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# Industrial Digitalization with Four Dimensional (4D) Printing - Novel Technology: Brief Review on Developments, Challenges and Applications

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**Highlights**

- Described about basic differences between 3D & 4D printing technologies
- Illustrated different smart self healing material & Technologies.
- Listed various potential applications in the emerging areas of engineering.
- Described the procedure for selection of suitable material for 4D printing.
- Includes data on recent developments, challenges in 4D printing technologies.

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**Abstract**

The latest advances in additive manufacturing methods (AMM) generally called as three-dimensional (3D) printing permitted to design and generate complicated profiles which are not possible with regular fabrication methods. A branch of new fabrication technique initiated from three dimensional (3D) printing further it is called as four dimensional (4D) printing with self healing materials that can react to outer stimuli by subjecting external pressure on it. Also, day to day advancements in fashion in the lifestyle of public, industries are not capable to satisfy their requirements with conventional manufacturing techniques with conventional materials because of increased cost to alter the design, manufacture and process layout for each fashion style. It is impossible to satisfy with conventional materials as well as processing methods, so more competition existed in the present industrial sectors according to market demands as per customer requirements. Advancements in additive manufacturing techniques covered this gap by day-to-day developments in materials and their methods, provide a variety of designs and fabricate them with a short time by sustaining less investment. In this article, recent developments of smart materials discussed and innovations in 4D printing and challenges which are faced in the research and development divisions also described about a variety of application areas almost in all fields. This paper provides basic information data to the young researchers who are interested to do their work in this area and also discussed with the latest available data pertaining to 4D printing globally.

## 1. INTRODUCTION

At present modern production system is a complicated action taken by utilizing raw materials or in process components as input along with human power or by automation to convert them into acceptable form to the customers. Now a day's entrepreneurs or an industrialist (generally called as capitalists) wants to be more profits with less investment, this is possible only with advanced techniques available in the market. Digital manufacturing is one of the segments under Industry 4.0 in which products can be produced as per taste of the customers with multiple varieties by less utilization of human power by adopting advanced processing methods. Additive manufacturing is also a new technique to create complex parts by adding the raw material layer by layer and form a component using a designed tool like computer aided design and drafting (CADD) such a process called as printing. Further it is found that lot of advancements in the printing processes in the market such as 2D printing, 3D printing and so on. In this context reviewed briefly on further developments in the field of 3D printing technologies and found latest advancements in the material to be used in the case of 2D and 3D printing. Plastic deformation is a vital role in the printing, it is a material property exposed to heat and cannot retain its original shape after forming a solid structure. Some materials

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found from the literature having special properties such that when such material exposed to heat, light, moisture and water they change its structure and also modify the shapes [1,2]. The market experts say that production industry will change its methods of making parts in the next 10 years as follows new practices that are abandoned towards sustainable to eco-friendly environment, flexibility in the design and efficient technique to machine the parts. Now-a-days due to increase of technological innovations in the computer field, then mechanical engineers also utilize those soft technologies in the design and fabrication of components [3]. To substitute this only one way is to adopt 5G technologies to promote greater flexibility in the design of components, visibility in the future, versatility in alter the products, usability in multilevel and increase the efficacy of goods to sale in the global market by connecting internet of things or by cloud computing helps to promote and sharing the latest things in the commercial market especially manufacturing world to enhance the knowledge of engineers and technocrats. Recognizing the importance of manufacturing of goods to their industrial future, various countries have started its inaugural programs to create new startup companies by young minds supporting the deployment of these technologies to their domestic manufacturers. Recently, four dimensional of 3D printing technology under the revolution of rapid prototyping (RP) technology is introduced, and it is named by 4D printing [4]. One of the major classification of rapid prototyping under additive manufacturing method is four dimensional printing technique with modified printing mechanisms; liquid solidification, powder solidification, and direct material extrusion [5]. This printing methodology engages the self – remedial photo polymer, melt-material extrusion, and direct-ink printing [6]. The selection of type of printing process depends on both the smart materials, desired properties of the final shape and factors to influence on quality of the part to be print. In the previous literature numerous authors chosen printing speed, laser frequency and nozzle temperature are the most influential factors identified.

This process also used the same printers ,which are used in 3D printing technology and instead of polymers it needs shape mwmory polymers having special properties/features. The components prepared by 3D printing are going to keep their solid shape once printing is over, but the parts fabricated by 4D printing technology can alter their shapes once they subjected to variations occures in the moisture content surrounding it. Due to this special features, 4D printed objects can shrink and unfold or to fit into the available volumetric space or in some cases it can accommodate in two dimensions plane surfaces [7]. 4D printing is the system where three dimensional printed object changes itself into a different structure as the result of the impact of environmental stimuli such as moisture, temperature, light, or other factors [8]. 4D printing is a near future technology with a massive capability to build complex, stimuli-responsive structures. Some of the applications of 4D printing found from the literature, especially in the areas of bio medical technology, aerospace, consumer products and limb transplanting engineering [9]. At present, data science (DS) is the burning title in all fields with an aid of artificial intelligence (AI) and internet of things (IoT). These technologies support indirectly to share the design of parts in online mode without establish their own research and development department (R&D) ,causes reduction in initial investment further reduces the cost and lead time to the customers. Apart from this customers also feel happy with the components made by 4D printing are maintenance free because they are self healing property(self repair) once they undergoes any damage while functioning [10]. The modern manufacturers found the importance of 4D printing and also search for requirements needed to establish that new technology and look at to adapt the customers towards their products because of quality and variety obtain from this new technique by obsolesce of old technologies. [11-13].

## 2. DEVOLOPMENTS IN RP TECHNOLOGY-BEGINNING TO 4D PRINTING

Rapid development in the additive manufacturing methods in the area of RP technology from 2D to 3D printing, which is one of the methods to make a three-dimensional component just like an operation of xerox machine to produce a number of copies of similar shape what is on the manuscript on 2D paper. The introduction of the third dimension thickness added to 2D called as 3D by filling a material in the above mentioned direction. The materials used for this type has been able to possess the property like self changing with respect to environmental conditions like temperature effects, light effects, electromagnetic effects etc. This kind of experience in the three-dimensional printing of objects depends on the capacity of materials to convert with relevant time in response to external stimuli without interaction of human operators. So, 3D printing is one of the latest method to make a component in the short time in the field of contemporary

technologies, especially to implement in MSME to promote make in the digital India slogan. Three-dimensional printing is one of the new technologies found in the fabrication and innovation of shape memory alloys provide a path for utilization of the four dimensional in the printing technology, which may be replaced by 3D technology in near the future (described in the Table 1). The ability of a material to make a component or parts to rebuild their shape automatically with respect time is called as four dimensional printing [14]. The major comparison between 3D printing and 4D printing methods found from the previous literature is the usage of smart material and printing mechanism. The main differences identified from various authors mentioned in their articles are summarized and tabulated with brief illustration shown in Figure 1. 4D printing, a new era of rapid prototyping technology (RP) which was firstly identified by Skylar Tibbits, American research scientist in his self assembly lab, located at Massachusetts institute of Technology (MIT) and now it is further explored to another areas of engineering to construct complex structures [15].

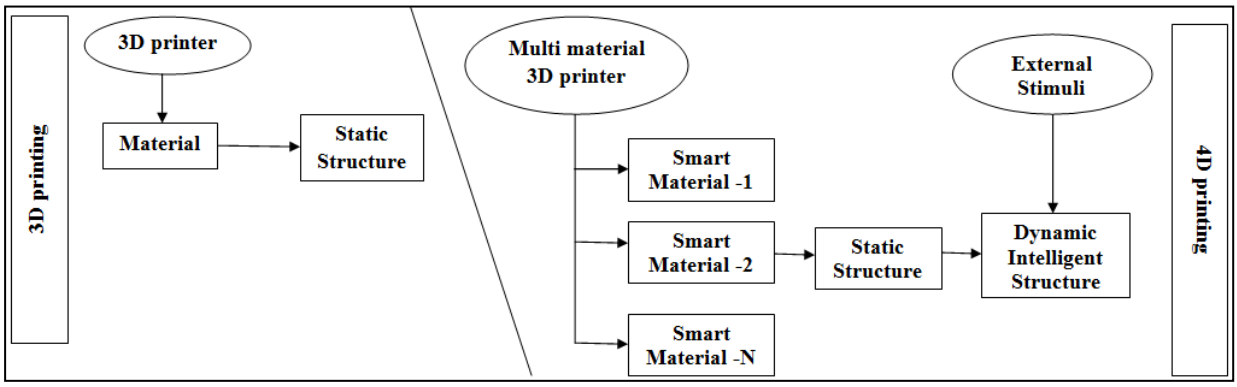


***Figure 1.*** *Contrast between three dimensional Vs Four dimensional printing technologies*

***Table 1.*** *Major differences between three dimensional Vs Four dimensional printing technologies*

| Description | Three dimensional printing | Four dimensional printing |
|---|---|---|
| Rapid change in the shape | No | Alter in color, shape, function etc. |
| Available materials | Thermo plastics | Self changing materials like shape memory alloy and polymers |
| | Metals & Alloys | |
| | Bio materials & gels | |
| | Nano materials | |
| Printing Facility | 3D Printer- Stereo lithography | 3D printer - Stereo lithography |
| | Fused Deposition Modeling | Multi Material 3D printers |
| | Selective Laser Sintering | |

## 2.1. Materials and Technologies

Four dimensional printing technology still under development phase, therefore few such materials said in the above Table 1 is used for making objects. On the other hand, it needs lots of research required in three-dimensional printing to communicate complete opportunity for four dimensional printing. The elementary investigation in this field of work is in the center of attention at present in the area of Four dimensional printing is illustrated in schematic format in the Figure 2.

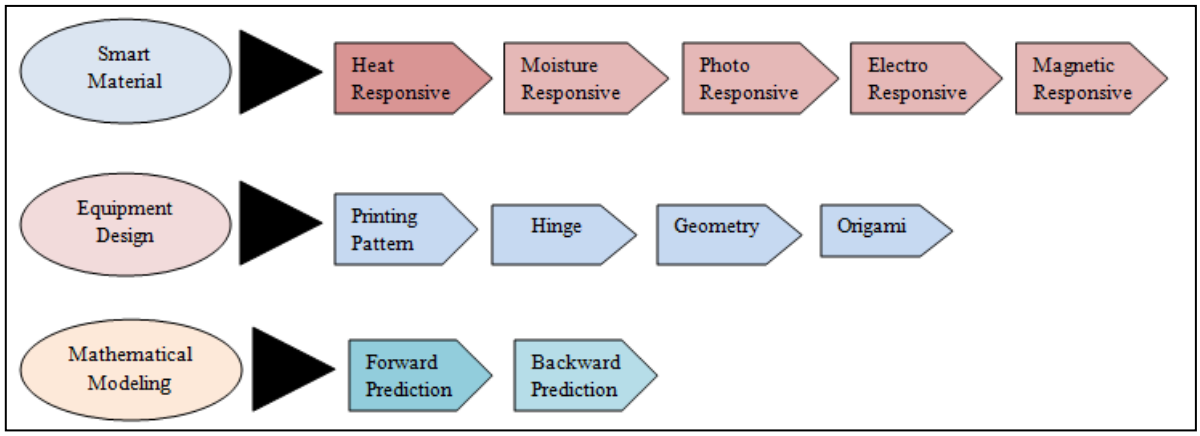


***Figure 2.*** *Major Research areas in four dimensional Printing*

The material which is used in 4 D printing is an important in the primary level of investigations in this field. In the nature some materials available to exhibits self alteration of shape when they undergo external stimuli such as mechanical or thermal effect. Once scientists are designing certain devices and fabricate to produce such material artificially then it is simple to adopt the 4D equipment designs. At present direct ink jet cure, fused deposition modeling, stereo lithography laser assisted bio printing and selective laser melting techniques are available in the commercial market for three-dimensional printing. These methods are not sufficient unless self healing materials applied as a raw material in the case of 4D the printing.

### 2.2. Materials with Self Changing Dimension W.R.T Time for 4D Printing

Materials which undergo deformation subjected to heat, moisture, electric/magnetic fields and pH from time to time are primarily called self healing smart materials, focused main role in 4D printing (the Four dimensional is time). From the previous literature given to 4D printing area found that it is burning topic in the manufacturing sector, especially biomedical applications [16–20]. In this section demonstrated some important feasible details in response of self healing materials (shown in Figures 3 and 4) that are widely useful for four dimensional printing technologies.

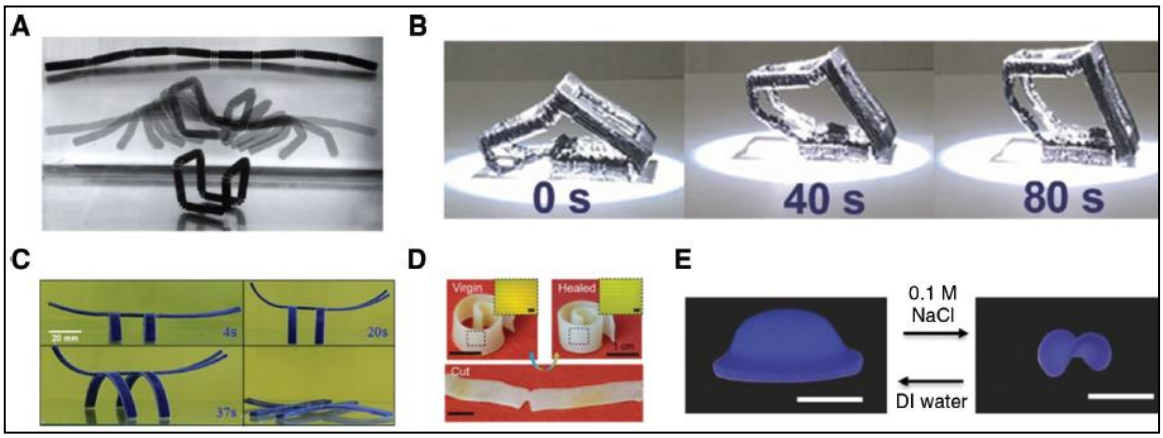


***Figure 3.*** *Four dimensional printing with smart materials*

(A) Four dimensional featured part that convert its shape from single dimension to multi- dimension as a cube [16] (B) The shape memory alloy from one form to another form of the cubic frame obtained under the influence of ultraviolet rays and doped by polyurethane [17] (C) Three dimensional printed objects imitate like an insect [18] (D) The images of the effect of self-healing materials on different objects [19]. (E) Four dimensional printed object with hydrogel technique [20].

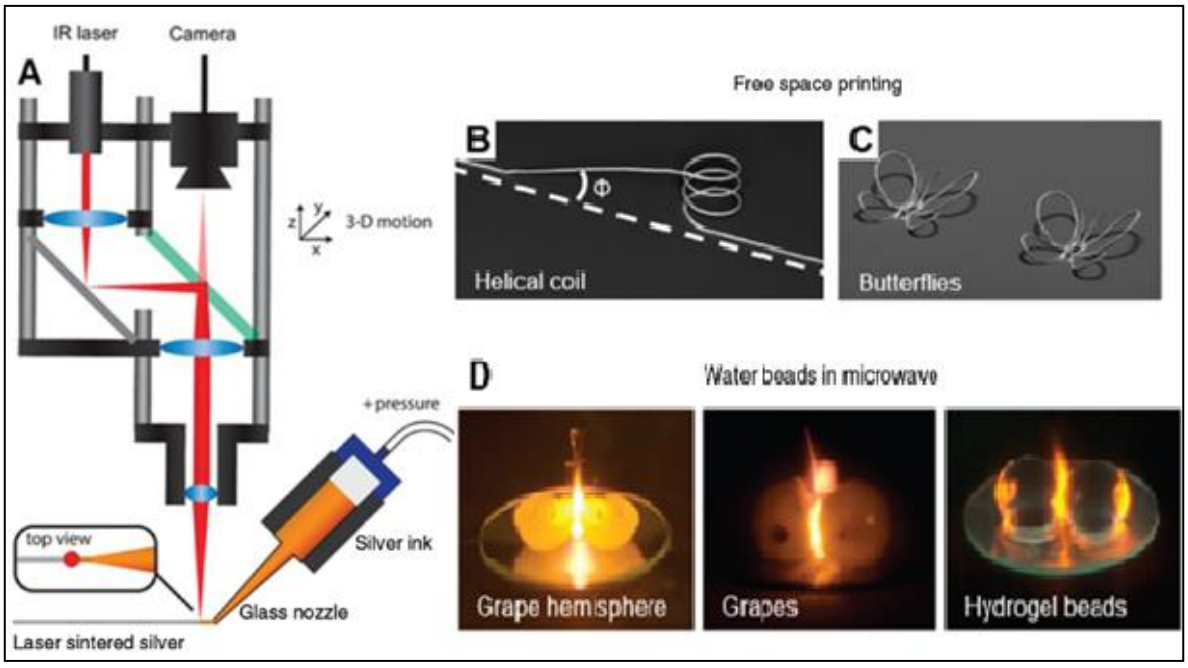


***Figure 4.*** *Eventuals of self healing materials*

(A) Block diagram of infrared laser sintering technology (B) self-supporting helical coils made in nano size (C) Self supporting printed wings of butterflies [21]. (D) Forming a hydrogel from grapes [22].

## 3. PROBABLE POTENTIAL APPLICATIONS

### (a) Self – repair system

If a piping system is designed and fabricated by self healing smart materials, then such pipes are used in household plumbing purposes, the pipe diameter can alter according to volumetric fluctuations in the demand and supply and also if there are any breakages occurred, then these materials can rectify such damages automatically by their self healing character.

### (b) Self – assembly furniture

In the nature some materials show different performance when subjected to $H_2O$ or exposed to light, with such a material household furniture was made then some water will pour on that it becomes flat so that volumetric space becomes saved and easy to handle. Other applications also found in the structural assemblies of aircraft maintenance to reduce the cost, in health care systems to replace with stents artificially with self healing material and fabricated with 4D printing technology because stent is a nano size material.

### (c) Foot wear and textile technology

Now a day's weather conditions are changed drastically from one place to another due to climatic change occurs by public habits. In this situation people want to wear the clothes which exist in all environmental conditions and satisfy, it is possible only with self healing smart materials utilized to fabric material. These are also used in the production of footwear for human beings, especially in sports personnel to get satisfying results to withstand in all types of weather conditions and prepared by a novel four dimensional printing technology.

**(d) Bio-medical technology**

It may, possible in the near future to develop a 5D (five dimensional) printing method to replace or substitute in the place of additive manufacturing process. In this method, the printer head & the printable component consists of five degrees of freedom produces curved layers. So the advantage of five dimensional (5D) printing is to manufacture a miniature components or human bone replacements by fabricating the human bone especially in the case of implant surgery, there the requirement by the doctors is to design and fabricate the implant according to x-ray image. So, it is possible only with a self healing smart material made by curved layer (because human bones are not flat) and improved strength so that it can self cure when any injury taken place while accidents [23].

## 4. SELECTION OF MATERIAL FOR 4D PRINTING

The basis of classification of materials used in four dimensional printing is categorized by the response of reaction with thermal, electrical, light and magnetic field effects [24] and shown diagrammatically in Figure 5:

**(i) Based on response taken from thermal effects**

These are classified again into the process on which they depend are shape memory alloys, shape memory polymers, shape memory hybrids, shape memory ceramics and shape memory gels. Numerous authors insisted the usage of shape memory alloys prefer in rapid prototyping 3D technology. These are formed by chemical processing in particular shape and formed into a new shape when heat or thermal energy is applied externally. Materials that react chemically by adding water or moisture content in the environment are under this category.

**(ii) Based on response taken from light/electric current/magnetic effects**

The substance which react some extent by focusing on electric circuits, optical systems and magneto effect field, then alters their shape from one form to another form, i.e. to say indirectly from 1D to 2D or 3D formations with respect to time. Chromophores are one example under this category infused with polymer gels at specific localized places when they are subjected to photo synthesis effect reacted with sun rays and catch swelling by absorbing sun rays. In the same fashion, when an electron flow passes through the same objects consists of ethanol composition, then ethanol is disappearing from that object and hence its size will be increased at a volumetric rate with respect to percentage of ethanol compound in that object contains. Some nanoparticles are bearing with magneto rheological properties, then such particles are to be mixed with the polymer used for printing of an object, then that is deformed certain extent when it works in the region of magnetic field. In the view of above material classification, the science and engineering people do more works to develop such a new material to enhance self healing capabilities from time to time [25].

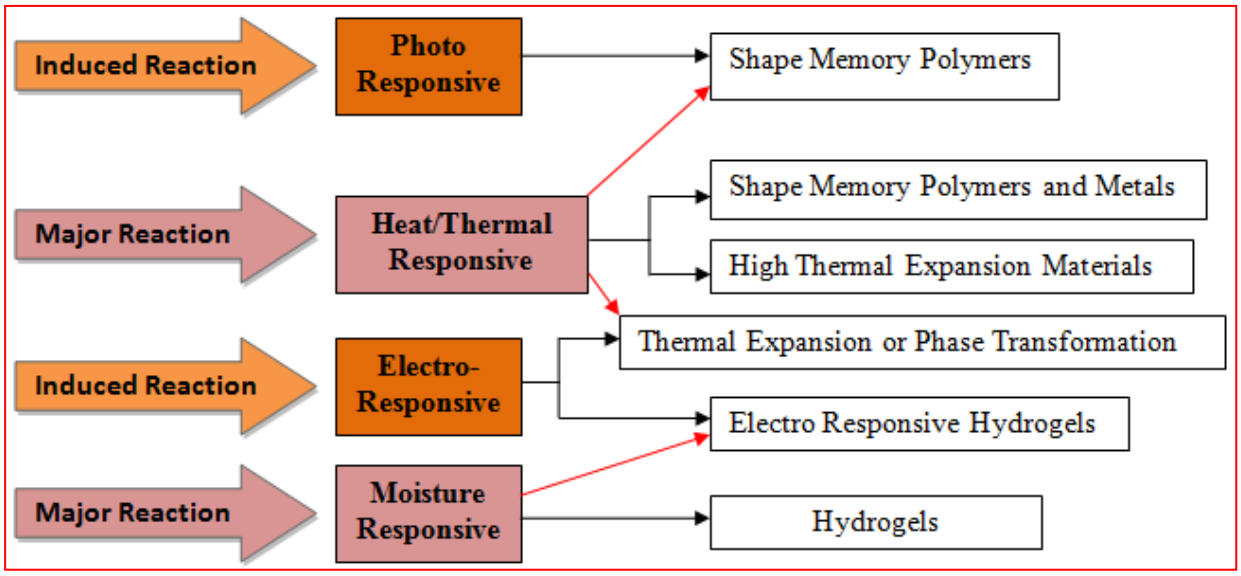


***Figure 5.*** *Smart materials and their responsive stimulus*

## 5. POTENTIAL PRODUCT DEVELOPMENTS IN THE FIELD OF 4D PRINTING

When air is contacted externally with an object prepared by adding silicon, it is observed that expansion like a balloon. So, silicon based materials exhibit a smart material property when exposed to air pulses can be utilized in four dimensional printing technology. Numerous applications of 4D printing technology found in healthcare organizations, market of that found in the future is billions of dollars in the field of targeted drug delivery, fabrication of nano size stunts and splints e.t.c [26] are illustrated in lucid manner in Table 2. Also, a lot of innovations in the field of soft robotics with self healing actuators operated by magnetorheological (MR) fluids are required for the modern engineering sector to prepare or fabricate advanced level of components suitable for precision applications [27]. In people work in the department of roads and buildings in Australia already utilized this technology (4D printing) to construct roads with materials which exhibits the self healing capability artificially and found lower maintenance cost and also observed time taken to formation of such roads are very less compared to conventional methods of construction.

***Table 2.*** *Probable future developments of 4D printing- as per product varieties*

| S. No. | Industry | Potential – new Product Technologies | Mid- term Eventual Product Technologies | Long-term probable Product Technologies |
|---|---|---|---|---|
| 1 | Electrical and electronics | Intelligent sensor technology | Arduino | Nanotechnology |
| 2 | Hospital management | Bio- artificial organ manufacturing techniques | Build with bio-inks | Prosthesis |
| 3 | Heavy equipment machinery | Revit structure software technology | Reverse Engineering by Apriorit researchers | -------- |
| 4 | Automobile and their assembly fittings | 3D modeling software | Computational fluid dynamics software (CFD) | CATIA, ANSYS and AutoCAD |
| 5 | Consummable products | Lifestyle | Household articles – Spinning technology | -------- |

## 6. TECHNOLOGY PUBLICITY CYCLE OF 3D PRINTING VERSES 4D PRINTING

Figures 6 and 7 shows the quantitative analysis of research articles published related to 3D and 4D printing including review articles since in the year 2010 to 2019. From this data, it is understood that these modern advanced RP technologies are on the verge of blooming and may more new achievements on the way in near future.

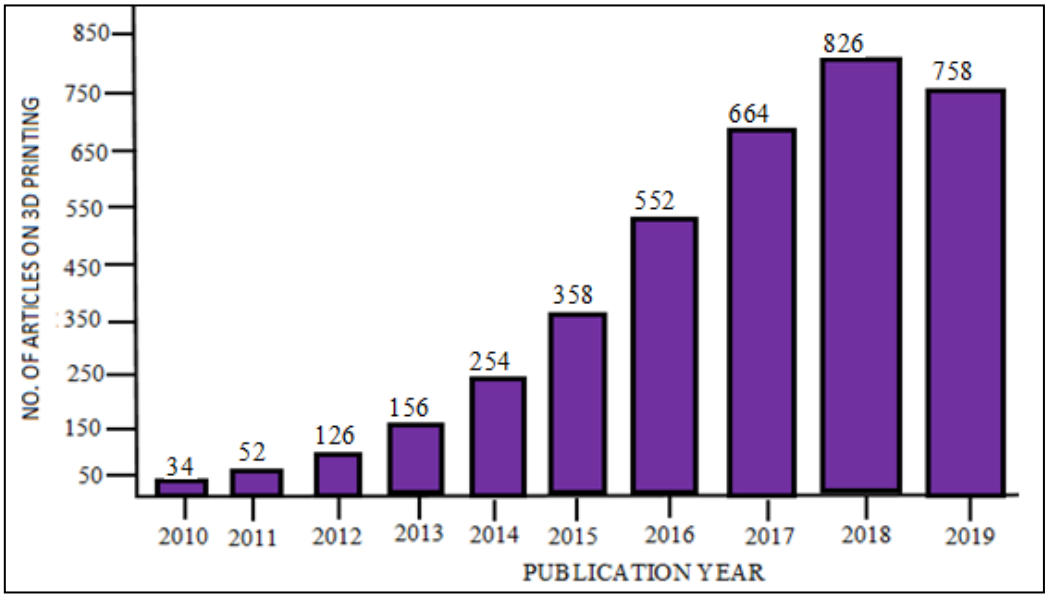


***Figure 6.*** *Statistical data of literature available related on 3D printing*

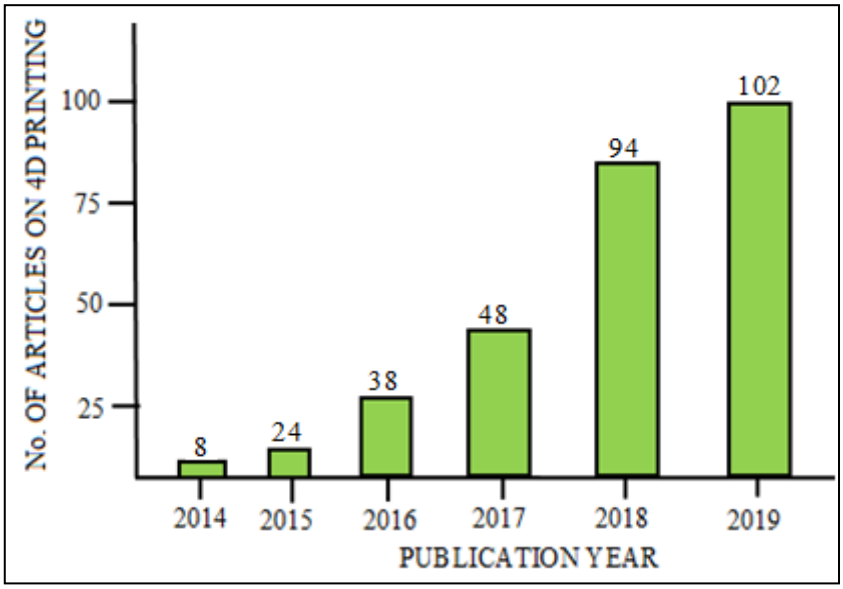


***Figure 7.*** *Statistical data of literature available related on 4D printing*

Lot of advancements in three-dimensional printing technologies still in the innovation stage and the novelty of the existing phase graphically shown in Figure 7. The three-dimensional printing has a time-consuming process even though to prepare a small objects but with four dimensional printing using self healing and changing its formation from ID to 2D and further expanded to 3D with time creates large scale production and do complicated components. Despite the capabilities of a 3D printer machine which is able to print several materials matching and to print on several axes, on other side researchers are concentrating their study on smart materials and mathematical modeling with the assistance of CAD/CAM/CIM/FMS

technologies with the aid to share the views from cloud computing or internet of things by development in the 5G communication technology.

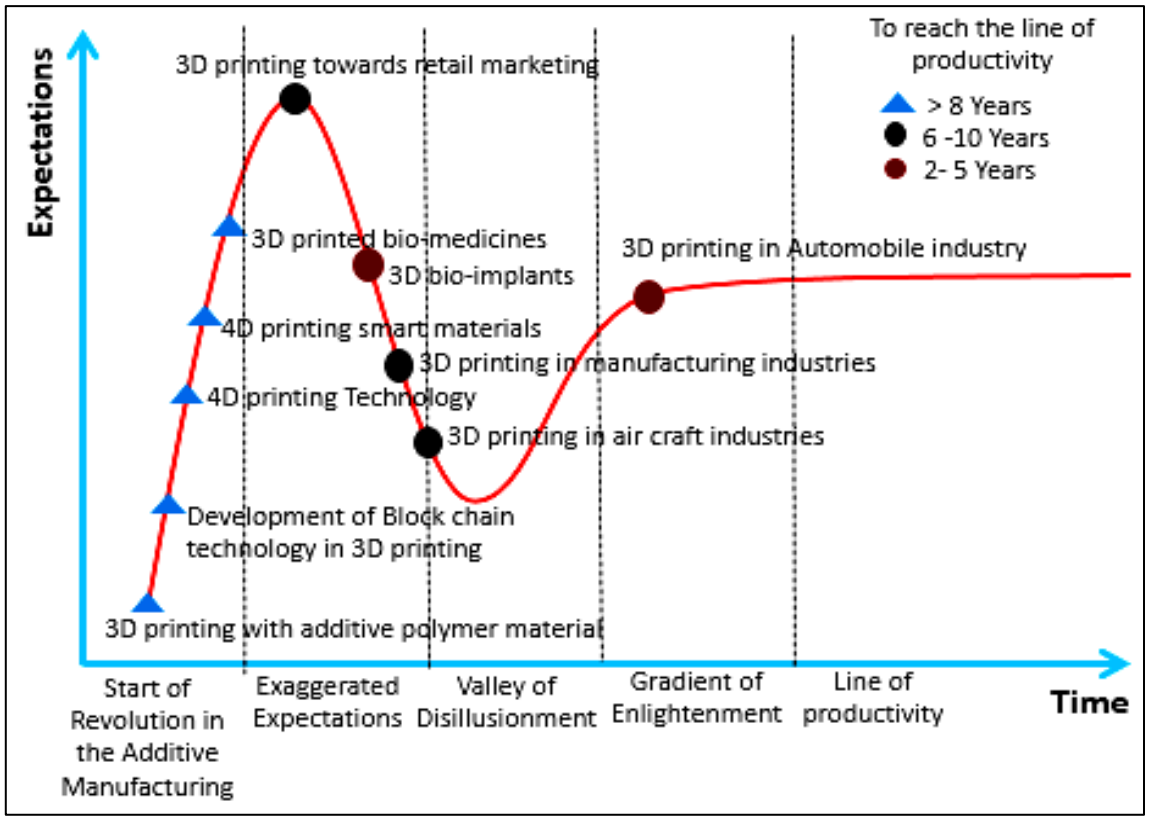


***Figure 8.*** *Graph of publicity cycle for Three verses Four dimensional printing technology[28]*

## 7. MARKET DEMAND FOR 4D PRINTING

The world wide bussiness on rapid protyping 3D printing industrial market [29] is expected to grow at a compound annual growth rate (CAGR) of 42.95% between 2019 and 2025. The market is classified on the basis of material segments into programmable carbon fiber, programmable wood grain and programmable textiles which is shown in Figure 9.

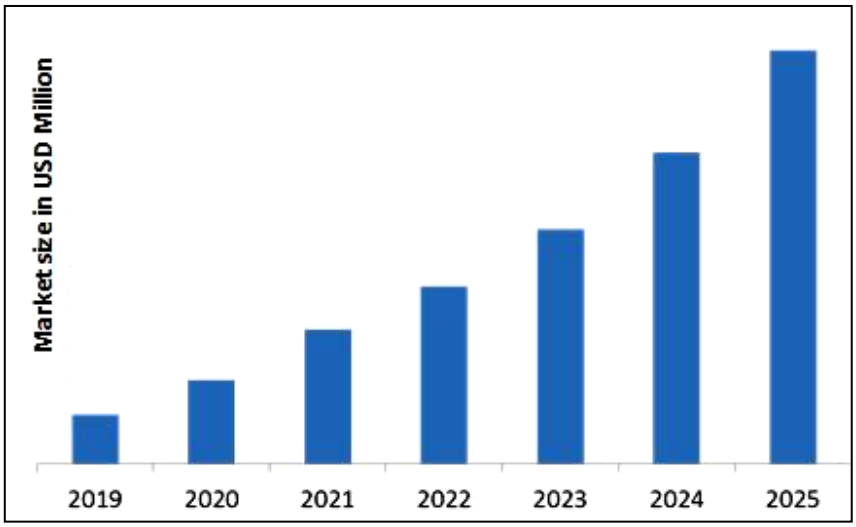


***Figure 9.*** *Four dimensional Printing Market – Global Trends & Forecasts to 2019 - 2025 (www.marketsandmarkets.com)*

The continuous carbon fiber reinforcement is expected to be the major contributor to to use in the preparation of smart material used in additive manufacturing with a share of approximately 62% of the rapid protyping 3D printing market in 2019. This global bussiness market report illustrates the supply chain for the 4D printing with all the major stakeholders in the worldwide market and their role analysis taking into consideration This report also includes the company bussiness profiles of the leading stake holders in the four dimensional (4D) printing manufacturers along with their new advancements in that field and other strategic commercial activities. The advancements in the technology of 4D printing growth in world wide market is also classified on the basis of end-user industry such as automotive, aerospace, construction, clothing, defense, healthcare and utility organizations. This report covers the 4D printing commercial market for geographic regions comprising overall globe. The US market expected to capture the 4D printing market at the highest compound annual growth rate of 44.01% between 2019 and 2025.

## 8. CONCLUSIONS

4D printing found on rapid prototyping (RP) technology is widely investigate in the course of the newest research database available from existing to just three years back in this review. This review aims to investigate the capability of material which is having self healing property to furnish a path towards job oriented printing system for multidisciplinary applications [30]. This comprehensive review described a lot of basic information on recent material developments for producing 4D printing objects in a lucid manner for students and young researchers. The paper also provides the information related to advance developments in emerging areas where outcomes could not be possible with other manufacturing processes. No doubt, 4D printing method further needs development of smart and intelligent materials shall remain in the primary stage and focused on the research and development in the future expectation. 4D printing – a new era of rapid prototyping technology will improve new exemplars and investigate new dimensions in every field of day to day life. It is one of the manufacturing platforms in the fields of medical implantation, tissue engineering and organ develop0ment in the near future.

## FUTURE WORK OR OUTLOOK OF THE REVIEW

Four dimensional printing technologies are still under initial stage, the significant research is required in multiple types of a new era of rapid prototyping technology significantly printing of abundant amount of smart components. A dedicated four dimensional (4D) printing method along with new developments while design of printing mechanisms yield some critical applications followed by cell culturing and implantation.

## CONFLICTS OF INTEREST

No conflict of interest was declared by the author.

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