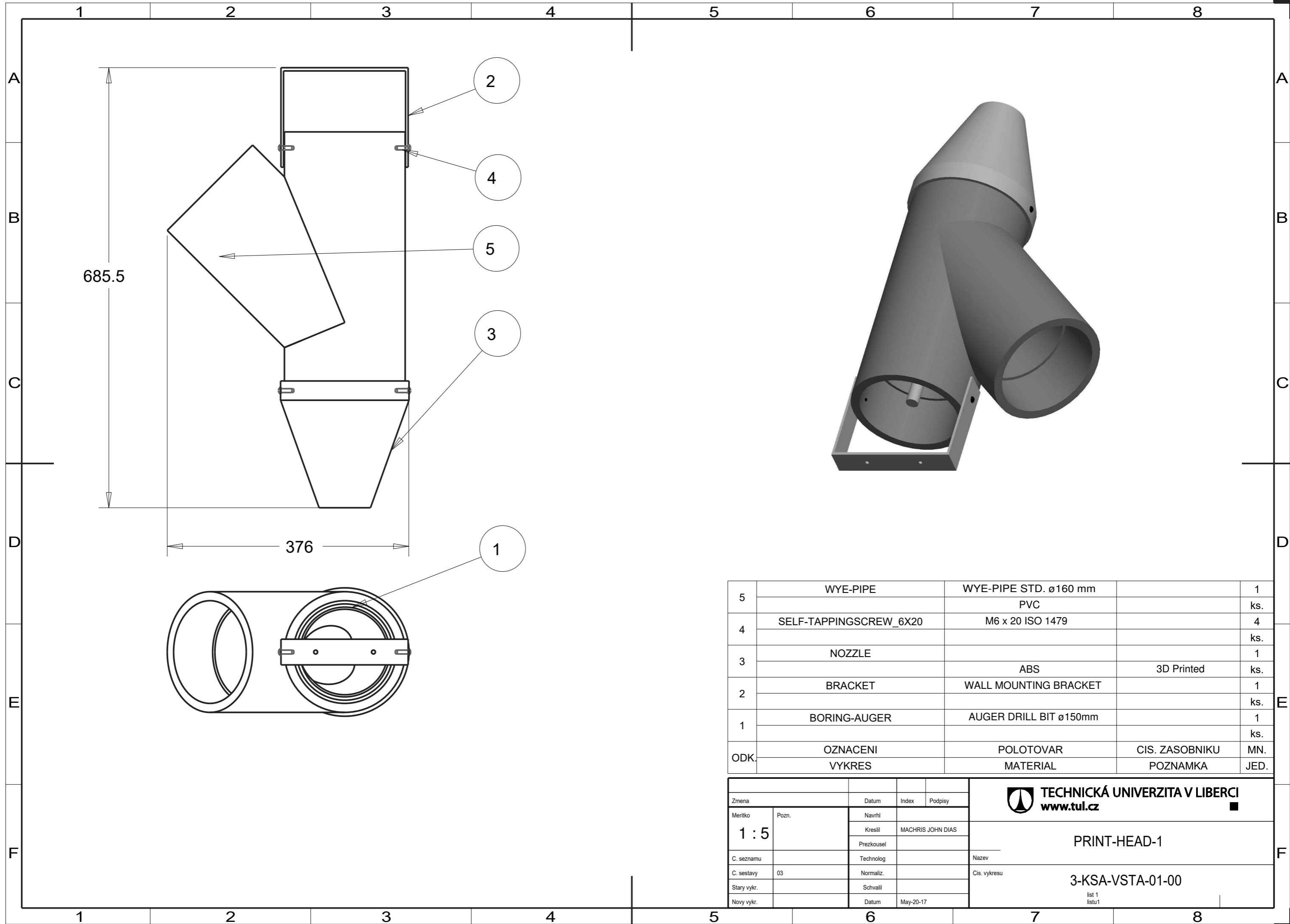
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## LIST OF ATTACHMENTS


1. Compact Disc with Final Thesis report and drawings
2. Technical Drawings
  - i. 3-KSA-VSTA-01-01
  - ii. 4-KSA-VSTA-01-02
  - iii. 3-KSA-VSTA-01-00
  - iv. 4-KSA-VSTA-02-01
  - v. 3-KSA-VSTA-02-00



685.5

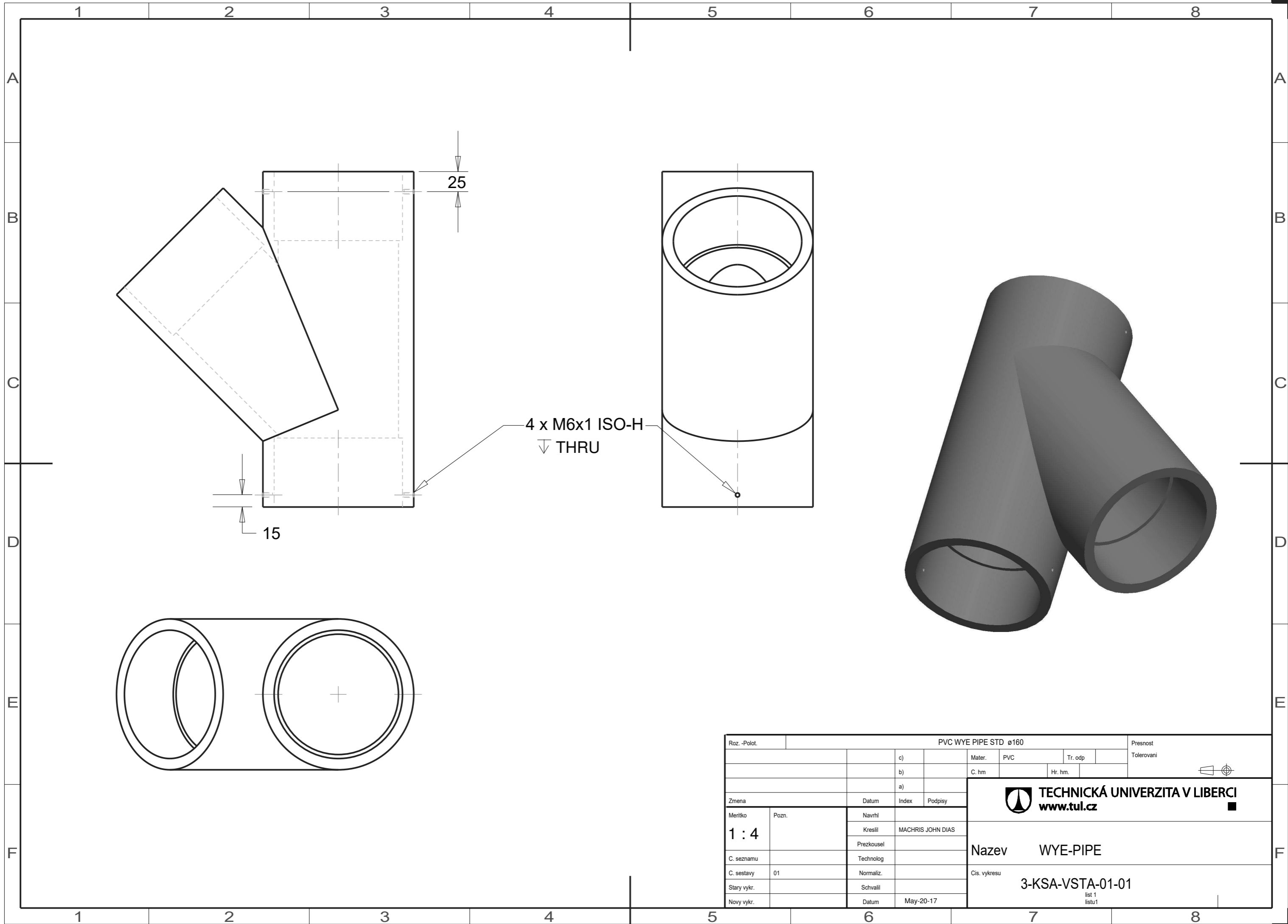
376

|      |                        |                              |                |      |
|------|------------------------|------------------------------|----------------|------|
| 5    | WYE-PIPE               | WYE-PIPE STD. $\phi$ 160 mm  |                | 1    |
|      |                        | PVC                          |                | ks.  |
| 4    | SELF-TAPPINGSCREW_6X20 | M6 x 20 ISO 1479             |                | 4    |
|      |                        |                              |                | ks.  |
| 3    | NOZZLE                 | ABS                          | 3D Printed     | 1    |
|      |                        |                              |                | ks.  |
| 2    | BRACKET                | WALL MOUNTING BRACKET        |                | 1    |
|      |                        |                              |                | ks.  |
| 1    | BORING-AUGER           | AUGER DRILL BIT $\phi$ 150mm |                | 1    |
|      |                        |                              |                | ks.  |
| ODK. | OZNACENI               | POLOTOVAR                    | CIS. ZASOBNIKU | MN.  |
|      | VYKRES                 | MATERIAL                     | POZNAMKA       | JED. |


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|--------------|-------|------------|-------------------|---|
| Zmena        | Datum | Index      | Podpisy           |  <b>TECHNICKÁ UNIVERZITA V LIBERCI</b><br><a href="http://www.tul.cz">www.tul.cz</a> |
| Meritko      | Pozn. | Navrhl     |                   |   |
| <b>1 : 5</b> |       | Kresil     | MACHRIS JOHN DIAS |   |
|              |       | Prezkoušel |                   |   |
| C. seznamu   |       | Technolog  |                   |   |
| C. sestavy   | 03    | Normaliz.  |                   | Cis. vykresu  |
| Stary vykr.  |       | Schválil   |                   | <b>3-KSA-VSTA-01-00</b><br><small>list 1<br/>listu1</small>   |
| Novy vykr.   |       | Datum      | May-20-17         |   |

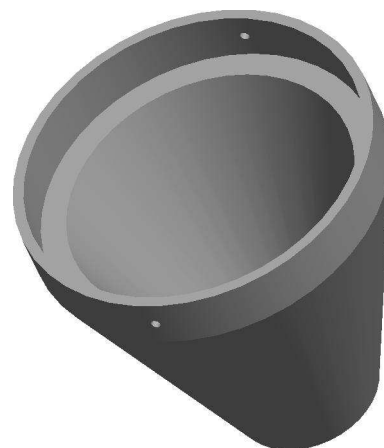
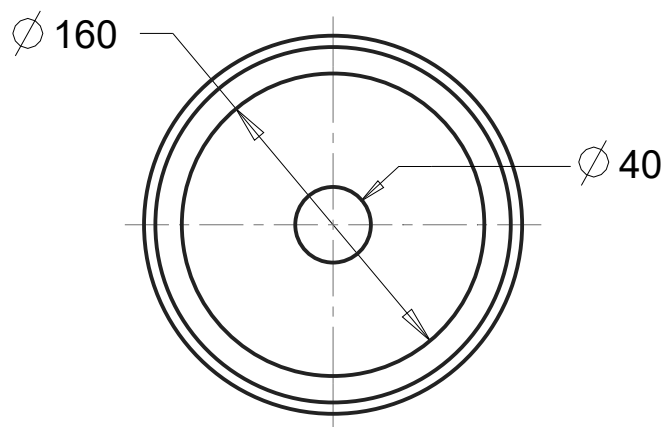
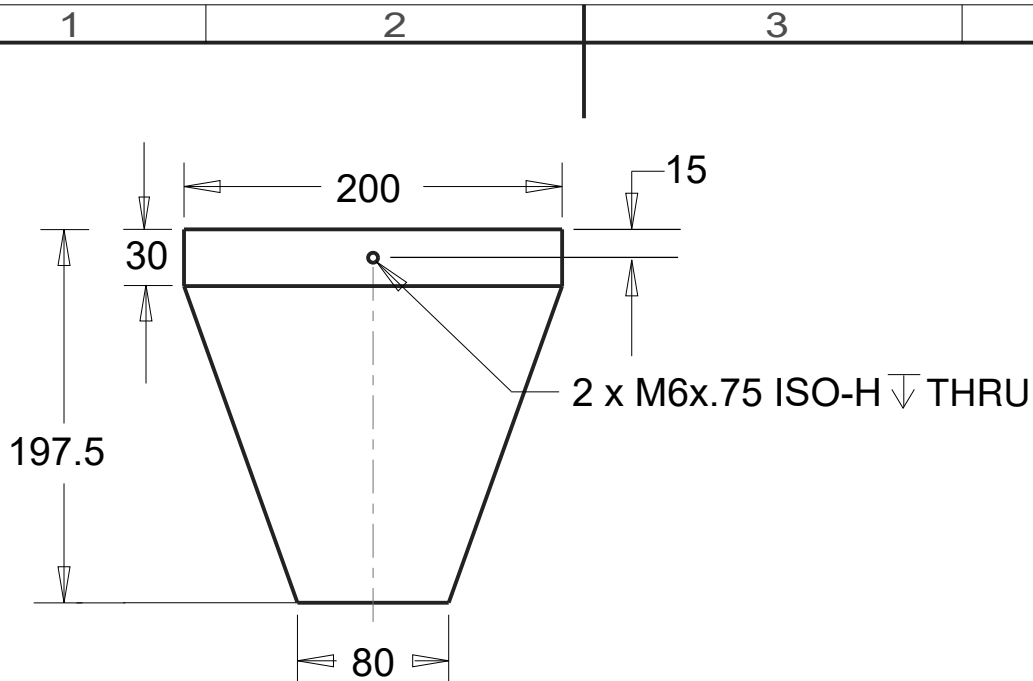
PRINT-HEAD-1

3-KSA-VSTA-01-00



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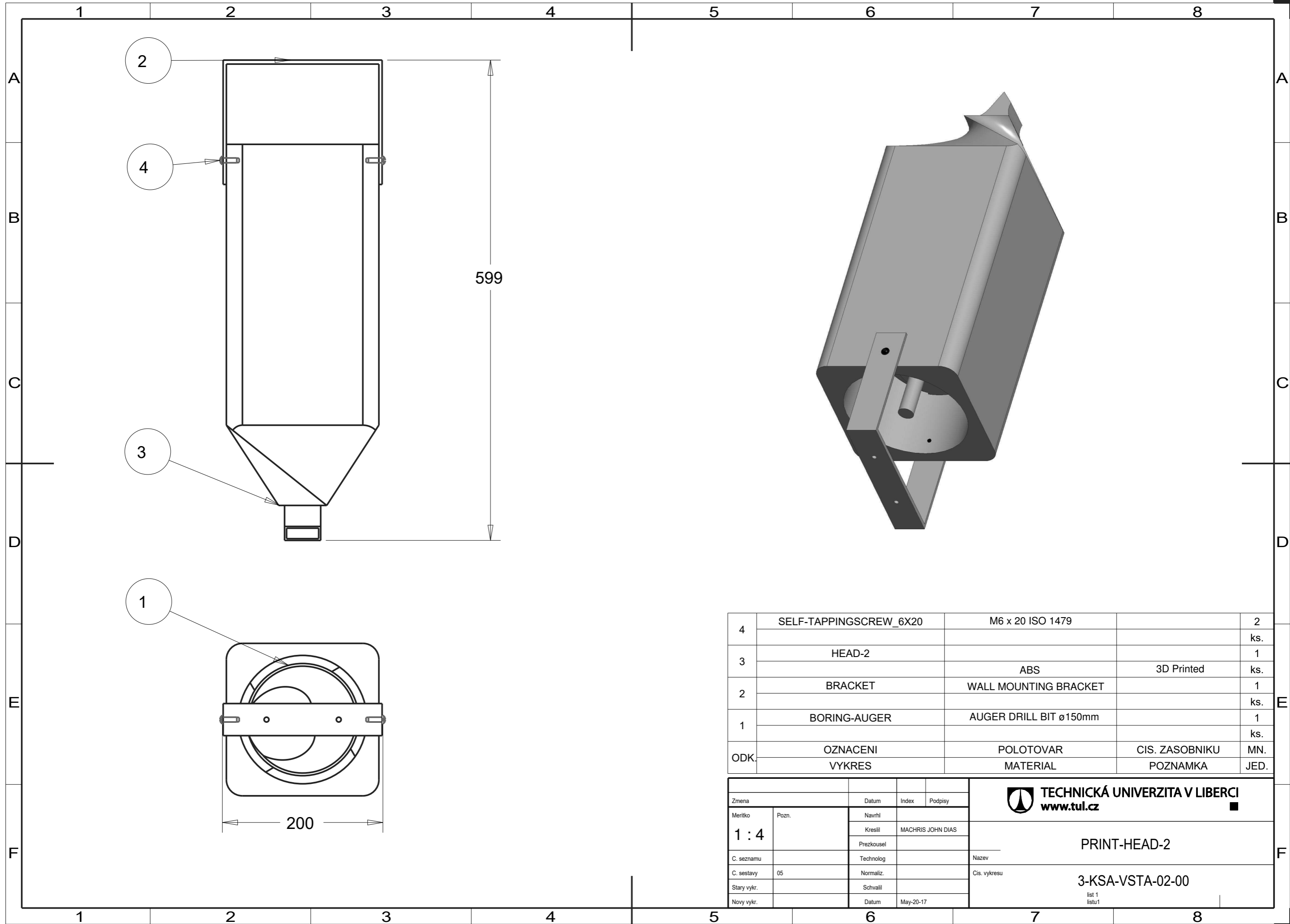
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| Roz. - Polot. |       | PVC WYE PIPE STD ø160   |                   |         |         | Presnost<br>Tolerovani |  |
|               |       | c)  | Mater.            | PVC     | Tr. odp |                        |  |
|               |       | b)  | C. hm             |         | Hr. hm. |                        |  |
|               |       | a)  |                   |         |         |                        |  |
| Zmena         |       | Datum   | Index             | Podpisy |         |                        |  |
| Meritko       | Pozn. | Navrhl  |                   |         |         |                        |  |
| 1 : 4         |       | Kresil  | MACHRIS JOHN DIAS |         |         |                        |  |
| C. seznamu    |       | Prezkousel  |                   |         |         |                        |  |
| C. sestavy    | 01    | Technolog   |                   |         |         |                        |  |
| Stary vykr.   |       | Normaliz.   |                   |         |         |                        |  |
| Novy vykr.    |       | Schvail   |                   |         |         |                        |  |
|               |       | Datum   | May-20-17         |         |         |                        |  |
|               |       |  <b>TECHNICKÁ UNIVERZITA V LIBERCI</b><br><a href="http://www.tul.cz">www.tul.cz</a> |                   |         |         |                        |  |
|               |       | <b>Nazev</b> WYE-PIPE   |                   |         |         |                        |  |
|               |       | Cis. vykresu<br><b>3-KSA-VSTA-01-01</b><br><small>list 1<br/>listu1</small>   |                   |         |         |                        |  |




\*Part 3D Printed - FDM

|               |       |            |                   |   |                  |          |            |
|---------------|-------|------------|-------------------|---|------------------|----------|------------|
| Roz. - Polot. |       |            |                   |   |                  | Přesnost |            |
|               |       | c)         |                   | Mater.  | ABS              | Tr. odp. | Tolerovani |
|               |       | b)         |                   | C. hm   |                  | Hr. hm.  |            |
|               |       | a)         |                   |   |                  |          |            |
| Zmena         |       | Datum      | Index             | <b>TECHNICKÁ UNIVERZITA V LIBERCI</b><br><a href="http://www.tul.cz">www.tul.cz</a> |                  |          |            |
| Meritko       | Pozn. | Navrhl     |                   |   |                  |          |            |
| <b>1 : 4</b>  |       | Kreslil    | MACHRIS JOHN DIAS |   |                  |          |            |
| C. seznamu    |       | Prezkousel |                   |   |                  |          |            |
| C. sestavy    | 02    | Technolog  |                   |   |                  |          |            |
| Stary vykr.   |       | Normaliz.  |                   |   |                  |          |            |
| Novy vykr.    |       | Schválil   |                   |   |                  |          |            |
|               |       | Datum      | May-20-17         |   |                  |          |            |
|               |       |            |                   | Nazev   | NOZZLE           |          |            |
|               |       |            |                   | Cis. vykresu  | 4-KSA-VSTA-01-02 |          |            |
|               |       |            |                   | list 1<br>listu 1   |                  |          |            |





|      |                        |                        |                |      |
|------|------------------------|------------------------|----------------|------|
| 4    | SELF-TAPPINGSCREW_6X20 | M6 x 20 ISO 1479       |                | 2    |
|      |                        |                        |                | ks.  |
| 3    | HEAD-2                 |                        |                | 1    |
|      |                        | ABS                    | 3D Printed     | ks.  |
| 2    | BRACKET                | WALL MOUNTING BRACKET  |                | 1    |
|      |                        |                        |                | ks.  |
| 1    | BORING-AUGER           | AUGER DRILL BIT ø150mm |                | 1    |
|      |                        |                        |                | ks.  |
| ODK. | OZNACENI               | POLOTOVAR              | CIS. ZASOBNIKU | MN.  |
|      | VYKRES                 | MATERIAL               | POZNAMKA       | JED. |

|              |       |            |                   |              |   |
|--------------|-------|------------|-------------------|--------------|---|
| Zmena        |       | Datum      | Index             | Podpisy      |  <b>TECHNICKÁ UNIVERZITA V LIBERCI</b><br><a href="http://www.tul.cz">www.tul.cz</a> |
| Meritko      | Pozn. | Navrhl     |                   |              |   |
| <b>1 : 4</b> |       | Kreslil    | MACHRIS JOHN DIAS |              | <b>PRINT-HEAD-2</b><br><b>3-KSA-VSTA-02-00</b>  |
|              |       | Prezkoušel |                   |              |   |
| C. seznamu   |       | Technolog  |                   | Nazev        | list 1<br>listu1  |
| C. sestavy   | 05    | Normaliz.  |                   | Cis. vykresu |   |
| Stary vykr.  |       | Schválil   |                   |              |   |
| Novy vykr.   |       | Datum      | May-20-17         |              |   |

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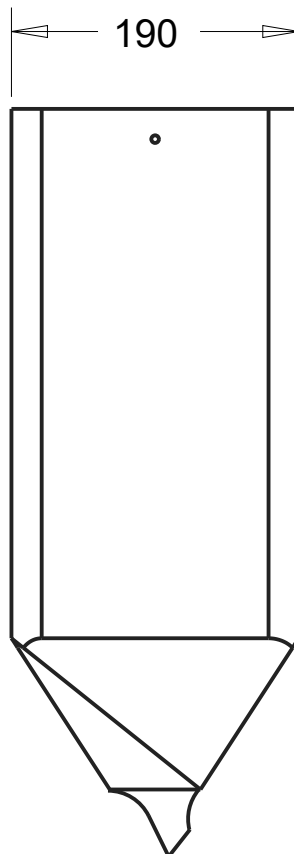
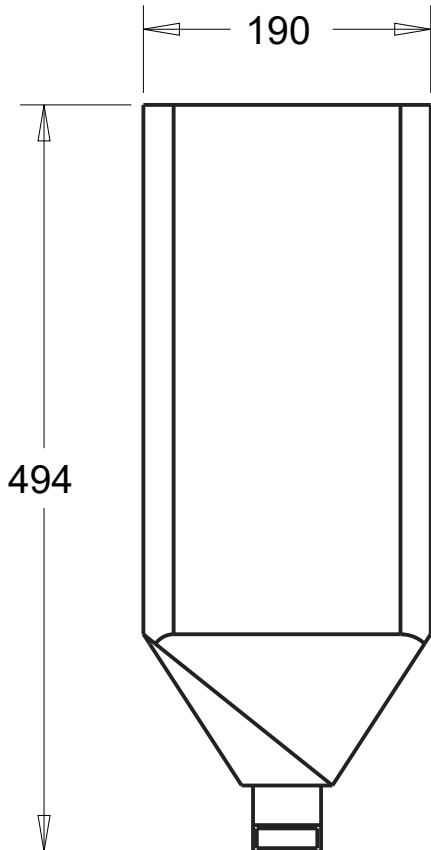
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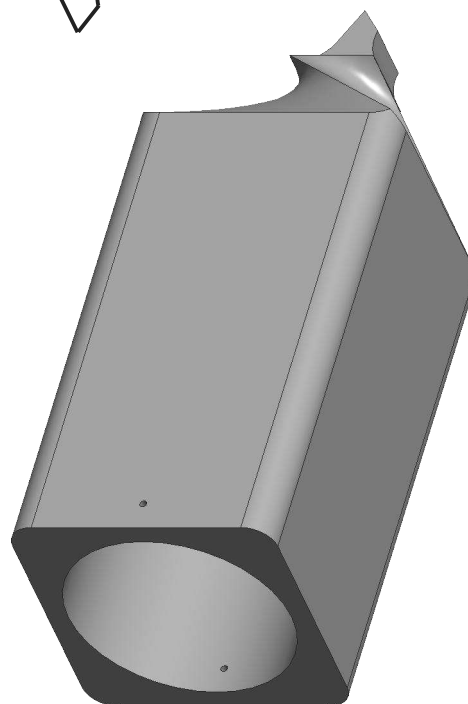
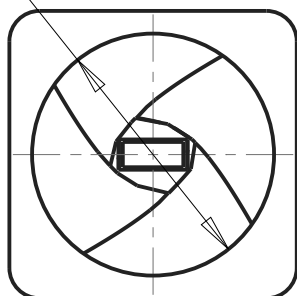
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∅ 160



\*Part 3D Printed - FDM

|               |       |            |                   |   |     |          |            |
|---------------|-------|------------|-------------------|---|-----|----------|------------|
| Roz. - Polot. |       |            |                   |   |     | Presnost |            |
|               |       | c)         |                   | Mater.  | ABS | Tr. odp  | Tolerovani |
|               |       | b)         |                   | C. hm   |     | Hr. hm.  |            |
|               |       | a)         |                   |   |     |          |            |
| Zmena         |       | Datum      | Index             | Podpisy   |     |          |            |
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| <b>1 : 5</b>  |       | Kreslil    | MACHRIS JOHN DIAS |   |     |          |            |
| C. seznamu    |       | Prezkousel |                   |   |     |          |            |
| C. sestavy    | 04    | Technolog  |                   | Nazev   |     |          |            |
| Stary vykr.   |       | Normaliz.  |                   | HEAD-2  |     |          |            |
| Novy vykr.    |       | Schvalil   |                   | Cis. vykresu  |     |          |            |
|               |       | Datum      |                   | 4-KSA-VSTA-02-01  |     |          |            |
|               |       | May-20-17  |                   | list 1<br>listu 1   |     |          |            |

1

2

3

4