ETM
ENGINEERING & TECHNOLOGY MANAGEMENT

TFDEA for 3D Printers

Course Title: **Engineering Management Synthesis**
Course Number: **ETM590**
Instructor: **Dr.Anderson**
Term: **Summer**
Year: **2013**

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ETM OFFICE USE ONLY	
Report No.:	
Type:	Student Project
Note:	

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Abstract

3D printing technologies have undergone a rapid change over the last 30 years from Charles Hull's Stereolithography to the first low cost 3D printer entering home use. This technology has improved on many fronts including three-dimensional parts layer by layer, functional organs, and actual working prototypes and model printing. Developments of new faster cheaper ways of manufacturing are critical to the ever evolving medical, industrial, and science industries. It requires many years of research and effort. In order to stay competitive and advance, it is critical to establish a roadmap of future technologies. This paper uses a framework to characterize, assess, and forecast the 3D printing technologies. A DEA-based methodology was used for determining the state-of-the-art (SOA) in future 3D printing technologies.

1. Literature review

Our data gathering process was based on the model in Figure 1. We reviewed papers from various sources on 3D printing and TFDEA. We identified various key words to find the right sources and identify the abstracts to help with our search. This helped us to filter the relevant data and discard that was not applicable. We followed these steps for our data gathering.

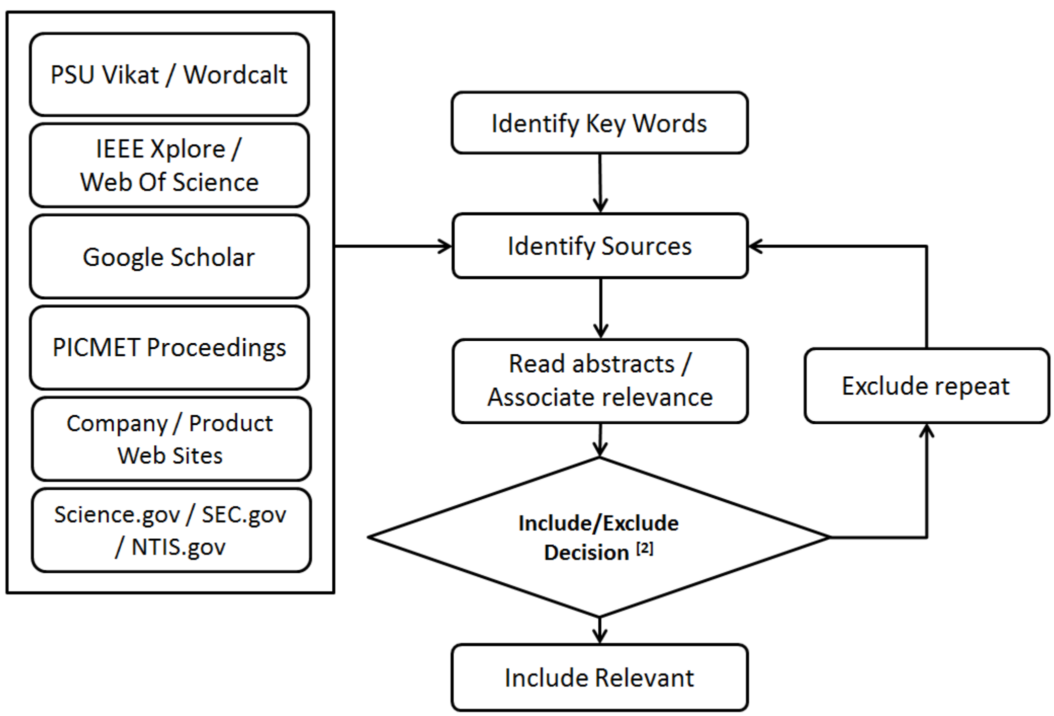

Figure 1 - Literature Review Model

There are several techniques that are commonly used today to develop technology forecasts. However there are three universally basic actions that can be used in the development of technology forecasting.

- *Framing the problem and defining the desired outcome of the forecast*
- *Gathering and analyzing the data using a variety of methodologies*
- *Interpreting the results and assembling the forecast from the available information.* [1]

A paper by Firat, Woon, & Madnick in 2008 provides a synopsis of the many methods that have evolved over time from these basic actions. Some of the earlier papers were written by Jantsch in 1967, Porter in 1999, and Ayres in 1999 to name a few of the many other researchers who have provided comprehensive applications of the number of approaches brought to light. [2] [3].

An example of a technique is the Delphi forecasting tool even with its issue involving a reduction in variance over rounds and whether it reflects true consensus is still used [4]. As time goes on, more and more methods are being combined like Bayesian weighting to a Delphi questionnaire in order to enhance the utility of the Delphi model [5]. This hybrid is only one example of the many methods that have evolved over time.

Quantitative and qualitative technology forecasting can be done depending on the application. [6] [7] Quantitative and qualitative technology forecasting Techniques have been researched and provided quite a few examples on these qualitative and quantitative research methods. These Methods can be placed into 9 categories: Valuing/Decision/Economics Methods, Expert Opinion, Monitoring & Intelligence, Trend Analysis, Modeling & Simulation, Scenarios, Statistical, Descriptive and outline various social, political and economic drivers resulting in technological changes [2]. It is challenging for the decision makers to understand the course of rapidly changing technology and there is a continuous need to keep up with these changes. As stated:

> "*New procedures will evolve to facilitate meeting the intelligence needs of a diverse set of technology managers and policy makers* [8]"

Thus there is a need for methods that can help with the technology forecast. Charles, Cooper and Rhodes developed Data Envelopment Analysis (DEA), a performance measurement technique which is used for evaluating the *relative efficiency* of *decision-making units* (*DMU's*) in organizations. This fall under the Trend Analysis and Creativity detailed in Technological Forecasting groupings mentioned before.

Technology futures analysis includes the many technologies and their consequences coexisting including forecasting, assessment, roadmapping, foresight, and technology intelligence. However as these has matured they have grown apart and share little information. As the Technology Futures Analysis Methods Working Group states:

> *"New methods need to be explored to take advantage of information resources and new approaches to complex systems* [9]*"*

A relatively recently developed extension of DEA is TFDEA; this technique is used to forecast future SOA technologies and developments. One of the first written practices of the

TFDEA was published in a book, "Technology forecasting using Data Envelopment Analysis" using three case studies to determine the method's validity [10]. In all three cases the TFDEA proved to be a better process with a more comprehensive evaluating forecasting technology method.

In 2005 TFDEA was used in a formal comparison with an already published application by Joseph Martino in Technological forecasting and Social Change Using the data that Martino already had, the 1944 to 1960 data was entered into TFDEA model and provided a more accurate prediction of the first-flight dates of fighter jets introduced between 1960 and 1982 [11].

TFDEA was used in studies outlining reasons for R&D target-setting difficulties step by step in the commercial airline industry [12]. The results included the rate-of-change variants in setting R&D target variants in technology for the aircrafts. By using TFDEA managers were left with less room to base target decision on only the most achievable goals for R&D. When using TFDEA:

> *"Decisions can now be based on rewards for meeting lower ends of possible technological progress or possibly higher rewards for reaching technological breakthroughs and pushing the State of the Art (SoA)* [12]*"*

2. Methodology

According to RepRap (Replicating Rapid), a user group dedicated to the advancement of Open Source 3D printing technologies, the group initiators did not try to forecast or give any future direction to the technology. The reason for this is that the project has taken on a life of its own and the developers of the project are no longer leading the charge in this technology. Instead they predict that those developments will come from the RepRap community [13] [14].

Using TFDEA our team used available historical data and information of different models and designs to try and determine the future of the direction to the 3D FFF technology. TFDEA uses the general notion of SOA and DEA to establish trends in historical data in order to determine future changes in technology. The assumption of the data is that it is linear and therefore can be used to calculate the rate of change at which time new technology forecasts can be based on. Tudorie 2012 summed TFDEA up best with:

> *"TFDEA uses the efficiency frontier found with DEA to determine the SOA technology frontier, which contains the recognized superior technologies at different points in time. Next, the annual rate of change (Roc) in benchmarks is determined. The rate of change is then used to forecast future performance trendsetters. The weaknesses of the method are the sensitivity to disruptive technologies and its reliance on the assumption of a constant rate of technological change (RoC)* [15]*"*

We will walk through the following TFDEA sequence below from Inman, O. L. (2004):

1. Determine the scope of the forecast
2. Define a product
3. Define SOA characteristics
4. Determine the DEA model
    a. Orientation
    b. Returns to scale
5. Collect data
6. Analyze technological Progress
    a. Mapping technological progress
    b. Time considerations
    c. Forecasting future technologies
7. Examine results

The purpose of the RepRap printing FFF and FDM forecast under discussion is to determine the current status of the technology and to determine how the FFF and FDM printing will change in the future. Under the guidance of Dr. Anderson we were informed to get as much data as possible and to have abroad scope. This will allow us to study the different possible market changes, segments, and disruptive technologies [10].

We have defined the scope and have narrowed down our decision making units (DMUs) product line type of printers to the FFF and FDM models. The release date of each product has been acquired to assist in the final calculation later on. A list of the SOA characteristics have been selected and entered into a spread sheet including weight and speed of each model.

The TFDEA model that will be used will be an output-oriented model. An output-oriented model can be calculated by hand, but for this paper due to the numerous amounts of input data linear programming software will be used.

Managing multiple Input and Output variables with different units is allowed on a TFDEA model and according to Inman there is no requirement on the independence of the variables. The input will be from the gathered data for FFF 3D printer robots and FDM printers as the technology is similar. This includes release date and selected technology attributes with well-defined data.

The data consists of models from 2008 to present and all have the same basic information in the data categories of design, speed, and market. Using this information will allow us to map the DEA efficiency score and use it as a technology index. This can be used to compare with the SOA.

Do to time constraints our product information data size is limited and there for is room for error, but we will make the most of it and present our results of what maybe the future of FFF and FDM printing technology.

3. Technology characterization

There are several different technologies and systems for 3D printers that have been developed over time. Many technical classifications and features are currently being used in the 3D market place. The main difference lies in how the 3D printer creates these layers in order to create a three dimensional object and what materials are used. Many of these printing methods used 3D printing technologies are outlined below:

1. **Stereo lithography (SLA) –** Also known as stereolithography apparatus, is the oldest 3D printing technology invented in 1984 by Charles Hull [16]. This technology uses a laser to solidify the liquid resin in a VAT on build platform. The perforated platform is then lowered inside the VAT and another layer is created by hardening using the laser. The iterative process is used to print the complete object. After printing, the part is cleaned in a chemical bath, and cured in an UV oven [16] [17] [18] [19] Another variation of this technology is the DLP (Digital Light Processor), which uses a projector to solidify one complete cross section instead of using the laser to trace, thus it is more faster process [16] [20].

2. **Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) –** A three-dimensional printing process that uses a high power laser to fuse small particles of plastic, metal, ceramic, or glass powders into a mass that has a desired 3-dimensional shape [21] [22]. A thin layer of powdered of the desired material is spread on to a bed. The laser draws the outline cross section one layer at a time. When a cross section is complete, then the build plat form is indexed down to make room for the next layer. A new layer of powder is laid across the surface ensuring an even cote is spread over the object and the laser draws the outline cross section one layer at a time. This process continues until the object is built from the bottom up. The object is then removed and cleaned once completed. Additional finishes can be done from this point on. The extra materials is then recycled for the next project.
   The main difference between SLS and DMLS is the material being fuse together and the laser used to fuse the material [20].

3. **Fused Deposition Modeling (FDM) –** This technology was invented in late 80s and commercialized it through his company Stratasys in 1990. The FDM technology uses a nozzle to extrude the material and move the material over the build platform. The next layer is added by lowering the build platform to write another section of the object [19]. The most common material extruded is the thermo-plastic from a temperature controlled print head. This method prints object with high degree of accuracy and robustness [16] [17] [18]. A three-dimensional printing process that makes a solid object from a computer 3D imaging program by using a machine to construct the part one layer at a time on a build platform. Thread like spools of thermo plastic or filament are then slowly fed into a heated liquefier and extrude through a nozzle. The extrusion nozzle then lays down

precise thermo plastic according to the outline cross section one layer at a time. The extrusion nozzle continues to move in a horizontal XY plain. When a cross section is complete, then the build platform is indexed down to make room for the next layer. This process continues until the object is built from the bottom up. The object is then removed and cleaned once completed. Additional finishes can be done from this point on [20] [21] [22] [23] [24]

Many models have two heated liquefiers and extruder nozzles. One used for the Thermo plastic and the other is used for support material that is added as the object is being built to give supplemental strength to fine structures and down facing surfaces. This material is later removed after the build process is complete [21] [22] [23] [24].

Additional models have two or four heated liquefiers and extruder nozzles. These machines can print in dual color mode, but are more expensive. There are many other variations depending on the available kits and parts for each machine.

4. **Fused Filament Fabrication (FFF) –** This technology is very similar to Fused Deposition Modeling. The main difference is that Fused Filament Fabrication systems are designed to be able to replicate their own parts so as to literally be able to print out another printer piece by piece. It is a robot that uses the FFF technology to copy itself and other objects with a variety of thermoplastic polymers. This ability also gives the owner access to 3D printer capabilities. The printing principles are the same with minor differences per open source design per machine [13]

5. **Three Dimensional Printing (3DP) –** This technology was invented in 1993 at MIT and was commercialized by Z Corporation [19]. This is a flexible process and can create parts of any geometry, and out of any material, including ceramics, metals, polymers and composites. Also, it can exercise local control over the material composition, microstructure, and surface texture. This technology functions by building parts in layers. From a computer (CAD) model of the desired part, a slicing algorithm draws detailed information for every layer. The computer 3D imaging program then instructs the Z-Corp 3D printer to spreading a 0.089mm layer of powdered material on to a bed. Then an inkjet head deposits a binder or glue in an outline of the image cross section of the object being printed. When a cross section is complete, then the build platform is indexed down to make room for the next layer. A new layer of powder is lade across the surface ensuring an even cote is spread over the object and the inkjet head despots the next layer of bonding agent until the object is completed. Following a heat treatment, the object is then removed. The object is cleaned and unbound powder is removed, leaving the fabricated object. [20] [25] [26]

6. **Polyjet Matrix Printing –** This 3D printing technology creates objects by using a light source to solidify a liquid photopolymer and was pioneered by a company called Object.

The process includes forming object layers by emitting liquid photopolymer from an inkjet-style, multi-nozzle print head. After each layer is printed a powerful UV light is then used to set it solid before the next layer is printed [16]. This additive layer technology utilizes a high precision 3D printing process and can print parts and assemblies made of several materials with different mechanical and physical properties all in one build process. [20] [27]

7. **Electronic Beam Melting (EBM)** – This printing process is developed by Arcam which was founded in 1997. This process uses a powder which is fused together on a build platform by an electronic beam. By lowering the build platform and redistributing the powder using a wiper, the next layer can be build. The process is similar to SLS but uses an electronic beam instead of a laser. The powders are always metals with different types of alloys. The build chamber is a vacuum and heats up until 700 – 1000C. [19]

8. **Laminated Object Manufacturing (LOM)** – This technology is developed by Helisys. It uses thin sheets of material which is cut by either a laser or a knife according to the outline of the part. Next the sheet is glued on top of the previous cut sheet of material. After printing the excess material is "broken" off and you are left with the printed parts. LOM printers mostly use paper, and various plastics. These are the most 3D printing technologies manufactured today. There are more technologies and variations available in both research and production, but they focus on real niche areas. [19]

The second is the target market place. For the most part 3D printers could only be purchased by companies or individuals with the financial means. However in the last thirteen years this has changed as there is now Fused Filament Fabrication printers that have come forth in recent years that are design to self-replicate or create all the parts needed to create another printer. Many users are buying these printers for their 3D printing ability so they can print their own item.

4. Scope

Based on the research done in the 3D Printing Industry, several product segments were identified. These segments are represented in **Error! Reference source not found.** and are described below:

- Industrial:
  - Manufacturing: This segment represents printers that are used for manufacturing components at an industrial scale [28] (i.e. high product volume from different materials including metal and silicon-based supplies).
- Laboratory:

- Education: This segment represents the 3D printer customers that belong to educational or government institutions. Typically these products are used for printing prototypes or models of academic or research projects.
- R&D: This segment represents 3D printing customers in the industry R&D organizations. The primary use of 3D printing is building models or prototypes that are then commercialized using technologies other than 3D printing.

- Consumer:
  - Commercial-of-the-shelf (COTS): This segment represents the line of products that are suited for small shops and home use. Typically these are the commercial products with the lowest cost of acquisition and ownership.
  - Do-It-Yourself (DIY): This segment represents the product parts that are sold as proprietary or open-source kits for customers to assemble and customize their own 3D printers.

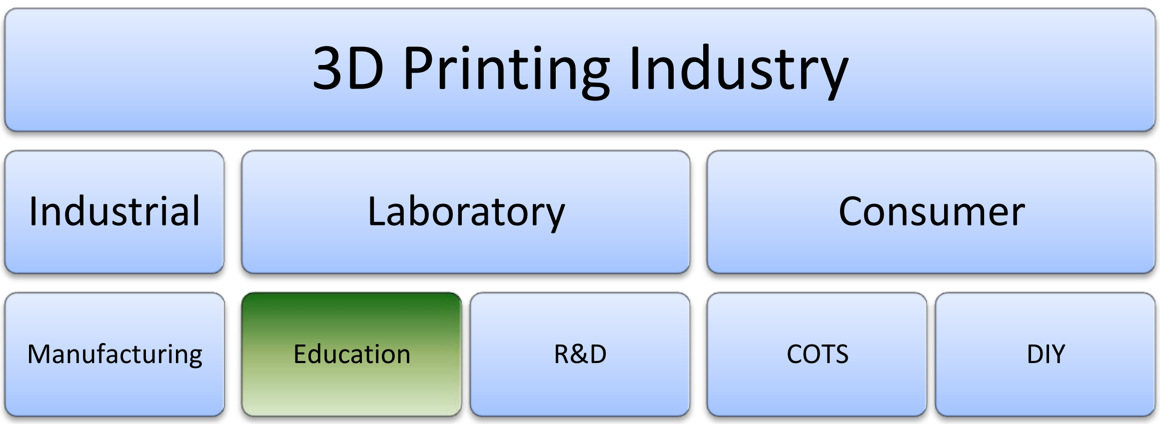

Figure 2 - 3D Printing Market

While the industrial market is expanding and the number of dollars spent in purchasing industrial 3D is predicted to increase in the coming years [28], the expected increase in the actual number of consumer 3D printers sold will dwarf the industrial market.

Signs of this trend are already been seen with the explosion of consumer 3D printer manufacturers and products, including commercial and open-source DIY kits for users to assemble their own printers. Additionally, the next planned version of Microsoft Windows [29], 8.1, will include drivers and an Application Programming Interface (API) to support 3D printers when it is released to manufacturing (RTM) on Q3 2013. This is of great significance given that Windows is the most widely adopted personal computer Operating System in the world. Based on this analysis we identified the segment with the largest growth potential and the fastest adoption rate as the consumer COTS segment.

However, at this point most of the adoption in the Education and R&D markets; for this reason the focus of the study is in these markets. This market profile draws parallels with other technologies, e.g. personal computer, Internet, in the early adoption stage in which expert users were only found in Universities and laboratories that could cover the expenses of a high cost of ownership.

5. Industry Players

According to a survey done in 2012 by Statistical Studies of Peer Production, 446 people who responded were using 3D printers from these manufactures [30] See Figure 3.

3D Systems	BitsfromBytes	Dimension	EOS	MakerBot	Objet	RepRap Project	Stratasys	Ultimaker	Zcorp
37	21	23	32	79	42	116	35	21	40

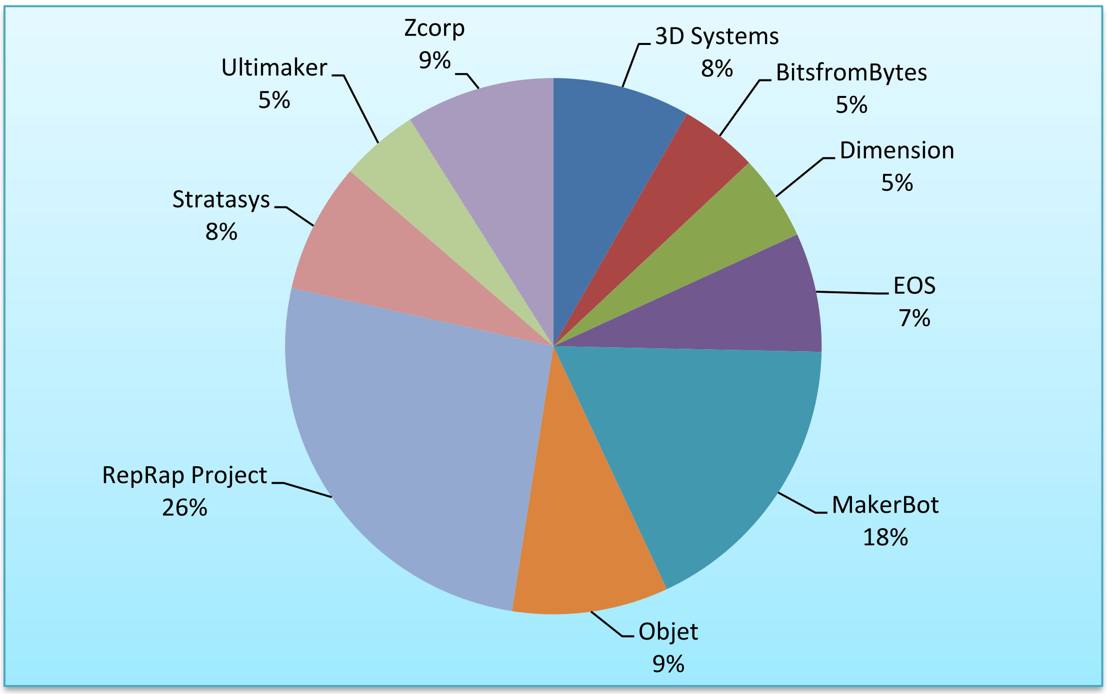

Figure 3 [30]

Many of these companies have merged since this survey and are working on improving the technology or consolidating brands.

6. Technology Assessment

Recent 3D printers include various sizes of models which were not available in the past due to copy, and patent rights. Since self-replicating printers are open source any one can have a relatively affordable 3D printer. At this time there are more startup companies and veteran printer companies entering the market and growing sales of Fused Filament Fabrication modeling printers being sold in the consumer COTS and DIY markets. This was due to the

Replicating Rapid Prototyper (RepRap) project that was started by Dr. Adrian Bowyer in 2005 at the University of Bath in the United Kingdom [14].

7. Technology forecasting Data Envelope Analysis (TFDEA)

TFDEA is a forecasting method that has been introduced by Anderson *et al.* [31]in 2001 to forecast the technological trend of SOA microprocessors. Since then it has been applied in many applications like fighter jets [11], wireless communication technology [32] and LCD panels [33]. In their study, Anderson et al. extended Moore's law by distinguishing that the performance of microprocessors is not only limited to the number of transistors and there are more factors which contribute to the efficiency of microprocessors [34].

Data Envelopment Analysis (DEA) is a powerful, nonparametric benchmarking tool that has widely been used for measuring the relative performance of organizational units where the presence of multiple inputs and outputs makes comparisons difficult [35]. It is useful when multiple outputs need to be considered where no single output metric captures performance comprehensively, especially in cases where several dimensions of performance are important.

It has been used in many different application areas like education, health and banking and also to compare different products including computer printers, robotics and automobiles [36] [37] [38]. DEA is an extreme point method and does not average the dataset and allows for identifying best performers or the frontiers [34].

The main limitation in DEA is that it calculates the efficiency of entities at one point in time and does not consider how the performance of the entities changes over time. Anderson *et al.* enhanced the process of DEA by adding this functionality and introduced Technology Forecasting using DEA (TFDEA) which finds the trend of best performers over time [31]. The first step in using TFDEA is to build the DEA model and select the input and output parameters [34]. Figure 1 shows a general DEA model [34].

TFDEA is conducted in two main steps; the first step is the model validation and the second step is actual projection of the future frontiers. We can do several iterations to validate the model by selecting and testing different input and output parameters that could present the performance of DMUs [34]. To apply TFDEA, the release date of the DMUs has to be collected. The dataset is divided into two parts for the model evaluation process at the specific point in time. The DMUs with release dates before the dividing point are used as the "training data" to find the Rate of Change (RoC) of the best performers. RoC is calculated by comparing the performance values of the frontiers in one year to the frontiers in the former years. It shows how much the performance parameters of the frontiers improved from one year to the other. The RoC from the training data will then be used to forecast the release date of DMUs released after the dividing point. The difference between the forecasted date by TFDEA versus the actual release date of the DMUs determines the accuracy of the model used [34].

DEA Model [39]

For every DMU *k*,
k = 0 the DMU being analyzed

Objective: maximize the performance ratio, $\frac{Y_0}{X_0}$

Decision variables: *ui*, *vr* for all *i* and *r*
Constraints:

$X_0 = 1$ (scaling of the input value)
$-X_k + Y_k \leq 0$ *for all k* (efficiency no greater than one)

TFDEA uses DEA to find out incremental innovation in technology. The efficiency frontier of DEA becomes the Technology frontier of TFDEA. TFDEA identifies the technology's historical stages and State-of-Art (SOA) to evaluate characteristics of that technology's future and track down the rate of change (ROC). TFDEA identifies efficient technologies at each period by comparing them with each other, and shows how much the output of a particular technology should increase in order to be SOA at the time of commercialization [39].

To build a model in TFDEA we first break the technology to be forecasted into products of that specific technology in terms of functional and structural elements. Functional elements are the functional performance attributes and Structural elements are defined as the critical factors for the product to function [39].

TFDEA Model [39]

t_k = release date of product *k*
t_f = frontier period
$x_{i,k}$ = *i* input of product *k* – structural characteristics
$y_{r,k}$ = *r* output of product *k* – functional performance attributes
$\lambda_{j,k}$ = how much of technology *j* is used to set a target for technology *k*
$\emptyset_k^{t_f}$ = how much the output of technology *k* should increase to become SOA technology at period t_f

- Every product *k* is analyzed
- For every potential technological frontier period, t_f, from start time, t_0, to in time *T*, data is analyzed
- The process compares each product to a weighted mix of its peers indicated by $\lambda_{j,k}$
  Products that were state-of-the-art (SOA) upon release time t_k, $\emptyset_{t_k} = 1$, and are no longer SOA are used to determine the rate of change (RoC) by using the effective time, t_{eff}, and the time which benchmark is SOA at time t_f

- This result is then used to calculate the mean effective RoC for that product. During each period, the mean technological RoCs for all formerly SOA product *k* at time *t*, λ may then be used.

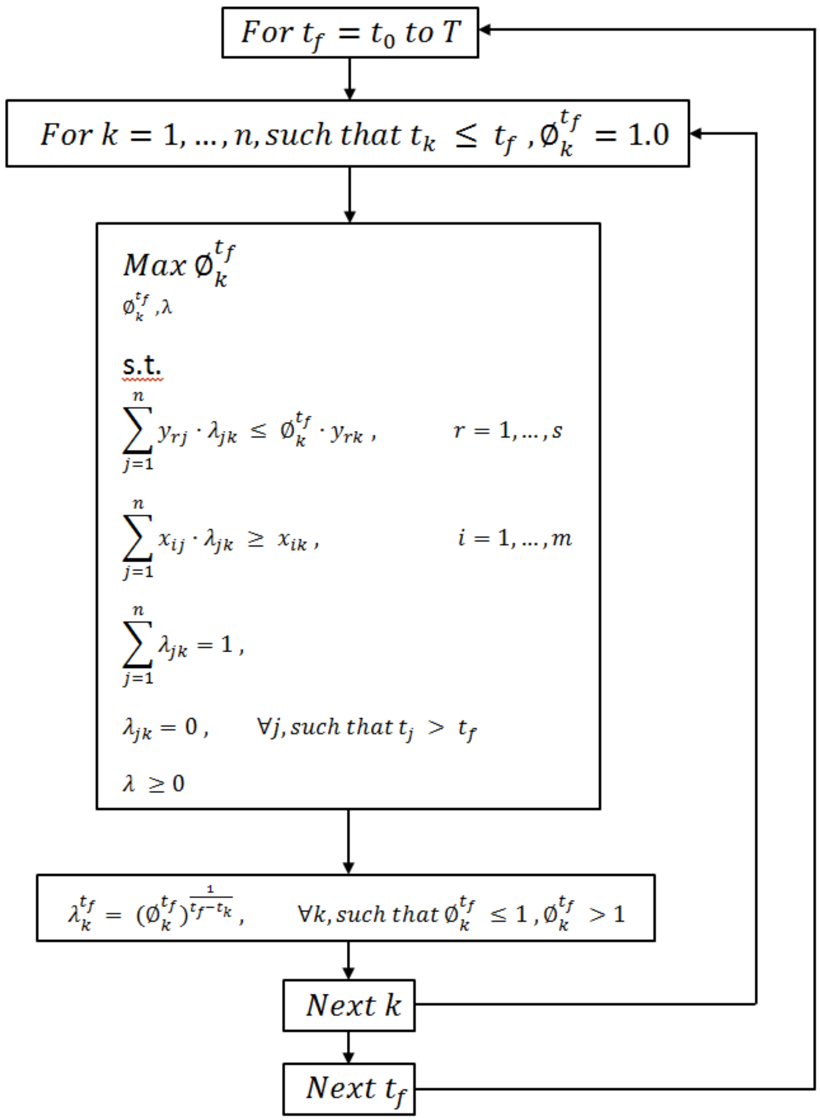

Figure 4 - TFDEA Algorithm

8. TFDEA Model

In order to build the TFDEA model the steps in the following sections were followed, these are based on previous TFDEA methodologies used by the Extreme Technology Analytics Research group at Portland State University [40] [33].

8.1. Development

8.1.1. Variable Selection

The first step in developing the model is selecting the variables depending on the perceived value of features to the experts we surveyed. The importance of the variables is calculated by normalizing the survey responses, i.e. each of the 10 responses was given a value 1/10 and then multiplied by the user selected weight on a scale of 1 to 5; these values where then added up to obtain the Normalized Weights for each of the categories. The variables that are perceived to be most important for the users are underlined in **Error! Reference source not found.**.

Table 1 - Normalized Weights for Product Features

Variables (Product Features)	**Least**		**Medium**		**Most**	**Normalized Weights**
	1	2	3	4	5	
Speed	0.10	0.00	0.30	0.40	0.20	3.60
Prints in multiple materials	0.20	0.10	0.20	0.20	0.30	3.30
Accuracy (Layer Thickness)	0.00	0.00	0.10	0.30	0.60	4.50
Build Size	0.00	0.10	0.40	0.20	0.30	3.70
Printer Weight	0.60	0.30	0.10	0.00	0.00	1.50
Printer Price	0.00	0.10	0.20	0.40	0.30	3.90
Resolution	0.10	0.00	0.10	0.20	0.60	4.20
Number of Heads (Colors)	0.30	0.30	0.30	0.10	0.00	2.20

The variables selected to build the model were the top five most important variables to the experts. Additionally 'Printer Weight' was included given that it is one of the two, the other being 'Printer Price', structural product characteristics included in the survey that changes over time and could be used as an input. 'Number of Heads' was another structural characteristic included in the survey but, based on the our product data research, this characteristic has not change over time as there have been a number of models with one to three heads across the span of our model research. For this reason 'Number of Heads' was not considered for the model.

Table 2 - TFDEA Model Variables

Variable Name	Units	Definition	I/O Type
Price	USD	Price is defined as the monetary expenditure that is incurred for the purchase of a system that is completely assembled in.	Input
Weight	Kg	This is the weight in kilograms of the assembled device.	Input
Accuracy	Mm	It is defined as the surface quality and dimensional correctness of the finished product.	Output
Build Envelope	mm^3	It is the total product size that can be effectively printed in a 3D printing system. This criterion is a function of the effective usable base (X and Y) times the tallest (Z) object that can be printed by the system	Output
Resolution	Mm	Printer resolution describes layer thickness and X-Y resolution in dpi (dots per inch)	Output
Speed	mm/sec	This is the speed at which the device can print in a linear dimension.	Output

Additional data normalization operations were performed to add consistency to the DMUs Inputs and Outputs. These operations for each of the variables are explained in detailed below:

Price

The dataset was limited to those models on sale in the US so all prices for fully assembled models were originally in USD; for Open Source projects where the price of the Bill of Materials (BOM) could not be found in USD a currency conversion was used taking into consideration the publication date. In order to calculate the present equivalent price for all the datasets collected all prices were adjusted for inflation using the Consumer Price Index (CPI) with the formula below, where i is the product release year. The CPI is provided by the Bureau of Labor Statistics at the US Department of Labor. For this study all prices are adjusted for inflation at 2013 prices.

$$Price_{2013} = Price_i * \frac{CPI_{2013}}{CPI_i}$$

Another consideration was calculating the price of a fully assembled product having the cost of the 3D printer Build Kits or Bills of Materials. Based on our research for 2013 prices, most companies that market both kits and fully assembled products charge an extra amount of US$100 [41] to US$500 more [42] for the fully assembled product, products that are SOA have higher assembling costs. For this reason we added the assembling cost of US$500 (in 2013 USD) to the original kit prices. We made this assumption because the cost for assembling a device for the average inexperienced user will be at least this amount for the time and money invested in procuring the necessary tools, acquiring the required skill set and learning how to assemble a specific make and model. This is a conservative estimate and is consistent with what enthusiasts report in user forums at the time of SOA product releases.

For Open Source projects that publish only the products BOMs we estimated that the hidden cost for researching suppliers and ordering materials would be 10% of the BOM cost. This is a conservative ballpark estimate since kit resellers are able to negotiate better pricing for buying parts in bulk, and save on shipping, processing orders and researching suppliers. [43]

Accuracy and Resolution

During the research we found inconsistencies in the units used to measure accuracy, mainly between US customary units and metric units. For this reason, accuracy measurements were all converted to metric units so the model could be run with consistent DMUs. Additionally because the model is Output Oriented, outputs are expected to grow over time to reflect the expected improved performance. In the case of ‘Accuracy’ and ‘Resolution’ performance improves when these dimensions decrease, for this reason the reciprocal number of this measurements was used instead.

Build Envelope

Build envelopes were also converted to metric units. Additionally, for the purpose of this study the volume measurements are treated independently of the different width, height and depth dimensions.

Speed

Printing speed was considered as a linear dimension given the different maximum widths and depths of the printing. Most of the products researched had the linear speed as a specification, for those products that did not publish this information the linear speed (mm) was calculated from the volume speed (mm^3/s) taking in consideration the average printing width and depth. For illustrative purposes, consider a product with a published theoretical volume speed of 24 mm^3/s with a Z dimension of 2 mm and a Y dimension of 3 mm, in this case the calculated X dimension linear speed was 4 mm/s. None of the products researched make a distinction between the X and Y dimension as far as accuracy and resolution so we were able to make this transformation with considering the X and Y linear speeds as interchangeable.

8.1.2. Parameter Selection

The Input parameters constrain the model algorithm to values that reflect the nature of the products, technologies and industry.

Decision Making Units (DMUs)

The DMUs are the sets of data collected for each of the researched products. In this case a DMU consists of a model name, manufacturer, release year and the values for the model variables.

Orientation

This parameter describes the model goal; Input Orientation (IO) describes a scenario in which the primary goal is minimizing the input(s) while Output Orientation (OO) describes a scenario in which the primary goal is maximizing the model output(s). Based on the responses from the 3D expert users we conclude that, at this stage of the industry maturity, the primary goal is increasing the products performance so OO was selected.

Return to Scale (RTS)

Variable Return to Scale describes the way the model inputs are related to the outputs from the customer perspective. In this case an increase in the input results in a increase on the output albeit not in a proportional manner, e.g. a 2X increase in price for a new generation of products would likely result on an increase on printing speed but not necessarily a 2X increase.

Frontier

Using a *static frontier* products are compared to products from a single year only, for example comparing 3D printers from 2010 to printers from 2011. Using a *dynamic frontier* products are compared against products from different years, for example comparing 3D printers from 2008 to printers from 2010 and2011. For this model a dynamic frontier was selected so the models could be compared to other SOA products.

The Output parameters capture the nature of the TFDEA model. These parameters are then interpreted and analyzed in order to provide information for forecasting.

Efficiency at Release: Indicates the quality of being SOA when the products were first released to the market.

Efficiency at Frontier: Indicates the quality of being SOA at the time of the frontier selected when building the model.

Effective Date: For an SOA product *p* with an efficiency of 1 at release time, the Effective Date indicates the date at which *p* is being compared with other products *q*, *r*, *s* that make it have an efficiency greater than 1.

Average Rate of Change (Avg. ROC): Indicates the average pace at which overall performance (output variables) change over time. For example a 1.10 Avg ROC means the performance improved 10% YOY during the course of the study period.

Forecasted Year: Indicates the year at which the model calculates a certain product would have been released according to the DMUs.

8.2. Runs

After investing some time normalizing the data and making adjustments to the variable values as explained above, two final model runs were performed based on the time span of the data collected (2008 to 2013). These were run using R and Excel based software developed by Dong-Joon at the Engineering and Technology Management Department at Portland State University.

8.2.1. Validation (1st Frontier Year: 2011)

This calculated the RoC for the period 2008 to 2011 using *backtesting*, i.e. it helped 'forecast' the expected behavior from 2011 to 2013 according to the model. Comparing the actual collected data from the forecasted period with the calculated forecast would, in theory, help us validate the model.

8.2.2. Extrapolation (2nd Frontier Year: 2013)

Applying the same model for the period 2008 to 2013 we can obtain information about RoCs for products and forecast the behavior of the current SOA products in the coming years.

8.2.3. Results

Because of the nature of the industry our dataset had a limited timespan. We were not able to obtain meaningful information about the forecasted product Release Dates. However, the results obtained from the RoC shed some light on the industry development that combined with the knowledge we've developed on the industry serves a corner stone for further research on the industry.

The Rate of Change for SOA products from the first wave of pre-industrial, offered as a BOM or as a kit, printers indicates that they have become obsolete in 2 to 3 years. In the first years of our research span there were a very limited number of printers available in the market.

The explosion of new products since 2010 has significantly increased the availability of products making the selection process more complicated. The Rate of Change for some SOA industrial printers, offered as fully assembled, has shorten the SOA periods and they have become obsolete the same year they are released.

Based on the product research we believe this trend will continue for the next couple of years before consolidating as more companies continue to mushroom through the world. According to our findings, in 2012 the first commercial 3D printer from a Chinese company (MBot 3D printer) was released to the market joining the industry pioneers from EMEA and NA. This could further change the industry dynamics and increase adoption by providing access to more affordable products.

9. Applications

There are several implications of this study. The study can be applied to strategic decision-making in new product planning and towards technology road mapping. By observing the Rate of Change (RoC) and the output parameter performance needed, the 3D manufacturers can use the TFDEA model to determine the SOA printers. The results of this research analysis can be can be used in new product development in order to validate, or invalidate, design plans and R&D target-setting. [12] Also, the 3D suppliers can also use the RoC to project the necessary performance capabilities of printer parts and parameters.

10. Future Research

Because this is a nascent industry data gathering proved a challenge given the different ways manufacturers publish their specifications. This was particularly challenging for the printer speed performance. Different methods [44] [45] for finding an equivalent measure for speed have been proposed but so far no standard exists to benchmark different models. We believe further development in this research area could help the industry develop a faster because it would greatly improve the quality of information that is available to consumers.

As far as the 3D printer market is concerned this study focuses on the 3D printer market for the R&D and Education markets where products are in the mid-range pricing. Future research on this industry needs to consider the other two sectors identified on this research: industrial and consumer. Because the user profiles are entirely different we expect forecasts for those sectors to differ in some categories as well. However, identifying the commonalities among these sectors would provide valuable information about the kind of R&D investments that would benefit the industry as a whole.

On the methodology side, incorporating 'Value Judgment' constraints as proposed in previous TFDEA studies [46] would provide a more realistic view of what the market is expected to see in products (pull), as opposed to what industry players are willing and able to market (push). This methodology takes into consideration the importance of the model variables to stakeholders, in our study's case these are the final users. We believe this would significantly improve the accuracy of the forecast because it would include the areas that are more likely to be invested on based on user preferences.

11. Conclusions

The use of TFDEA provided valuable information on the 3D printer industry dynamics, however, in order to increase the value of the TFDEA results there needs to be a more solid dataset to build the TFDEA model. This data should have not only a wider time span but also dimensions (model variables) that are more valuable to the particular sector of study.

The challenge on this particular industry is the rate of change it has experienced in the past three years. In addition to growth in manufacturers and models, the multitude of features brought to the market makes benchmarking products a more complex task. For example; how to weight usability for a product that offers a semi-automated user interface on three major desktop OSs versus a product that offers a fully automated user interface with a plug-n-play driver for only one desktop OS, or how to measure portability when a suitcase shaped product specifically designed to be transported is not the lightest product in the market.

Having stated that, we believe the stage at which this industry stands today presents an opportunity for using TFDEA and other forecasting models and gain valuable insight on a growing and profitable industry.

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Appendix I: Survey

Survey-

Name: ________________________________ Phone: __________________________________

Company: __________________________ email:________________________________

Position: ____________________________________ Years in Industry: ______

Background: We are conducting a survey for a research conducted for ETM 590, Synthesis, at Portland State University in Portland, Oregon on the Summer 2013 term. Our research will use several modeling techniques to forecast technological innovation over time in the 3D Printer market. One important input to this research project is expert opinion that will help us determine which parameters to study. As an expert in the industry we would sincerely appreciate your help/insights. We will share the results of the research with all the participants when the project is complete.

When considering technological leadership at any point in time, which features weigh most heavily in your selection of the most advanced product(s)? Please rank the following features from 1 to 5 based on importance (1 being least important; 5 being most important) and include and rank any important factors that we have not considered. See the *Glossary* at the end for a detailed description of these parameters.

	Least				Most
	1	2	3	4	5
a) Speed	_____	_____	_____	_____	_____
b) Prints in multiple materials	_____	_____	_____	_____	_____
d) Accuracy (Layer Thickness)	_____	_____	_____	_____	_____
e) Build Size	_____	_____	_____	_____	_____
f) Printer Weight	_____	_____	_____	_____	_____
g) Printer Price	_____	_____	_____	_____	_____
h) Resolution	_____	_____	_____	_____	_____
i) Number of Heads (Colors)	_____	_____	_____	_____	_____
l) Other ______________________	_____	_____	_____	_____	_____
m) Other ______________________	_____	_____	_____	_____	_____

Thank you for your participation and your help!

Glossary

a) Speed - It is defined as the time that it takes to complete a model, and is a function of the rate that material can be extruded from the print head.
b) Material (Single or Multiple) - **Materials** are defined as the number of different materials that can be processed through the extruder.
c) Accuracy – It is defined as the surface quality and dimensional correctness of the finished product.
d) Build Size – It is the total product size that can be effectively printed in a 3D printing system. This criterion is a function of the effective usable base (X and Y) times the tallest (Z) object that can be printed by the system
e) Weight of Printer – Total weight of printer.
f) Printer Price - **Price** is defined as the monetary expenditure that is incurred for the purchase of a system that is completely assembled.
g) Resolution - Printer resolution describes layer thickness and X-Y resolution in dpi (dots per inch).
h) Print Heads - a single head extruder only holds **one color** filament, a dual headcan have **two colors** of filament.

Appendix II: Dataset

This is the dataset used for the TFDEA calculations, for the actual product data please refer to Appendix V: File attachments

DATE_Year	NAME	O_Speed_mm|s	O_Build_mm^3	I_Weight_kg	I_Price_2013	O_Accuracy_mm_Rec	O_Resolution_mm_Rec
2008	RepRap Darwin I	120	5290000	14	1333.44	10	3.333333333
2009	Cupcake CNC	77	1300000	5	1316.31	0.33333333	11.76470588
2010	Thing-O-Matic	83.33	1000000	8	1811.78	0.33333333	50
2011	Printrbot Jr	35	1061208	4.98	518	0.33333333	10
2011	Printrbot Plus	200	8365427	7.711	1225.62	0.33333333	10
2011	Printrbot LC	200	3511808	6.8	1069.9	0.33333333	4
2011	Mosaic 3D	150	2048383	8.6	1537.04	0.57142857	6.666666667
2011	Ultimaker 3D Printer Assembled	50	9261000	10	1764.73	10	50
2012	Printrbot JR	70	1627920	5	905.79	0.57142857	2.857142857
2012	Replicator Makerbot	40	4893750	14.5	1778.79	90.9090909	5
2012	Replicator 2 Makerbot	90	6758775	25.4	2236.45	0.33333333	10
2012	Replicator 2X Makerbot	200	6000000	12.6	2846.67	0.57142857	10
2012	MakerGear M2	150	10467086	11	1321.12	0.57142857	50
2012	Mbot3d Cube	40	8000000	8	1016.01	0.57142857	10

2012	Mbot3d Cube PVC	40	8000000	15	1219.42	90.9090909	10
2012	Mbot3d Cube II	100	11960000	18	1524.53	10	10
2012	H-series H479	30	2646000	5	1626.23	10	6.666666667
2012	Cube	375	22984000	4.3	1321.12	200	4
2013	Printrbot Simple	60	1000000	3.325	799	10	10
2013	Printrbot Go	60	5550000	6.8	1999	0.33333333	10
2013	CubeX 3D Systems	750	17490000	36	2499	8	10

Appendix III: Validation Results

avgroc	Mad	mapd
1	1	!

t1.Orientation	t1.SecondGoal	t1.RTS	t1.AvgROC	t1.Frontier	t1.MAD
OO	Min	VRS	1	2011	!

t2.Inputs	t2.Outputs	t2.SOA_r	t2.SOA_f	t2.ROC_c	t2.RBF	t2.RAF
2	4	11	7	0	0	0

t3.DMU	t3.Name	t3.Year	t3.Efficiency_R	t3.Efficiency_F	t3.Effective_date	t3.RoC	t3.Forecasted_Year
1	RepRap Darwin I	2008	1	1	2008	-	-

2	Cupcake CNC	2009	1	1	2009	-	-
3	Thing-O-Matic	2010	1	1	2010	-	-
4	Printrbot Jr	2011	1	1	2011	-	-
5	Printrbot Plus	2011	1	1	2011	-	-
6	Printrbot LC	2011	1	1	2011	-	-
7	Mosaic 3D	2011	1.310410697	1.310410697	2010.87106	-	-
8	Ultimaker 3D Printer Assembled	2011	1	1	2011	-	-
9	Printrbot JR	2012	2.78550009	0.635575733	2010.550287	-	!
10	Replicator Makerbot	2012	1.940832595	0.11	2008	-	!
11	Replicator 2 Makerbot	2012	2.539327565	1.310220488	2011	-	!
12	Replicator 2X Makerbot	2012	1.585152838	0.989938513	2010.931726	-	!
13	MakerGear M2	2012	1	0.593095091	2010.902946	-	!
14	Mbot3d Cube	2012	1.526347886	0.769462521	2010.966992	-	!
15	Mbot3d Cube PVC	2012	1.454990532	0.095131798	2008.419479	-	!
16	Mbot3d Cube II	2012	1.639691804	0.69628574	2010.507395	-	!
17	H-series H479	2012	1.905405405	0.037184595	2011	-	!
18	Cube	2012	1	-1.00E+30	NaN	-	!
19	Printrbot Simple	2013	1	-1.00E+30	NaN	-	!
20	Printrbot Go	2013	2.67742554	1.075847363	2010.321189	-	!
21	CubeX 3D Systems	2013	1	0.248415716	2010.486692	-	!

Appendix IV: Extrapolation Results

Avgroc	Mad	Mapd
1.395106158	N/A	N/A

t1.Orientation	t1.SecondGoal	t1.RTS	t1.AvgROC	t1.Frontier	t1.MAD
OO	Min	VRS	1.395106158	2013	N/A

t2.Inputs	t2.Outputs	t2.SOA_r	t2.SOA_f	t2.ROC_c	t2.RBF	t2.RAF
2	4	11	7	4	N/A	N/A

t3.DMU	t3.Name	t3.Year	t3.Efficiency_R	t3.Efficiency_F	t3.Effective_date	t3.RoC	t3.Forecasted_Year
1	RepRap Darwin I	2008	1	2.92576493	2012.010459	1.306940643	-
2	Cupcake CNC	2009	1	1.793916127	2011.840918	1.228395067	-
3	Thing-O-Matic	2010	1	1	2010	-	-
4	Printrbot Jr	2011	1	1	2011	-	-
5	Printrbot Plus	2011	1	1.436747449	2011.881089	1.508760864	-
6	Printrbot LC	2011	1	1.343231398	2011.687195	1.536328056	-
7	Mosaic 3D	2011	1.310410697	2.347689531	2012.08444	-	-
8	Ultimaker 3D Printer Assembled	2011	1	1	2011	-	-
9	Printrbot JR	2012	2.78550009	2.78550009	2011.482854	-	-
10	Replicator Makerbot	2012	1.940832595	1.940832595	2011.875996	-	-
11	Replicator 2 Makerbot	2012	2.539327565	2.539327565	2012	-	-
12	Replicator 2X Makerbot	2012	1.585152838	1.906880674	2012.198053	-	-
13	MakerGear M2	2012	1	1	2012	-	-
14	Mbot3d Cube	2012	1.526347886	1.526347886	2011.620094	-	-
15	Mbot3d Cube PVC	2012	1.454990532	1.454990532	2011.873369	-	-
16	Mbot3d Cube II	2012	1.639691804	1.639691804	2012	-	-
17	H-series H479	2012	1.905405405	2.976794214	2011.808043	-	-
18	Cube	2012	1	1	2012	-	-
19	Printrbot Simple	2013	1	1	2013	-	-
20	Printrbot Go	2013	2.67742554	2.67742554	2011.343894	-	-
21	CubeX 3D Systems	2013	1	1	2013	-	-

Appendix V: File attachments

TFDEA_R_Results.xlsx

TFDEA_PrintersDataSet_.xlsm