3-D Printing as a Veritable Tool for STEM and Non-Technical Education

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Abstract
Rapid Prototyping, which can also be referred to as Solid Freeform Fabrication, Additive Manufacturing, Layered Manufacturing, or 3D Printing is a process of making a three-dimensional solid object of virtually any shape from a digital computer model. This paper reviews the advances in this printing technology with a view to popularizing its use for STEM and non-technical education among other uses. Illustrations were done using models of Mathematical objects including Hypercube and Icosidodecahedron; Engineering Objects including Automatic Transmission Gearing System, Brake Caliper and Suspension Bridge. Some of the other objects shown to have been 3D printed include: Building, Drone, Human Skull, Humanoid Robot, Human Teeth and Archeological Objects. The paper aims to enthuse and attract a large number of academics to embrace this technology that is already redefining a wide variety of systems and processes and also encourage materials scientists and engineers to expand the frontiers on range of feedstock materials that can be explored and used for 3D printing.

Keywords: Rapid Prototyping, Solid Freeform Fabrication, Additive Manufacturing, Layered Manufacturing, 3D Printing, STEM

1. INTRODUCTION

Typical manufacturing techniques are known as 'Subtractive Manufacturing' because the process is one of removing material from a preformed block. Processes such as Milling and Cutting are subtractive manufacturing techniques. This type of process creates a lot of waste since the material that is cut off generally cannot be used for anything else and is simply sent out as scrap.

Rapid Prototyping, also commonly referred to as Additive Manufacturing or 3D printing technology, on the other hand is the process of making a three-dimensional solid object of virtually any shape from a digital computer model. It refers to a process that builds up a component in layers, as opposed to a subtractive operation, which removes matter from a block of material to form a product. The technology is largely capable of manufacturing structures with internal pores and external/internal shapes with high complexities (Jahangir *et al*., 2018) while eliminating waste since the material is placed in the location that it is needed only while the rest is left out as empty space. An increase in customer demand for customizable, quick turnaround, low cost products has opened the door for Rapid Prototyping processes to enter the large scale production market once dominated by subtractive processes. This technology is beginning to show itself as the next technology that will have the most profound effect not only in science and engineering but also in arts, architecture, archeology, defense, medicine, cosmetics, fashion, education and in endless areas of human endeavors. The global consensus of adapting the 3D manufacturing system over traditional techniques is largely attributed to several inherent advantages including fabrication of complex geometry with relatively high precision, maximum material savings, flexibility in design, and personal customization (Ngoa *et al.* 2018; Camacho *et al.* 2018).

Two other terminologies that are also sometimes used to describe this awesome technology are Solid Freeform Fabrication and Layered Manufacturing. 3D printers have been around for about 30 years (Joanna *et al*., 2014) but they have been largely inaccessible due to their huge costs. This accounted for why they were initially available only in big industries. In recent years, prices of 3D printers have fallen more than tenfold, owing to the fact they are used not only in large enterprises but also in all kinds of educational institutions, small businesses or in do-it-yourself men's houses. The main advantage of this technology is that the prototype being created is in one step, and the initial data for it is the geometric model of the part. There is therefore no need for sequencing technological processes requiring special equipment for processing of materials at each stage of manufacturing, transportation from one type of machine to another (Peleshenko *et al.* 2017).

The 3D printing industry started in the late 1980s (with some initial experiments in the 1970s), but these expensive machines limited the use to professionals. The current expansion of new 3D technologies has benefited from the expired 3D printing patents for FDM (Fused Deposition Modeling), where objects are built up layer by layer with extruded melted plastic.

This method which Chen *et al* (2018) also described as fused deposition of ceramics (FDC), is one of the most popular and commonly used 3D printing techniques.

2. TECHNOLOGIES OF RAPID PROTOTYPING

Rapid Prototyping processes are engineered to use material more efficiently, give designs more flexibility and produce objects more precisely. The information needed for fabrication is acquired from the CAD model of the part to be manufactured. The geometry is then converted into a sliced model, which approximates the continuous geometry information as a sequence of cross-sections and equate their thickness to the layer thickness (Hitzler *et al.* 2018). Figure 1 shows comparison between conventional subtractive method of manufacturing and modern additive approach in the production of a sphere.

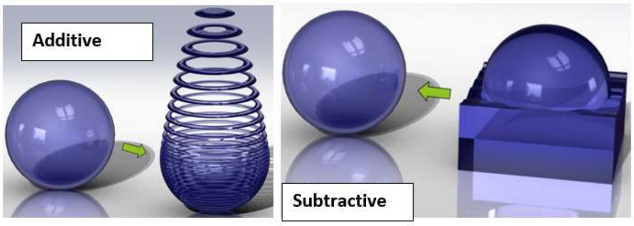

Figure 1: Comparison between Additive and Subtractive Manufacturing

Although several rapid prototyping techniques exist, all employ the same basic five-step process. The steps are:

- Create a CAD model of the design
- Convert the CAD model to STL format
- Slice the STL file into thin cross-sectional layers
- Construct the model one layer atop another
- Clean and finish the model

Each of the Rapid Prototyping systems has its advantages and disadvantages. The main considerations include speed, the cost of the prototype, the initial cost of the rapid prototyping machine, the choice of materials and colour capabilities.

Rapid Prototyping is currently carried out using one of the following six techniques:

1. Stereolithography (SLA): Stereolithography is the most widely used rapid prototyping technology. Each layer is fabricated by scanning a laser beam, guided by a moving mirror, to cure selected parts of a thin film of a liquid photo-sensitive resin as shown in Figure 2.
2. Laminated Object Manufacturing (LOM): In LOM, the prototype or model is built up from layers of paper, polymer or even metal, laminated with a heat sensitive polymer (Figure 3).
3. Selective Laser Sintering (SLS): Thermoplastic powder is spread by a roller over the surface of a build cylinder. A laser beam is then traced over the surface of this tightly compacted powder to selectively melt and bond it to form a layer of the object (Figure 4).
4. Fused Deposition Modelling (FDM): FDM is the second most widely used rapid prototyping technology, after stereolithography. A plastic filament is unwound from a coil and supplies material to an extrusion nozzle. The nozzle is heated to melt the plastic and has a mechanism which allows the flow of the melted plastic to be turned on and off as shown in Figure 5.

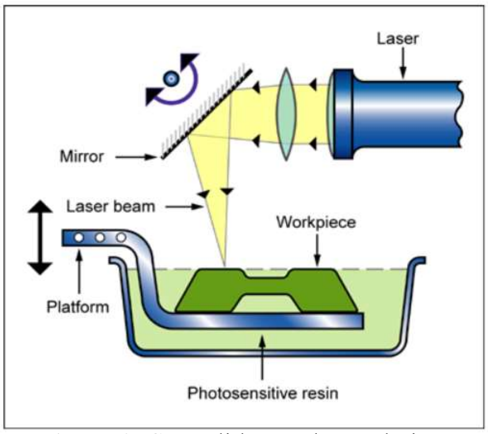

Figure 2: Stereolithography Technique

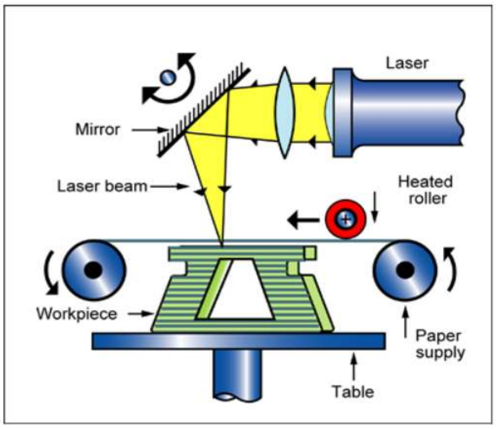

Figure 3: Laminated Object Manufacturing

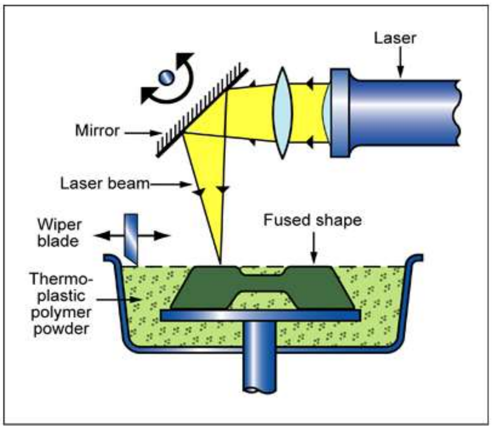

Figure 4: Selective Laser Sintering (SLS)

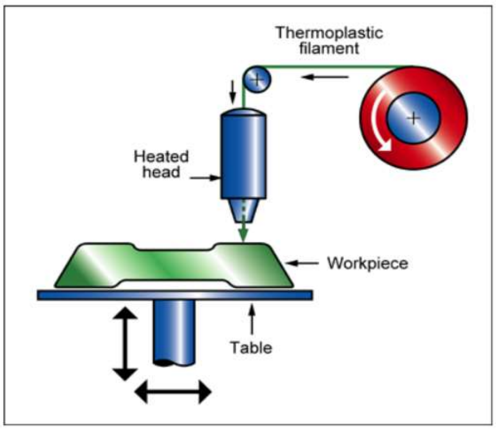

Figure 5: Fused Deposition Modeling (FDM) Technique

5. Solid Ground Curing (SGC): This is somewhat similar to stereolithography (SLA) in that both use ultraviolet light to selectively harden photosensitive polymers. Unlike SLA, SGC cures an entire layer at a time. Figure 6 depicts solid ground curing, which is also known as the solider process.
6. 3D Inkjet Printing: Ink-Jet Printing refers to an entire class of machines that employ ink-jet technology. Instead of ink, the print-head deposits thermoplastic polymer that quickly sets. An ink-jet printing head selectively deposits or "prints" a binder fluid to fuse the powder together in the desired areas as depicted in Figure 7.

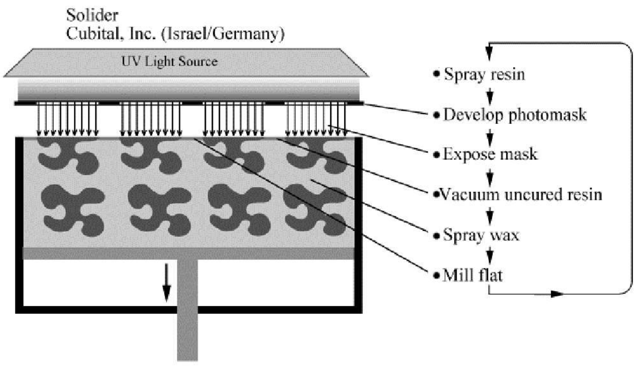

Figure 6: Solid Ground Curing Technique

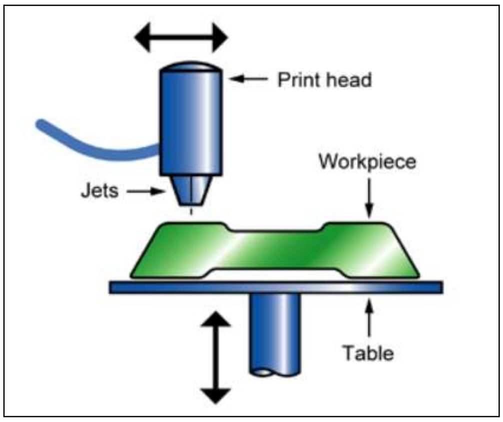

Figure 7: 3-D Ink-Jet Printing

Fused Deposition Modeling (FDM) machines are currently believed to have the largest unit shipments among various types of 3D printers mainly due to their various comparative advantages, such as flexible unit size, simplicity in the building process and more importantly, the low cost of both the machines and the feedstock materials. The market for commercial extrusion based Additive Manufacturing systems is currently dominated by FDM (Turner *et al.,* 2014).

Thermoplastic polymers, such as ABS, PC, PA and PLA, in filament forms are the most common used materials for FDM 3D printing. In a typical FDM process, the material filament is supplied continuously to and heated within a moving nozzle at a temperature just above its melting point in order for it to be easily extruded through the nozzle and form layers. Upon extrusion, the material solidifies almost immediately over the previously printed layer. The platform then lowers to allow the extrusion of the next layer to take place (Chen *et al.* 2018; Uppala *et al.* 2017).

3. STEM EDUCATION USING RAPID PROTOTYPING

Canessa *et al.* (2013) opined that although Rapid Prototyping was still in its infancy, it was rapidly maturing, with seemingly unlimited potential. With its capability to reproduce 3D objects – from archaeological artifacts, complex mathematical surfaces, up to medical prostheses – the technology holds a particularly promising future for science, education and sustainable development. Five years after this assertion (2013 – 2018), the growth and proliferation of this technology has been phenomenal. Some selected objects/designs (both technical and non-technical) have been selected in this paper to demonstrate how Rapid Prototyping or 3D printing can aid better visualization of concepts and impact more knowledge not only in the teaching of science, technology, engineering and mathematics but also in virtually every other human endeavor.

Tack *et al.* (2016) emphasized the need for improved visualization and surgical outcomes while undergoing medical studies which has given rise to 3D-printed anatomical models, patient-specific guides, and 3D-printed prosthetics. Harun *et al.* (2018) together with Perica and Sun (2018) corroborated this point of view by also asserting that implants are currently being preferably fabricated using advanced manufacturing techniques, such as metal additive manufacturing technologies for customized properties and also that 3D printed models are currently being used to understand the complex and largely variable anatomical characteristics of the liver.

Computer Aided Design for 3D Printing

3D printing generally enables the fabrication of 3D objects based upon computer-aided design (CAD) models (Chen *et al.* 2018). All objects and constituent parts, where applicable, created using a 3D printer needs to be designed using a CAD software. The quality of the final product depends largely on the quality of the CAD design and also the precision of the printer. There are many types of CAD software available, some are free while others are paid for or subscribed to. Deciding what type of CAD software is good for use will depend on the requirements of what is being designed. Some of the relevant software for this purpose are: Pro/E, PTC Creo, SolidWorks, CATIA and Autodesk Inventor.

When designing a part to be 3D printed, Domain Group 3D Printing Workshop Notes (2013) listed the following points that need to be kept in mind:

- The part needs to be a solid, that is, not just a surface; it needs to have a real volume.
- Creating very small, or delicate features may not be printed properly, this depends greatly on the type of 3D printer that is going to be used.
- Parts with overhanging features will need supports to be printed properly. This should be taken into account since after the model needs to be cleaned by removing the supports. This may not be an issue unless the part is very delicate, since it might break.
- Be sure to calibrate the 3D printer before using it, it is essential to ensure that the part sticks properly to the build plate. If it does not, at some point the part may come loose and ruin the entire print job.
- Some thought should be given to the orientation of the part, since some printers are more precise on the X and Y axes, then the Z axis.

Selected 3D Printed Educational Objects

3D printing is now being used for production of prototypes and mockups, replacement parts, dental crowns, artificial limbs, and even bridges among others (Chen and Lin, 2016). Yao *et al*. (2016) also highlighted the popularity of 3D printing in the last decade for the production of a variety of medical applications as educational and training tool and for preoperative planning. Some selected areas where 3D printing can serve as teaching aids for better visualization are as outlined.

Rapid Prototyping for Mathematical Visualization

Several Mathematical Objects have been 3D printed for better visualization and understanding. One of such interesting objects is the Hypercube. "Impossible World", an online educational platform, describes a hypercube as an n-dimensional analogue of a square (n = 2) and a cube (n = 3). It is a closed convex figure consisting of groups of opposite parallel line segments aligned in each of the space's dimensions, at right angles to each other. It is also known as tesseract. The tesseract is to the cube as the cube is to the square; or, more formally, the tesseract can be described as a regular convex 4-polytope whose boundary consists of eight cubical cells.

Mathematician and artist Henry Segerman of Oklahoma State University, Stillwater, is one of those that have successfully printed many Mathematical objects including the Hypercube as shown in Figure 8.

Another important Mathematical object that has been 3D printed for better visualization is the icosidodecahedron.

In geometry, an icosidodecahedron is a polyhedron with twenty triangular faces and twelve pentagonal faces. An icosidodecahedron has 30 identical vertices, with two triangles and two pentagons meeting at each, and 60 identical edges, each separating a triangle from a pentagon. This object has been successfully 3D-printed and posted online on 'Thingiverse' as recent as April 10 , 2018. The object is shown in Figure 9

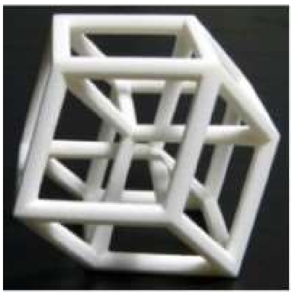

Figure 8: 3D Printed Parallel projection of a Hypercube

Figure 9: Icosidodecahedron (Da Vinci and Pacioli) Published on April 10, 2018
Source: https://www.thingiverse.com/thing:2856169

Rapid Prototyping for Engineering Conceptualization

i. Automatic Transmission Model

Narayana *et al* (2006) described a typical automobile gear box as consisting of a cast iron or an aluminium housing, four shafts, bearings, gears, synchronizing device and a shifting mechanism. Figure 10 depicts the assembly of such a gear box, partially sectioned. The assembly part list is shown in Table 1. This gear box provides four forward speeds of the ratios 4:1, 2.4:1, 1.4:1 and 1:1 and a reverse speed.

While it is expected that an engineering student should be able to understand and analyze such drawings, when a 3D model of such assembly is however available for demonstration, it will make the teaching more impactful. An example of such 3D printed Automatic Transmission Model is as shown in Figure 11. It has six forward speeds and one reverse. Real automatic transmissions have a hydraulic or electrical system that engages different clutches and brakes to shift gears depending on the driving situation. With this model, those simplified brakes and clutches can be controlled by the demonstrator himself. The clutch is actuated by sliding the drive shaft through to different positions (which each has two gear markings), while three separate brakes each also have two gear markings. A gear is selected by engaging the brake and clutch position associated with the desired gear.

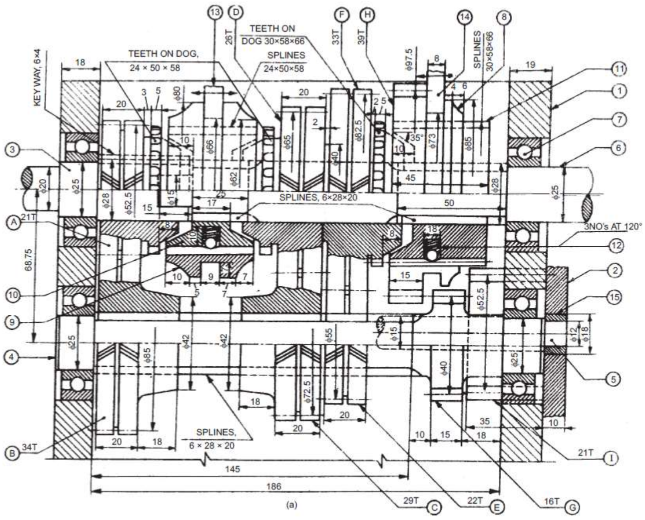

Figure 10: Automobile gear box
Source: Narayana *et al.* (2006)

Table 1: Parts List of the Automobile gear box

Part No.	Name	Matl.	Qty.
1	Housing	Al alloy	1
2	Shaft support	Al alloy	1
3	Input shaft	MCS	1
4	Intermediate shaft	MCS	1
5	Reverse gear shaft	MCS	1
6	Output shaft	MCS	1
7	Ball bearing 6205	—	4
8	Toothed ring	MCS	1
9	Toothed ring	MCS	1
10	Sleeve	MCS	1
11	Sleeve	MCS	1
12	Spring loaded ball	—	6
13	Fork	Forged steel	1
14	Fork	Forged steel	1
15	Bush	Bronze	2
A, B, C, D, E, and F Herring bone gears		Forged steel	
H and I, Spur gears		Forged steel	
G, Spur gear		—	
All gears, module 2.5 mm			

The designer (Emmett 2002) made the gear ratios to be fairly close to what some real cars use, and this is the result, where the input is the crank and the output is the annulus. The gearing and transmission system will undoubtedly be better appreciated and understood using the printed gearing system.

ii. Brake Caliper

In automobiles, brake calipers are some of the most important components that are part of modern disc brake systems. They work together with the brake pads and rotors, along with the rest of the hydraulic system, to slow and stop the vehicle. When the pedal is pressed, brake fluid pressure is pushed through the master cylinder to the caliper, which extends the piston and forces the brake pads against the rotors to slow the vehicle. This important braking system component has been 3D printed for demonstration and educational purpose as shown in Figure 12 using plastic. The caliper can be pulled apart and re-assembled, thereby making it possible for students to have a hands-on and visual understanding of the caliper and how each component functions. This has now metamorphosed into the 3D printing of a functional and highly efficient brake caliper by Bugatti, one of the fastest and most expensive vehicles in the world, as shown in Figure 13.

Figure 11: 3D printed Automatic Transmission Model

Figure 12: 3D Printed Plastic Brake Caliper

Figure 13: 3D Printed Bugatti 8-piston functional monobloc brake caliper produced with titanium

iii. Suspension Bridge

This is a type of bridge which has cables between towers, also referred to as "suspension cables" and from them vertical "suspender cables" (or hangers") that hold the deck. Suspension cables are normally anchored at each end of the bridge and they carry the majority of the load. Figure 14 shows the drawing of a typical Suspension Bridge while Figure 15 shows the 3D print of a rough approximation of the suspension bridge between Covington, Kentucky and Cincinnati, Ohio opened to traffic on January 1, 1867. The printed bridge will definitely be a good teaching aid in explaining the underlining design principles.

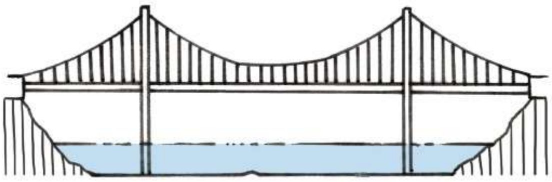

Figure 14: Drawing of a Suspension Bridge

Source: http://www.mstworkbooks.co.za/tech-nology/gr9/gr9-technology-04.html

Figure 15: 3D Print of a Suspended Bridge

Other Notable 3D Printed Objects for Educational Purpose

There are several other objects that have been 3D printed which are very useful for educational and demonstration purposes.

Some of such objects, which have earlier been compiled by Oyelami and Olusunle (2005), are as shown in Figures 16 to 20 while Figures 21 to 23 were previously compiled by Canessa et al (2003) and they have all been produced using Rapid Prototyping/3D Printing technology.

4. Current Status of 3D Printing in Nigeria

Oluwole (2017) identified Medical and Biomedical Engineering Field as well as Logistics and Supply Chain as some of the areas to exploit 3D printing in Nigeria. He is of the view that the technology can be used to create 3D-printed prosthetic limbs to address the health issue relating to amputation as a result of high

Figure 16: 3D Printed Humanoid Robot

Figure 17: 3D Printed Drone

Figure 18: 3D Printed Automotive Alternator

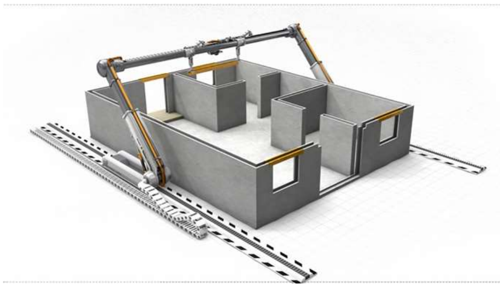

Figure 19: 3D Printed Building

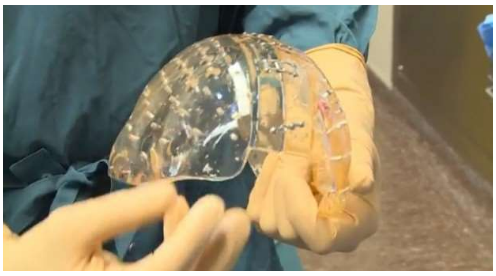

Figure 20: First 3D Printed Skull

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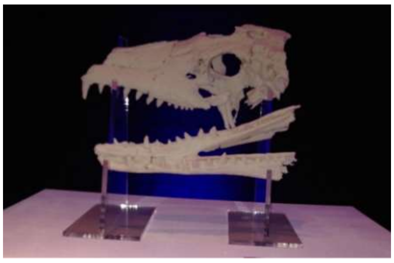

Figure 21: 3D printed replica of a fossil skull
Source: Canessa *et al* (Ref)(2013)

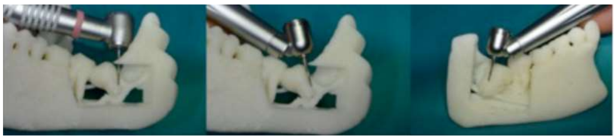

Figure 22: Teaching Plan of Eights Teeth Extraction
Source: Canessa et al (2013)

(a) **(b)**
Figure 23: EMDI, Akure 3D Printer

rate of motor accidents. He also opined that the technology will result to mass customization which will reduce inventory levels since goods can be made to order. The current level of awareness/usage of this technology is however low. Only few Universities and Institutes in Nigeria are currently making use of the technology. Some of the identified institutions using 3D printer for teaching and demonstration purposes in Nigeria include Federal University of Agriculture, Abeokuta; University of Ibadan; National Agency for Science and Engineering Infrastructure (NASENI), Abuja; Engineering Materials Development Institute, (EMDI), Akure; Prototype Engineering Development Ilesa (PEDI). Others identified by Balogun *et al.* (2018) include Edo University Iyamho (EUI) in collaboration with Federal University of Petroleum Resources, Effurun (FUPRE), Ahmadu Bello University Zaria, Federal University Oye Ekiti, Afe Babalola University Ado Ekiti (ABUAD) and ELIZADE University Ilara Mokin. One of such 3D printers belonging to EMDI Akure is as shown in Figure 23a while Figure 23b shows the printer in operation.

5. CONCLUSION

The role and relevance of rapid prototyping/3D printing to aid teaching and concept demonstration most especially for STEM and non-technical education at this age cannot be over-emphasized. If Bugatti, a very popular and highly sought-after automobile brand that combines an artistic approach with superior technical innovations in the world of sport can opt for rapid prototyping technique to produce a functional and efficient brake caliper among other items, it goes a long way to reaffirm the importance of this technology at this age. Engineering, as well as science and other non-technical education will become more interesting and demystified if 3D printing can be adopted as a major teaching aid to have higher impact and assimilation. It is highly recommended that the Nigerian Universities and Educational Sector in general should join this bandwagon now and utilize the benefits the technology has to offer. Rapid Prototyping is definitely one of the leading technologies that is currently reshaping how things are done globally.

The technology also provides a great opportunity for the materials scientists and engineers to work on more diverse ways of recycling waste materials and synthesizing new ones that can be used to expand the range of possible feedstock materials for this awesome technology.

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