Technology Roadmap for Consumer 3D Printing

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ETM 534/634
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PORTLAND STATE UNIVERSITY

8/14/2013

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Introduction

3D Systems Corporation is a leading provider of 3D content-to-print solutions andis the market leader in the industrial manufacturing space [1].Their 3D printers can print almost anything including medical, aerospace, andautomotive products to individualized home products, customized jewelry and toys. They have become the leader in the industry by leveraging their Intellectual Property in 3D printing and digital manufacturing.The company has been instrumental in changing the manufacturing environment over the recent past.And, this emerging industry is gaining momentum.However, their momentum to ensure leadership moving into the next decade must expand into the consumer market space[1].They plan to accelerate adoption of their products and services into small scale manufacturing at home by providing more affordable and simple products. Their initiative has already been launched with introduction of the Cube™ in December, 2012 and can be followed on the cubify.com website [2].

Because the Cube™ was a responsive action to catch the leaders in the consumer space, it is critical that the company create a comprehensive technology roadmap (TRM) to help create a plan that supports the company's strategic objective.While it is urgent that the range of affordable printers is extended into homes, the initiative must be executed with a comprehensive plan that tightly ties the research and development activities to the consumer market drivers.This paper not only shares a direction for future alignment of activities, but it also uncovers barriers and gaps in the current technological platform.The TRM presented in this document could be used to communicate plans and gaps to other departments within 3D Systems and their development partners. The internal knowledge in their commercial 3D printer division must be leveraged to address market drivers that are different for the home and professional spaces.In part, the TRM could be used to internally communicate how the R&D efforts must be shifted to consider the market drivers in the consumer division with their clearly communicated requirements and demands.

"Technology roadmapping (TRM) is a comprehensive approach for strategy planning to integrate science and technological considerations into product and business aspects." [3] It is a tool that has been effectively used by others in the manufacturing, energy, and hi-tech industries [4].However, to effectively use this tool, it must be modified to fit the specific needs of the 3Dprinting business model.The literature reveals that there are many formats and types of TRMs. [5]Additionally, 3D printing is considered an emerging industry which adds to the complexity of developing a TRM [6]. This paper shares the research and models that have been developed to apply to the home 3D printer market division in creation of this TRM.

Background

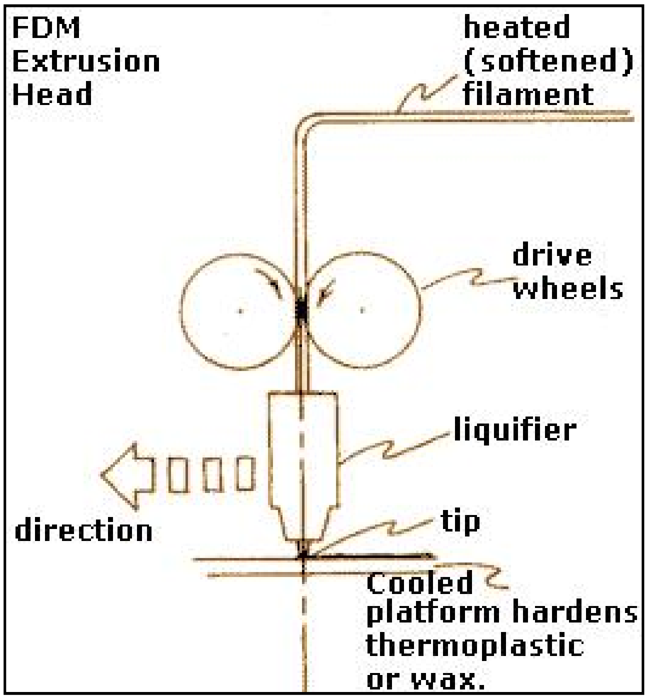
Three dimensional printing (3D printing) is the process of making a 3D solid object of any shape from a digital file.The technology and process was first developed by Charles Hull- a co-founder of 3D Systems; in 1984 [7]. He originally called it stereo lithography and obtained a patent in 1986.

In this process, a sheet of photosensitive polymer material is put down, and a laser or strongly focused beam of ultraviolet light is used to "draw" an object on its surface layer–by-layer.This "exposed" object then undergoes a "cross-linking" chemical reaction using curing techniques to become a solid object [8].

The next generation of three dimensional printing is based on a technology known as FDM or Fused Deposition Modeling, invented by Scott Crump in the late 1980's, and commercialized by 1990[9], through the company StratasysInc, which he co-founded[10].

The FDM process works on an "additive" principle by putting down material in multiple layers, in this process, a plastic wire is threaded through a heated extrusion nozzle, which can move in an X or Y direction. The nozzle iscontrolled by a precision servo motor.This setup is directly linked to a computer which has a three dimensional software package.Once the nozzle is heated, the plastic will melt and can be extruded or "pushed through" the nozzle in small beads. This melted material is used to form layers, which then are built up to make the model or part[11]. An image of an FDM process is shown in Figure1.

Figure 1: The FDM Process[11]



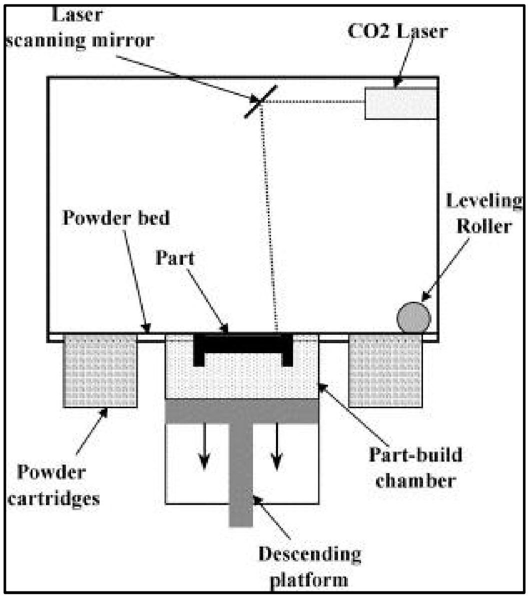
The FDM method has been popularized by manufacturers of 3D printers such as Stratasys, Ltd. Some of the main applications that FDM is used for include rapid prototyping as well as in the medical field for making prosthetic and dental molds.

Another widely used method has been Selective Laser Sintering (SLS) application. SLS Applications were originally commercialized by a company called Nova Automation, which was folded into another company DTM Corp, which then was eventually bought by 3D Systems to provide a secondary printing technology.

As the name suggests, a high intensity laser is used to fuse small particles of plastic or metal together into a desired three dimensional shape by scanning cross-sections generated from a 3D digital description of the part[12].These powders sit atop a "powder bed". As the sintering for each layer occurs, the "bed" is lowered by one layer of thickness and subsequent application of a new layer of material. The process is then repeated till the part is completed.

SLS is used for multiple applications like prototyping, toy manufacture etc. that require a high level of surface quality (finish) and resolution. Figure 2 shows the SLS process.

Figure 2: The SLS Process[12]



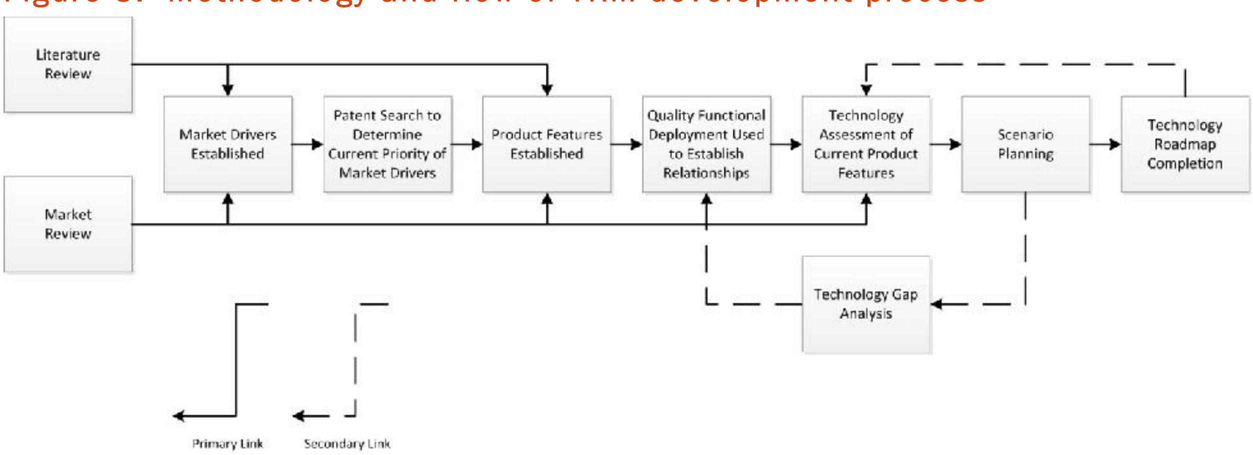
There has been a heavy level of consolidation within the three dimensional printing industry. 3D Systems and Stratasys have bought out a lot of smaller manufacturers such as MakerBot and DTM. This has led to a significant level of Intellectual Property ownership by the main players, which could stunt the growth of new commercial products introduced in the future.

This is another strong reason to create a concrete Technology Road Map – to outline the potential challenges due to manufacturing and IP consolidation, as well as attempting to chart a potential path forward.

Methodology

A methodological approach was used to manage the complexity in the development of this TRM.Figure 3 shows how the flow was iterative and required multiple literature searches, data analysis methods and modified tools.

Figure 3: Methodology and flow of TRM development process



Multiple data bases were searched for different required components. Capturing the knowledge from one database or source was not sufficient. While five (5) key word searches were performed to capture data for our analysis, additional documents were included and additional research performed to identify potential resources and further understand the technology. This additional research was alsoused to modify the data set used for market drivers and product features. Table 1 shows the key words as they were applied to the different drivers and components of the TRM.

Table 1: Literature review for small scale home 3D printing TRM.

TRM component	Research Area	Key Words	Data Bases (sources)
Market Drivers	Small Scale Manufacturing Forces	Additive Manufacturing, 3D printing, trends	Compendex, google scholar
Market Drivers	3D printing home consumer market drivers	3D printing, market, home, manufacturing, small	Google scholar, (3D systems website, Cubify, 3D Systems, Inc. 10K)
Market Drivers, Technologies	Patent Search	Market drivers listed in table 2 were used for the key words	USPTO
Product Features	3D printer features, content creation apps, authoring solutions	3D printer, feature, consumer, specification	Google, Google Scholar, (Cubify.com)
Format, presentation	TRM applications and tools	TRM, case study, format, type	Compendex, ETM 543 article reading list.

The initial focus was on the small scale manufacturing industry forces. Consumer 3D printing in the home is an emerging industry, which adds a level of complexity. The first search provided content to answer the question about where small scale manufacturing was headed in the future. The information was organized using a roadmap tool to model an emerging industry. The Science-Technology-Acceptance-Market (STAM) roadmap provided clarity for the search for the consumer market TRM drivers[13]. The Cube, introduced as the 1st product offering to the consumer market by 3D Systems was used as the starting point[2].

A content analysis of the 3D and small scale manufacturing market literature obtained from the two searches provided a list of market drivers. This list was prioritized by performing a keyword search of each of the market drivers in the USPTO patent databases. The time range was open and the criterion was then prioritized based upon the quantity of patent applications filed. A weight was then assigned to each of the market drivers. (See appendix A)

A technology assessment was performed on the literature obtained in the product feature search. The result of the assessment was a list of product features being used in the 3D printer market. This list was then grouped into product feature categories. A quality function deployment (QFD) matrix was created using the market drivers and product features. The goal of the QFD was to translates market drivers into prioritized product features[14][15]. Several scenarios were developed and discussed that expanded the consumer product line and identified future market opportunities.

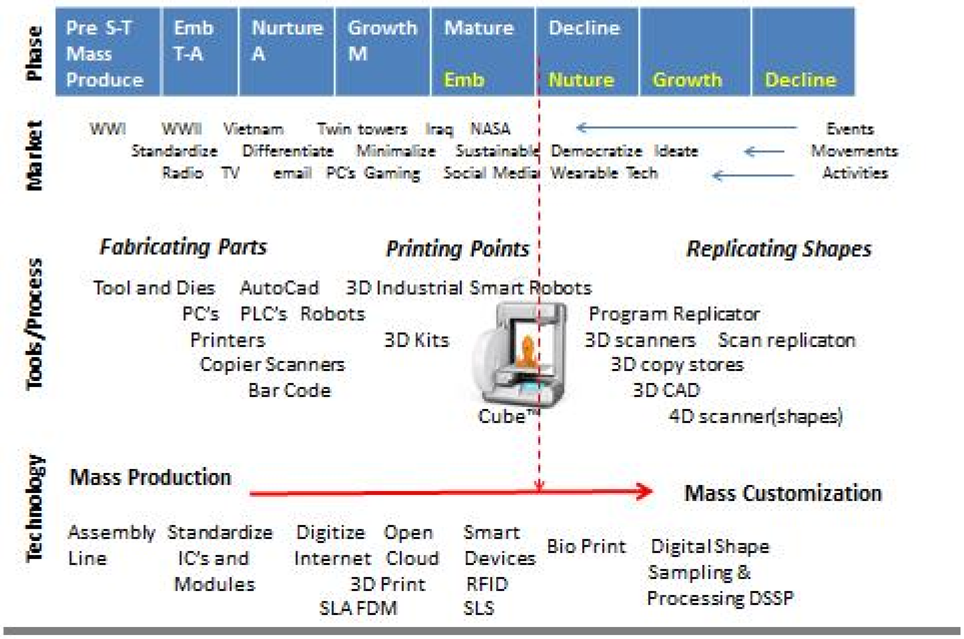
The type and structure of the TRM is flexible.Several formats were selected to communicate different messages.A master TRM with color coded linkages was developed.Then, several simplified TRM's were developed for targeted communication where the R&D department was considered a key audience.

Market Forces

3D printing is changing the manufacturing environment.Many authors are starting to believe that "a third industrial revolution" is coming in the form of small scale manufacturing[16][17].One author[18] attributes this trend to "the growing consumer focus on localism, craftsmanship and sustainability." Supporting this shift in culture and values, new manufacturing techniques allow for faster product innovations and changes.This trend will intensify as local manufacturers can quickly respond to changing local tastes of consumers.The third driving force is manufacturing cost reductions.Manufacturing efficiencies are being realized because "tools are changing in a number of remarkable ways[19]." Many advances in conventional production equipment will result in shrinking factories and the need for factory workers. The location of manufacturing will change from a many produced in few locations model to fewer being produced in many locations model. The literature supports that the manufacturing environment is facing another industrial emergence with the additive manufacturing technology[20]. The STAM model was selected to analyze these forces because it provides a framework for mapping science and technology-based industrial emergence[13]. The purpose of this analysis was to understand the nature and characteristic of the emergence phenomena as a basis for research for market drivers for the 3D home consumer market space.

"Emergence maps depict the dynamics of how industries evolve and develop, including growth, consolidation, maturity, decline and failure [13]." This framework is broken into 6 phases: precursor, embryonic, nurture, growth, mature and decline/renew.Each of these phases is applied to the emergence of technology.For example, the precursor phase is dominated by the emergence of science.The embryonic phase is dominated by technology emergence. The nurture phase is where these technologies start to be applied to the market.The growth phase is where the market is emerging and growing.The results of the Science-Technology-Application-Market (STAM) model analysis show that the industry is moving from the embryonic phase into the nurture phase.Manufacturing based upon mass production is in decline and the mass customization is somewhere between the embryonic and nurture phase as it is emerging.In terms of 3D printing this means that it is essential to get the "right" product to the consumer market.Figure 4 shows the forces as they are applied to the STAM Model.A dotted vertical line shows that the Cube™ is positioned at the beginning of the application phase. The movements such as standardization, sustainability concerns, democratization of designs and ideation are related to the market drives used for the development of the market drivers.

Figure 4: Manufacturing Industrial Emergence Roadmap[13]



STAM Model - Manufacturing Industrial Emergence Map

The horizontal slices of figure 2 starting with "market" depict the market demand, or pull dynamics.The section labeled tools and processes captured the value of the technology in terms of applications, products and services.The horizontal section labeled technology organized the data in terms of value creation.In general, the value creation provides the "push" dynamics and the market demand creates the "pull" dynamics for the product and service applications[13].The literature content discussing market trends, drivers and events, government policy, industry dynamics and movements and customer activities were organized according to precedence relationships.The horizontal dotted line in the figure shows that 3D printing is indeed impactingthe mass productionphase from maturity to decline and at the phase where mass customization is transitioning from the technology stage to the application stage.The Cube™ is positioned right at this transition point.Predicting future events that may pull the market could include the Olympics, NASA with space repair requirements or a future military conflict[21].Predicting other market drivers such as the need for smaller and lighter manufacturing, consumer's increased comfort with technology and 3D printing projects in the schools could be future consumer activities that also pull the market.The information obtained through this analysis was used as the basis to select key words specifically for market drivers impacting 3D printing products.

Market Drivers

Market Drivers are the primary forces that would drive adoption of 3D printers. The following attributes were selected as primary market drivers based on the literature and market review.

- **Total Cost**: The total cost describes the total amount of money that will be spent for the printer materials being used, software packages, as well as any external designs purchased[22]
- **Usability of Software:** This is a subjective driver, defining the ease of use of the software that is bundled with the printer. Due to the large variety of design formats, there are certain incompatibilities that exist between designs in one format being translated to a different one [23], [24], [25].

- **<u>Production Time</u>:** This describes the speed of manufacture of the product[26][27][28].
- **<u>Product Quality</u>**: This is defined as the finish and layering capability of the manufactured object, and how close to the original design, a manufactured object appears to be.
- **<u>Design Availability</u>:** Deals with the number of available design files for each model or part that are available to manufacture. This is important due to the potential for Intellectual Property issues, and was a main driver by number of citations[29].
- **<u>Safety</u>:** Safety as a market driver refers to any literature or patent references that had an improvement impact on the manufactured product. For example, this would refer to whether the object or model had an increase in the safety level, or a reduction in the smell of materials used etc. [24].
- **<u>Types of Materials Available</u>**: This refers to the availability of materials for 3-D printing. From the patent review, this was one of the highest referenced market drivers, therefore one of the most focused on areas from a development perspective[30].
- **<u>On Demand Manufacturing</u>**: Refers to the ability to manufacture in series of one. Effectively – at the press of a button. This is an attribute that driver that, although was not really cited as being as significant as others in the patent review; was very highly trending in the literature review with multiple articles citing the market strategy of many 3D printing companies being dependent on this factor[31]
- **<u>Customization</u>**:Customization refers to the degree to add personalization to the manufactured object [32][33].
- **<u>Reverse Engineering</u>:** This driver referred to the ability of the printer to be able to potentially "break down" an object into a digitized map, which could then be used to build other objects that would be identical to the original [29].
- **<u>Product Size</u>**: Describes the maximum size that an object can be manufactured [34].

Product Features and Technology Assessment

A technology assessment matrix was completed for the product features available in the marketplace today. To complete this assessment the products of Stratasys, Makerbot, and 3D Systems were benchmarked across their commercially available products in the personal, professional, and industrial product spaces. Company websites and public datasheets were used for this benchmark activity.To conduct this assessment technical brochure for the various products were reviewed online for the following product features.

- **<u>Materials</u>**: Materials is defined as the type of physical matter used for the 3D process. Current generation 3D printers offer the following construction materials:
  - **ABS**: Acrylonitrile Butadiene Styrene. The material is created by combining three different molecules. ABS was first discovered in WW2 and was used as an alternative to rubber. Properties of ABS include high heat resistance, high impact resistance, good flow, high gloss, good dimensional stability. Disadvantages of ABS include limited resistance to weathering, moisture and chemical resistance. ABS is also flammable at high heats with high smoke generation [35].
  - **PLA**: Polylactic Acid. PLA is made from plants and is biodegradable. PLA [36] "can be processed like existing thermoplastics into colored or transparent material and can be manufactured from renewable resources such as maize and sugarcane." One primary use for PLA today is for packaging food. PLA is biodegradable and can be composted. PLA is generally more rigid than ABS. One main disadvantage to PLA is its low melting point. PLA can start to deform at temperatures

common to many applications (e.g. sitting in a hot car [37]). PLA comes in a variety of colors and is glossy finishes.

- ABS and PLA are the two most common materials currently being offered for small scale manufacturing in the home. Both of these materials become flexible for deposition when headed then return to solid form once cooled. Materials used for 3D printing need to [37] "to pass three different tests; initial extrusion into Plastic Filament, second extrusion and trace-binding during 3D Printing process, then finally end use application." ABS is typically the best choice for making objects with interlocking parts as the flexibility of the material makes it easier to work with. ABS is soluble in Acetone, which allows users to connect (weld) pieces together using the Acetone to bond the two different pieces. Both PLA and ABS can be machined and sanded after cooling. PLA is more rigid than ABS, making intricate complex interlocking components more difficult to connect and work with. Table IV summarizes the ABS and PLA comparison.

Table 2: ABS and PLA Comparison[38]

ABS	PLA
Extrusion Temp: ~225°C	Extrusion Temp: ~180-200°C
Requires headed printer bed	Benefits from heated printer bed
Works well without cooling while printing	Benefits from cooling while printing
Adheres to Polyimide tape	Adheres well to most surfaces
Tighter filament tolerances (generally)	Well calibrated machine can produce finer detail
Prone to cracking, delamination, and warping	Prone to curling of corners and overhangs
More flexible	More brittle
Can be bonded using adhesives or solvents (Acetone or MEK)	Can be bonded using adhesives
Fumes are unpleasant in enclosed areas	More pleasant smell when extruded
Oil Based	Plant Based

- **Speed**: Speed describes how fast the 3D printer deposits material while making objects. Speed is listed in manufacture datasheets as mm/sec. Current generation printers, in the home consumer category, are in the 100 mm/sec range. Makerbot's Thing-o-matic, released in 2012, supports typical speeds of 30mm/sec [39]. The Makerbot 2, released in 2012 boasts speeds of 80mm/sec [40].
- **Price/Cost:** The price of the initial hardware purchase and bundled software and starter materials. Does not include on-going material costs, maintenance, or other fees.
- **Software:** The software product feature describes the ease of use of the system for the typical home consumer. Current generation printers come with bundled software which supports the various 'standard' file formats.
- **Surface Finish (Resolution & Color):** Resolution, or fineness of features, is directly related to the perceived quality of the printed object. A finer resolution results in smoother more detailed object features. Resolution for 3D printers is measured in microns or mm and represents the minimum height of material the printer is capable of depositing. Current state of the art home printers are typically able to deposit layers in the .1mm to .3mm (100 micron to 300 micron) range [41]. Current home printers are typically capable of printing between 1 and 3 monochrome colors at a given time, meaning they are not currently able to mix colors. Color ranges are vast given the ability to easily color the polymers (especially PLA as described above). Colors are limited to manufacturer color offerings.
- **Scanning Ability**: Scanning ability allows the user to create replicas of existing objects. A scanner is used to create a digital design file which can then be used directly or manipulated by the user. This allows users to 'reverse engineer' objects to avoid the need of recreating complex drawing or obtaining digital design files

from the original sources. Currently, [42]“a large obstacle to 3D printing adoption is the difficult in producing the 3D models required.”

- **<u>Print Envelope:</u>** The print envelope is simply the maximum size (volume) object which can be produced by the 3D printer. A larger print envelope requires a larger 3D printer. Current generation home printers are capable of print envelopes ranging from a few inches cubed to about one foot cubed. The current generation Cube™ is capable of 5.5”x5.5”x5.5” print volume[41].
- **<u>Safety</u>**: In addition to the obvious safety features (e.g. unit doesn’t shock the user, or cause other harm), the process of depositing the materials should be safe to the consumer. As mentioned above, heated materials can produce fumes and these fumes may be harmful to the consumer. Current generation home printers do not utilize any special venting or vapor capture. As additional materials options are available and home printing becomes more mainstream, safety could become a concern.

Using the information listed in the product brochures, an assessment table was created for each of the 3D printing categories.Table 3 illustrates a sample assessment matrix that was compiled with the product features listed in the table 2 above. The other tables for the professional and industrial printers are listed in the attached *Appendix C: Technology Assessment Tables*.

Table 3: Sample Technology Assessment Table

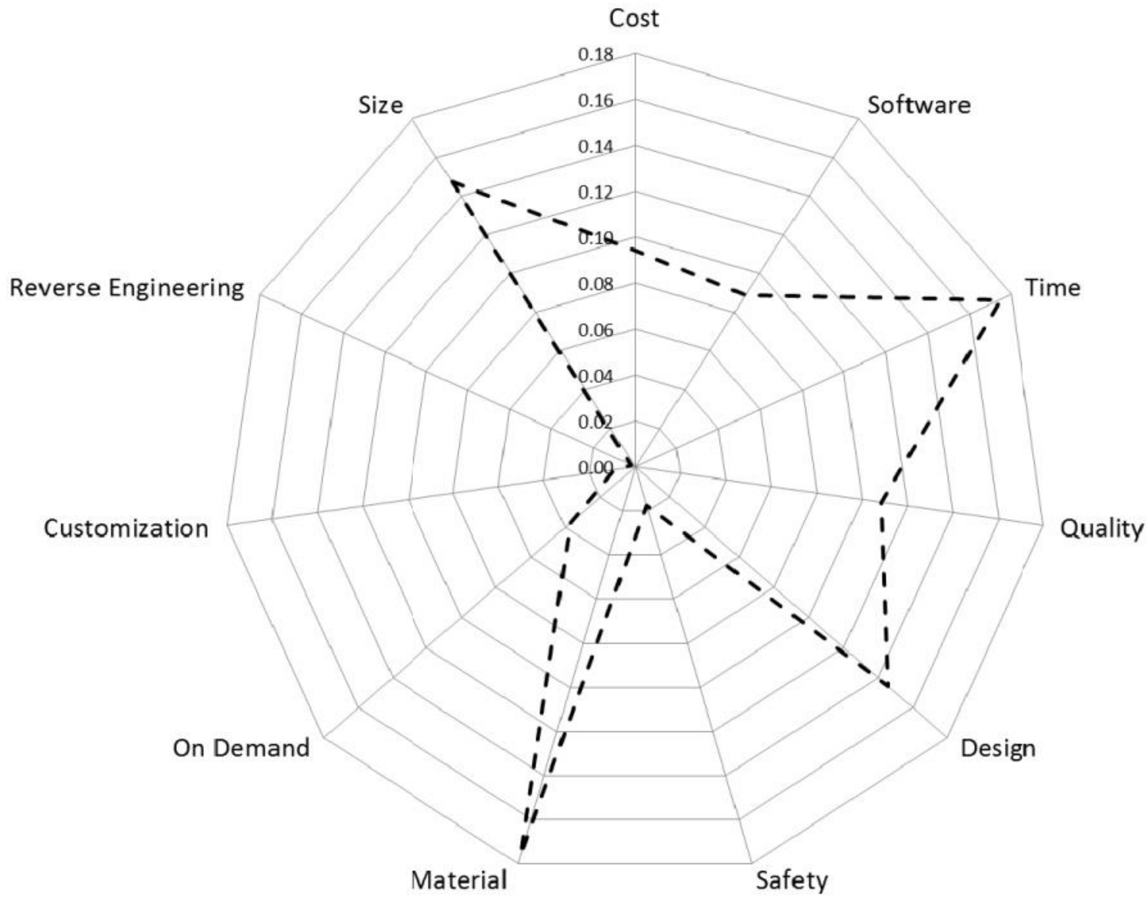
		Personal												
		Cube	Cube X	Cube X	Cube X	ProJet 1000	ProJet 1500	ProJet 160	ProJet 260C	Replicator 2	Replicator 2X	Mojo	uPrintSE	uPrint SE Plus
	System Manufacturer	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	Makerbot	Makerbot	Stratsys	Stratsys	Stratsys
Product Features														
Materials	Number of Plastic Materials	2	2	2	2	1	1	1	1	2	2	1	1	1
	Metal	No	No	No	No	No	No	No	No	No	No	No	No	No
Software	Support	No	No	No	No	No	No	No	No	No	No	Yes	Yes	Yes
	Bundle	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Speed	in^3/s or in/hr		0.000915	0.000915	0.000915	.5 in/hr	.8 in/hr	.8 in/hr	8 in/hr					
Surface Finish	X (DPI)	-	-	-	-	1024	1024	300	300	-	-	-	-	-
	Y (DPI)	-	-	-	-	768	768	450	450	-	-	-	-	-
	Z (DPI)	-	-	-	-	-	-	-	-	-	-	-	-	-
	Layer Thickness (in)	0.0079	0.0039	0.0039	0.0039	0.0040	0.0040	0.0039	0.0039	0.0039	0.0039	0.0070	0.0100	0.0100
	Colors	1	1	2	3	1	6	1	Basic CMY	1	2	1	1	1
Scanning Ability	Bundle	No	No	No	No	No	No	No	No	No	No	No	No	No
Print Envelope	X (in)	5.50	10.75	9.00	7.30	6.75	6.75	9.30	9.30	11.20	11.20	5.00	8.00	8.00
	Y (in)	5.50	10.75	10.75	10.75	9.00	9.00	7.30	7.30	6.00	6.00	5.00	6.00	6.00
	Z (in)	5.50	9.50	9.50	9.50	8.00	8.00	5.00	5.00	6.10	6.10	5.00	6.00	6.00
	Volume (in^3)	166.38	1097.84	919.13	745.51	486.00	486.00	339.15	339.15	409.92	409.92	125.00	288.00	288.00
Safety	Certification	No	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes

Key	
	Info Not Available

Quality Functional Deployment

To correlate the market drivers to product features a Quality Functional Deployment matrix [14][15]was utilized.The purpose of the QFD was to connect the market drivers to the product features and establish priorities of each of the product features.To complete this analysis the priorities of the market drivers were established by data mining the United States Patent and Trademark database (www.uspto.gov).This method was used to essentially capture the commercial interest of the each market driver and assign the priority for the driver.The attached Appendix A, titled *Patent Mining Methods*, identifies the process that was utilized to conduct the analysis including search keywords and dates for searching. Figure 6 illustrates the prioritization and influence that the driver has on the 3D Printing industry.

Figure 5: Market Driver Radial Plot



Using the priorities from the patent mining on the Market Drivers a Quality Functional Deployment Matrix was populated to correlate the **market drivers** to the p**roduct features** identified in the technology assessment tables created previously.The goal of this analysis was to transform the priorities of the **market drivers** to **product features** and apply a prioritization to the product feature.To complete this, the market drivers where listed across the top row of the QFD illustrated in figure 10.The bottom row identifies the priority that resulted from the patent mining exercise.The product features identified previously are listed on the left column of the QFD matrix.

The first step to complete the matrix is to identify a goal for each of the product features. The options for this section were to maximize, minimize, or set a target for the development process.For example the driver of *cost* and *production time* would have a minimizing goal, whereas *material availability* would have a maximizing goal.The following key illustrates the symbols that were used in this section of the QFD table.

Figure 6: Direction of Improvement Key

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

The second step of the QFD is to identify the correlations between the different market drivers, identifying the influence that each market driver has on the alternate market drivers.This aspect of the matrix is important because it identifies how minimizing of the cost driver can negatively impact the performance of the alternate market drivers.The following key identifies the different symbols that were used to identify correlations used in the QFD matrix.

Figure 7: Correlations Key

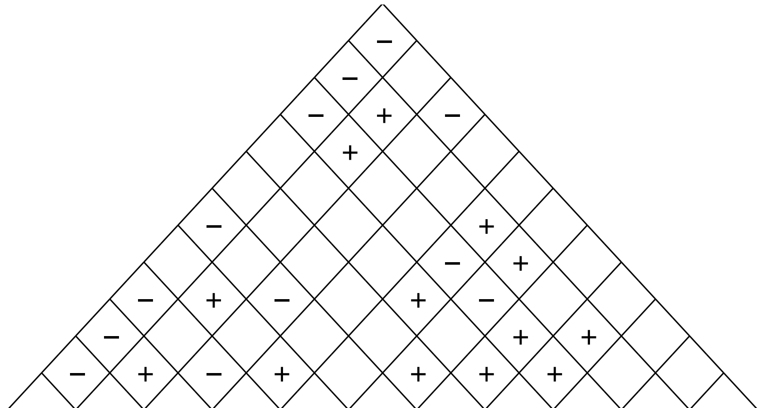
Correlations	
Positive	+
Negative	−
No Correlation	

The third step is to identify the relationships that each market driver has with the product features identified. For this assessment a three level scale scoring was utilized, establishing whether the item has a strong relationship, inverse relationship, or no relationship between the factors.The following figure identities the symbols that were used for the QFD matrix.

Figure 8: Relationships Key

Relationships	
Strong	●
No Relationship	○
Inverse	▽

The final step of the QFD assessment is to then transfer the market driver priorities to the Product Feature priorities. To complete this step, the relationships were transposed to either a 1=strong, 0=No Relationship, or -1=inverse relationship.Assigning these numerical values the priorities can be transposed onto the product features.The attached appendix C titled *Quality Functional Deployment and Product Feature Prioritization* illustrates the process that was used to transpose these items. Figure 9 shows the populated QFD matrix and the corresponding relationships that where built from the steps identified above.

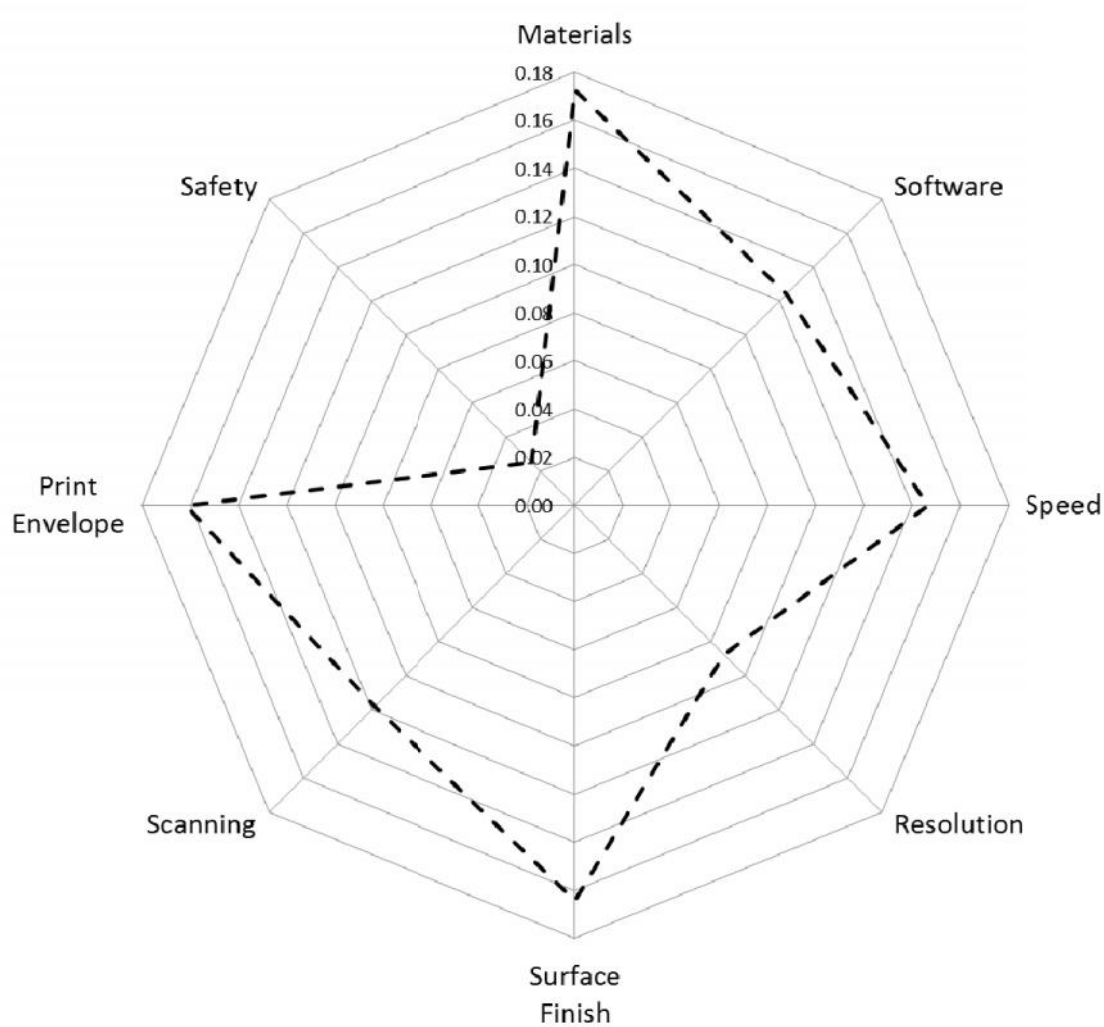


Row #	Product Features \ Market Drivers	Total Cost	Usability of Software	Production Time	Product Quality	Design Availability	Safety	Material Available	Localization (On Demand)	Customization	Reverse Engineering	Product Size	Relative Weight
	Column #	1	2	3	4	5	6	7	8	9	10	11	
	Direction of Improvement	▼	▲	▼	▲	▲	▲	▲	▲	▲	▲	▲	
1	Materials	▽	○	●	●	●	●	●	●	●	●	○	17.23%
2	Software	▽	●	●	○	●	○	○	●	●	●	○	12.43%
3	Speed	▽	●	●	●	○	○	○	●	○	○	●	14.66%
4	Resolution	▽	○	●	●	○	○	○	○	●	●	○	8.74%
5	Surface Finish	▽	○	●	●	○	●	●	○	●	●	●	16.43%
6	Scanning	▽	●	○	○	▽	○	○	●	●	●	●	11.81%
7	Print Envelope	▽	○	●	●	●	○	○	●	●	●	●	16.18%
8	Safety	▽	○	○	○	○	●	○	○	○	○	○	2.51%
	Relative Weight	9.41%	8.90%	17.47%	10.81%	14.56%	1.74%	17.64%	3.70%	0.90%	0.17%	14.73%	

Figure 9: Quality Functional Deployment

The following radial plot identifies and compares the priorities of the product features from the above QFD. As indicated by the plot the product features with the highest priority are material, speed, surface finish, and print envelope. This analysis indicates that the company should work on these higher hitters to get the most benefit from their R&D activity.

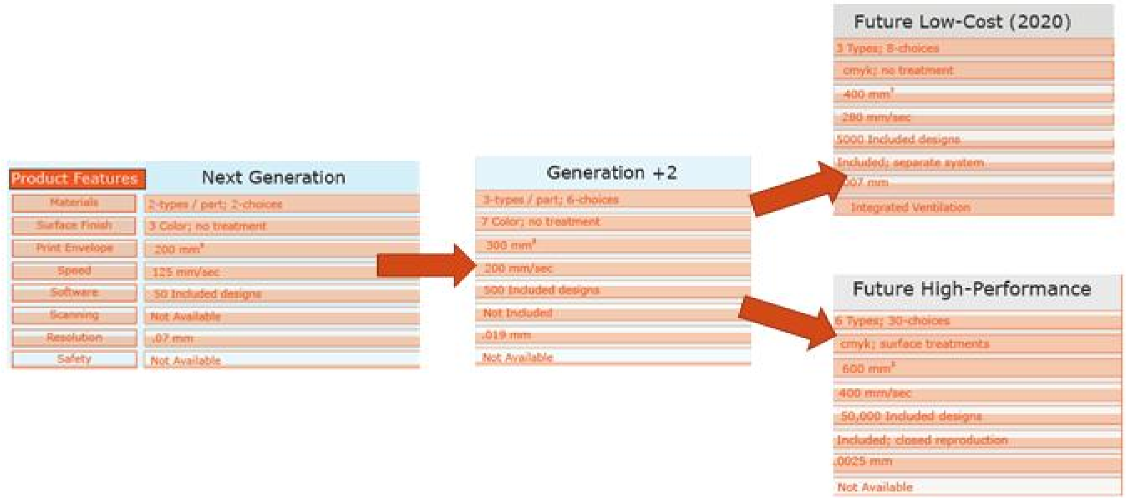
Figure: 10: Product Feature Prioritization



Technology Forecasting and Scenario Analysis

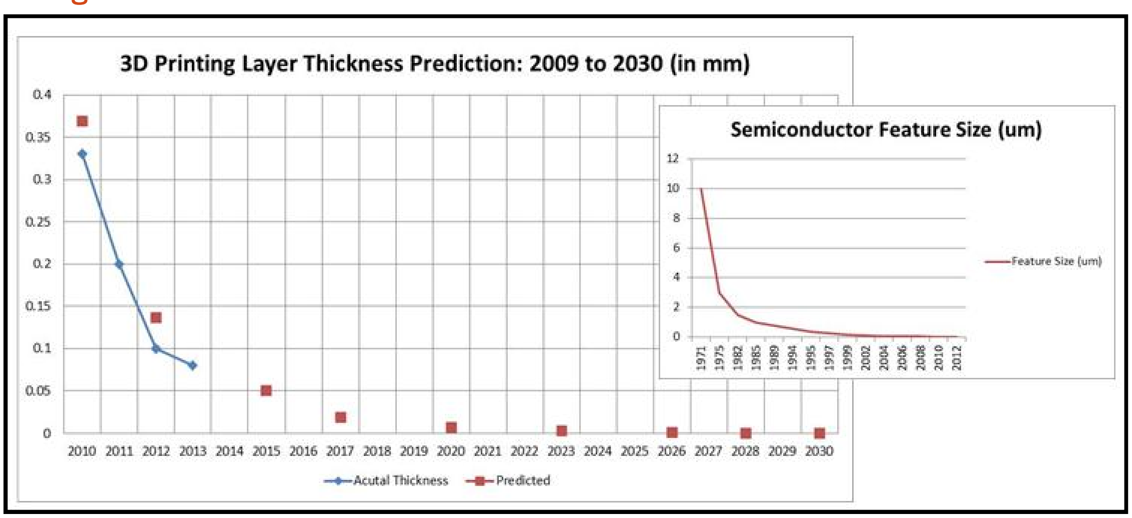
Based on market research, the team created two future scenarios for the product line. A low cost (LC) product line would be required in the future (estimated 2020) which would maintain current state of the art performance metrics while being tailored to the mass market home consumer. A high performance (HP) product line would continue to push the envelope of at home manufacturing performance for the more sophisticated users. The HP product line would provide a platform development opportunity which could be leveraged by the LC product line, allowing the LC line to benefit from the HP R&D investments. The product line split would take place after two generations (2020, Generation +2) of the existing product once essential market drivers could be met (i.e. resolution, speed, colors, etc.). This splitting product line is shown visually in Figure11.

Figure11: Product line vs. time showing product line split off for LC and HP



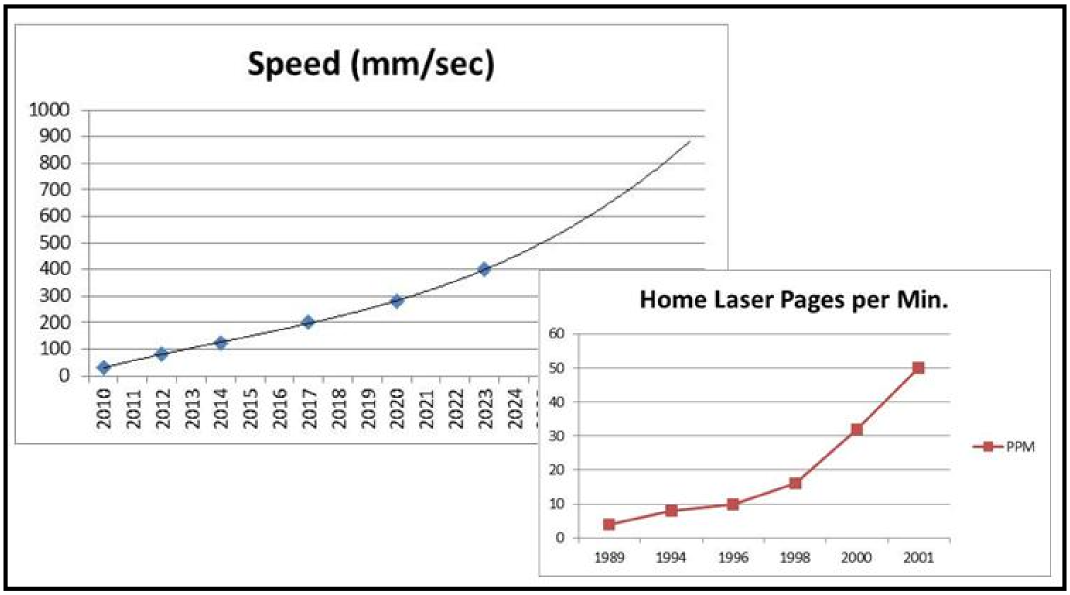
Printer ***resolution*** was forecasted using an exponential trend based on actual thickness improvements and benchmarked against semiconductor feature size from 1971 to 2012[43][44]. Actual 3D home printer resolution trends from 2009 to 2013 seem to be following a similar trend to that of early semiconductor feature size. The trend was used to forecast future resolution out in time. Figure12 shows the actual vs. predicted trend for layer resolution. The predicted values were used for forecasting future product requirements.

Figure12: Layer thickness (resolution) actual (2009 to 2013) vs. predicted using semiconductor benchmark



Speed was forecasted using pages per minute trends in home laser printing[45]. Home laser printing speeds have increased from <10pages-per-minute (PPM) in the late 1980s to over 50 ppm in 2001. This trend was used as a benchmark for predicting 3D printing speeds. The power curve for home laser PPM along with predicted 3D printing speed can be seen in Figure13.

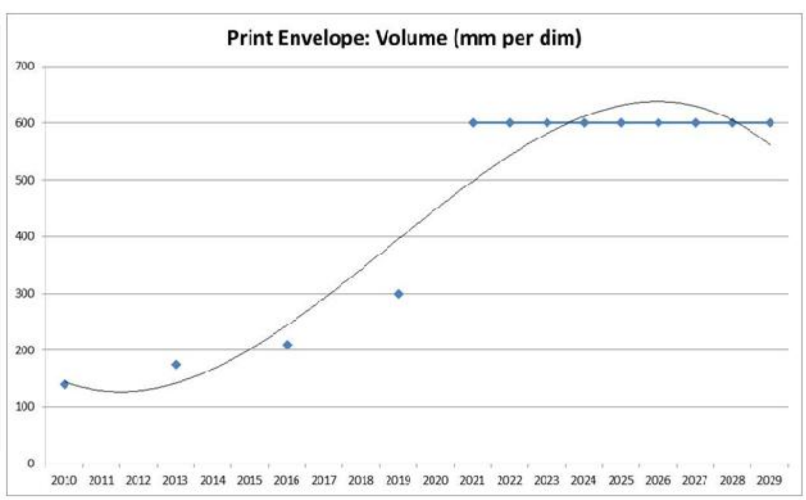
Fig 13: Predicted 3D printings speeds (mm/sec, top left) using home laser PPM speed trends (bottom right)



Print envelope/volumewas forecasted by looking at the maximum size the team felt the average consumer would need in terms of objects and the maximum size in terms of the actual printer appliance they could tolerate in their home. This prediction was somewhat subjective as research was limited in this area. Existing 3D printer envelopes were used to establish a somewhat linear trend which was capped off at 24"x24"x24". The feeling was that most objects a consumer would need to make would be less than this size. A prediction was also made that most consumers could tolerate an appliance roughly the size of a standard cooking oven, which also has an internal cooking area/volume of 24"x24Xx24". Figure14 shows the existing volumes (left) and the predicted volumes with capped line (right).

Fig 14: Print volume forecast

2010	Thing o matic	Volume (mm per dim)
2011	Cube	140
2012	Makerbot 2	
2013	sPro	
2014	Cube +1	175
2015		
2016		
2017	Cube +2	210
2018		
2019		
2020	Cube +3	300
2021		
2022		600
2023	Cube + 4	600



Based on the forecasts above, future product features were derived. Next generation, current Cube™ +1, are shown in Figure15. The product will feature a 3 color surface finish, an enlarged print envelope, faster speed, better resolution, and other improvements.

Figure15: Next Generation Product Features

Product Features	Next Generation
Materials	2-types / part; 2-choices
Surface Finish	3 Color; no treatment
Print Envelope	200 mm³
Speed	125 mm/sec
Software	50 Included designs
Scanning	Not Available
Resolution	.07 mm
Safety	Not Available

Current Generation +2 product features are shown in Figure16. This printer will offer more material choices, speeds of 200mm/sec, and resolutions of .019mm.

Figure16: Generation + 2 Product Features

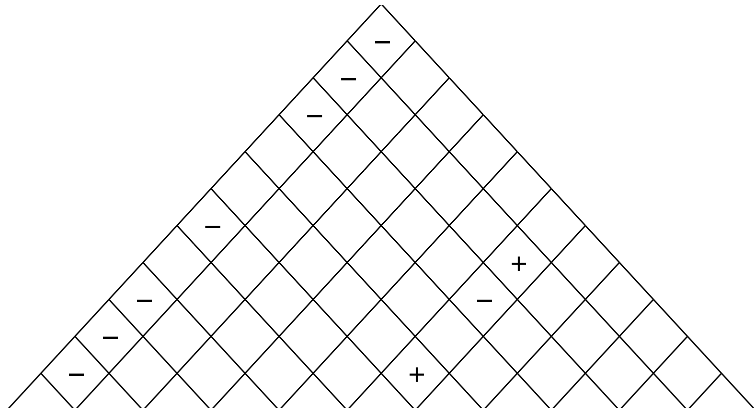
Product Features	Generation +2
Materials	3-types / part; 6-choices
Surface Finish	7 Color; no treatment
Print Envelope	300 mm³
Speed	200 mm/sec
Software	500 Included designs
Scanning	Not Included
Resolution	.019 mm
Safety	Not Available

Two separate QFDs were completed to help guide the LC and HP product line product features. These QFDs are shown in Figure18 and 19 respectfully. Based on the QFD analysis, the LC product line would focus on low cost, shown as "Total Cost", and safety. The assumption for the LC line would be that the other drivers and product features would be considered "good enough" for the average consumer and only incremental improvements would be required. Cost and Safety would become the primary drives for the LC line. For the HP line, the top product features will be materials, surface finish, and print envelope. A summary of the LC and HP product features are shown in Figure17.

Figure17: Future (2020) LC and HP product features

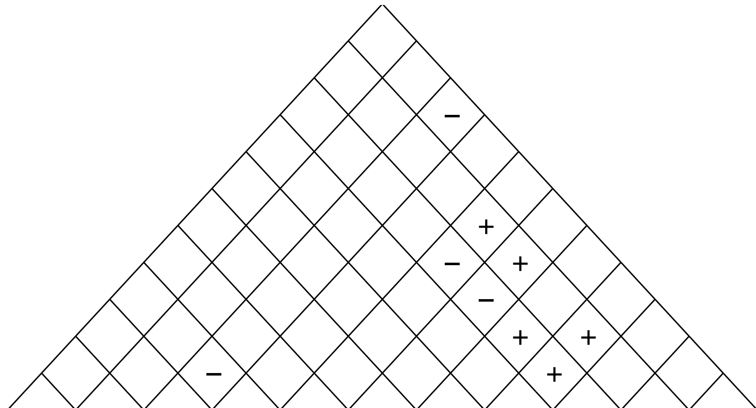
Product Features	Future Low-Cost (2020)	Future High-Performance
Materials	3 Types; 8-choices	6 Types; 30-choices
Surface Finish	cmyk; no treatment	cmyk; surface treatments
Print Envelope	400 mm^3	600 mm^3
Speed	280 mm/sec	400 mm/sec
Software	5000 Included designs	50,000 Included designs
Scanning	Included; separate system	Included; closed reproduction
Resolution	.007 mm	.0025 mm
Safety	Integrated Ventilation	Not Available

Figure18: Low Cost QFD



Row #	Market Drivers / Product Features	Total Cost	Usability of Software	Production Time	Product Quality	Design Availability	Safety	Material Available	Localization (On Demand)	Customization	Reverse Engineering	Product Size	Relative Weight
	Column #	1	2	3	4	5	6	7	8	9	10	11	
	Direction of Improvement	▼	▲	▼	▲	▲	▲	▲	▲	▲	▲	▲	
1	Materials	▽					●						18.18%
2	Software	▽					○						9.09%
3	Speed	▽					○						9.09%
4	Resolution	▽					○						9.09%
5	Surface Finish	▽					●						18.18%
6	Scanning	▽					○						9.09%
7	Print Envelope	▽					○						9.09%
8	Safety	▽					●						18.18%
	Relative Weight	50.0%					50.0%						

Figure19: High Performance QFD



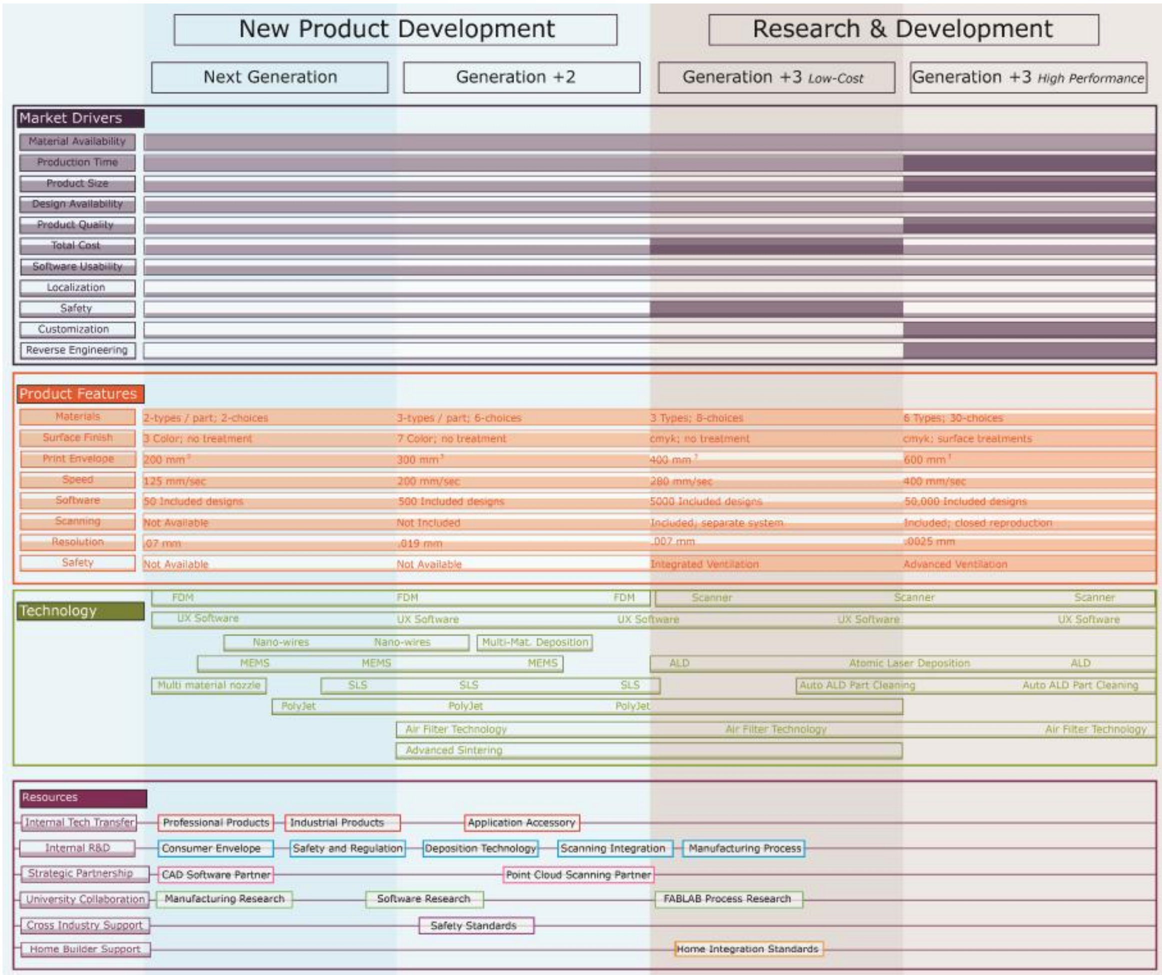
	Column #	1	2	3	4	5	6	7	8	9	10	11	
	Direction of Improvement	▼	▲	▼	▲	▲	▲	▲	▲	▲	▲	▲	
Row #	Market Drivers / Product Features	Total Cost	Usability of Software	Production Time	Product Quality	Design Availability	Safety	Material Available	Localization (On Demand)	Customization	Reverse Engineering	Product Size	Relative Weight
1	Materials			●	●					●	●	○	14.81%
2	Software			●	○					●	●	○	11.11%
3	Speed			●	●					○	○	●	11.11%
4	Resolution			●	●					●	●	○	14.81%
5	Surface Finish			●	●					●	●	●	18.52%
6	Scanning			○	○					●	●	●	11.11%
7	Print Envelope			●	●					●	●	●	18.52%
8	Safety			○	○					○	○	○	0.00%
	Relative Weight			20.0%	20.0%					20.0%	20.0%	20.0%	

Platform Based Technology Road Map

A Technology Road Map links insights from the Market Driver Analysis, Product Feature Availability Assessment, and Technology Assessment to Resources and upcoming product generations. The process of assembling the Technology Road Map is an expansion of the aforementioned methods section by shuffling the content around. There are two kinds of variables present in the TRM; flexible and stable variables. The stable variables have a degree of known certainty, whether in specification or in platform release. Flexible variables are indicated by the ability adjust activation and timing. In the TRM created for 3D Systems, an example of a stable/flexible relationship is found in the High Performance Future Generation platform. It is necessary for this platform to support at least 6-types of materials with at least 30 choices of sub materials; e.g. plastic, metal, sand, clay, concrete, plaster; each with variable types, this is a stable variable. Supporting this feature is Multi-Material Deposition Technology and Advanced Laser Deposition Technology; this is flexible. By identifying the stable variable, the flexible variable becomes solidified by its linkage. To further support the technology, a Deposition Research Team from the R&D department will be employed as a resource; also a flexible variable until linked to a stable chain. Once all variables are inputted to the TRM the processes is iterative and the TRM shifts until all relationships and needs are identified and met; all lone variables are eliminated from the map.

Below, Figure 20lays out the relevant variables for the TRM. The color level in each of the blocks signifies a priority, established in the QFD process. Although relationships have informed positions, no linkages have been represented.

Figure 20: Platform Based Technology Roadmap: Blanket Structure



TRMs are often several if not hundreds of pages long. The visual language of strategy and innovation is still not fully understood. With the right framework and guidance, the TRM is an effective and desirable strategy communication tool[46]. Often times if all of the information is laid out on one map, as it is in Fig. 21below,it is not practical as a communication tool as it is hard to read. While it is clear that the general direction of the technology momentum is forward it is hard to establish which variables are linked and in what order. All of the information needed to communicate to various groups is present and only needs to be uncovered.

It is clear to see there is variety in the kinds of stories that can be told. In this TRM a combination of the *Knowledge Asset Planning* and *Integration Planning* approach has been used to convey a variety of messages[4]. Each format lends to a variety of messages that can be communicated. In this case, one message could be to a specific resource; the Internal Technology Transfer Team might need to know that SLS and PolyJet technology needs to transfer from the industrial and professional divisions into the consumer platforms within the next generation. This could also be a communication tool for the product planning group; needing to know that Generation +3 requires many new innovations, the TRM can communicate all features that will need to be included and potential technologies that support those features. This information is necessary in support planning and product launching.

Figure 21: Platform Based Technology Roadmap: All Linkages for Planning

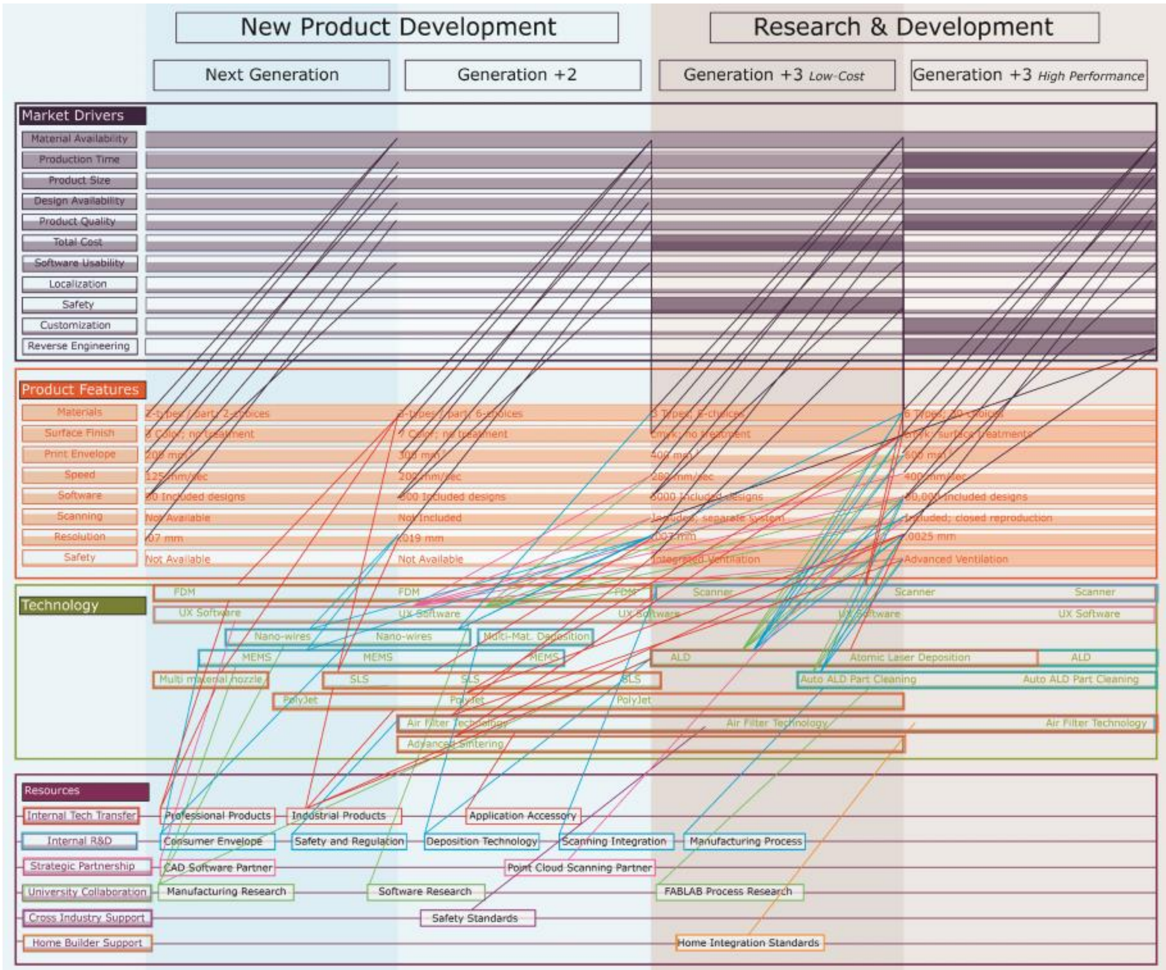
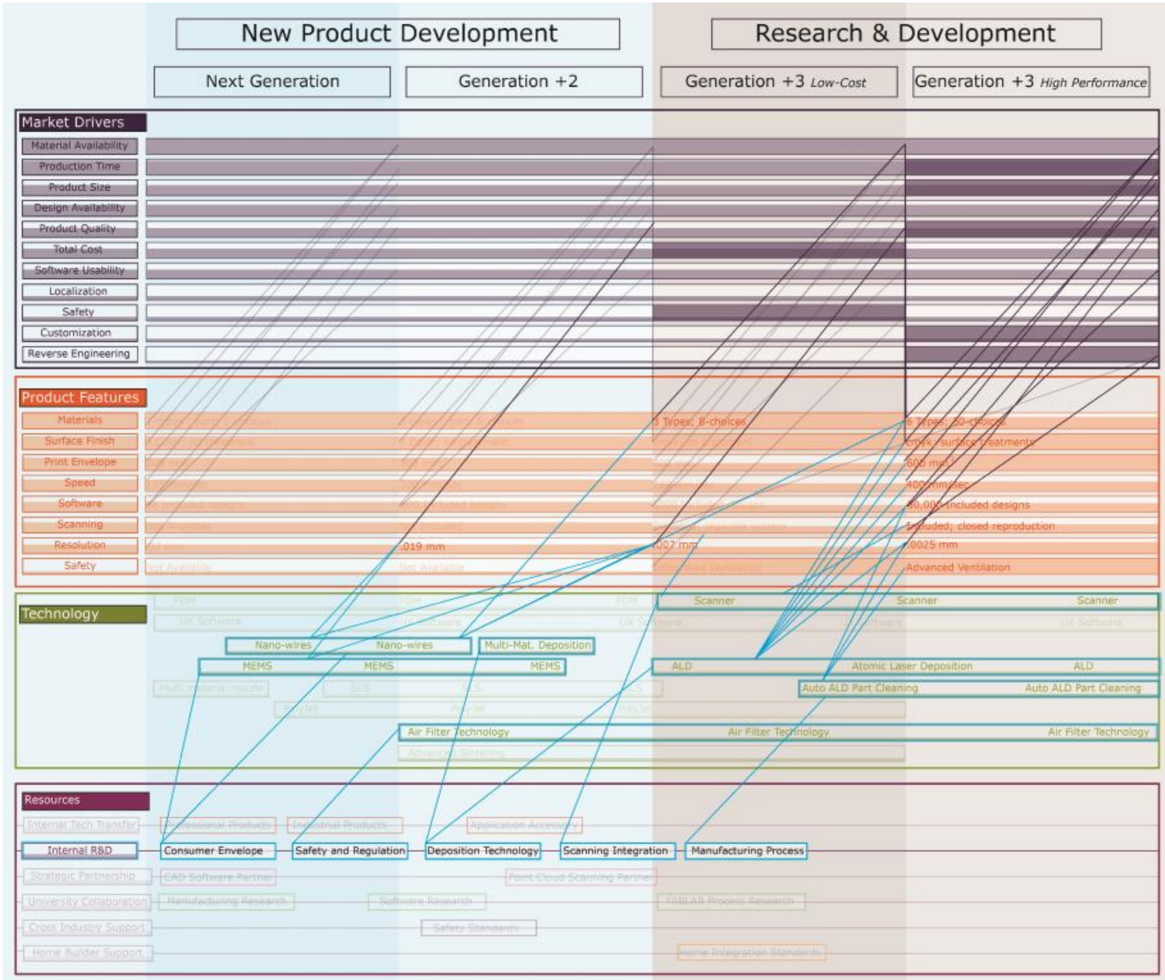


Figure22 belowis an example of how the TRM would be used to communicate to the R&D Team the kind of Research and Development as well as the cadence and duration of the projects to support the next 4 generations of product platforms, through linked technologies, product features, and market drivers. Laying out a plan in this way simplifies the intricacies of related variables. This also highlights the importance of project timing and the effects of shifting timing and order around.

Figure 22: Platform Based Technology Roadmap: R&D Team Planning



Conclusion

Often times the amount of information needed to manage multiple product lines, technology initiatives, resources, and changes in market drivers muddle the strategy and confuses the planning process. The Technology Road Map is a keen tool for first unloading all of the relevant information, disregarding the unrelated information, and communicating a message through a variety of paths.

Through the methodological development of the TRM, 3D Systems has a clear and deep understanding of the competitive landscape, internal strengths in technologies, and associated gaps/opportunities, which need to be addressed to further solidify their place in the consumer 3D printing market. Literature review and patent analysis established and prioritized Market Drivers. A detailed product roadmap was developed using the product features priorities established in the QFD Matrix along with forecasting trends using similarly high-end tech products as a trending benchmark.

A comprehensive TRM was prepared which helped visually communicate the relationship between R&D resources (internal and external), technology projects, product features, and market drivers. These graphical relationships can be used as a communication tool for the various functional groups within an organization. In this TRM, it is clear that 3D Systems has the technology and an opportunity to remain at the forefront of consumer technology by simply transferring existing technologies from the internal professional and industrial divisions. Laying the plan for the technology transfers ensures that the right parties start collaborating at the right time. With this clarity of strategy, 3D Systems may determine that a new Internal *Technology Transfer Team* should be established to ensure a frequent and successful internal collaboration between product divisions. After all, the TRM does not make the decisions; it allows the decision makers to be better informed.

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Appendix A – Patent Mining Methods

The patent mining procedure was completed utilizing the advanced search on the United States Patent and Trademark full text and image search [32].

To complete analysis the database was queried utilizing the criteria in the following table. The number of patents returned was then recorded in the table.

Table A.I: Patent Search Criteria

Search Criteria	Search Range	Date Searched	Number of Patents Returned
"3d Printing"	1976 to Present	7-30-2013	349
"3d Printing" and Cost	1976 to Present	7-30-2013	168
"3d Printing" and Software	1976 to Present	7-30-2013	159
"3d Printing" and Time	1976 to Present	7-30-2013	312
"3d Printing" and Quality	1976 to Present	7-30-2013	193
"3d Printing" and Design	1976 to Present	7-30-2013	260
"3d Printing" and Safety	1976 to Present	7-30-2013	31
"3d Printing" and Material	1976 to Present	7-30-2013	315
"3d Printing" and On Demand	1976 to Present	7-30-2013	66
"3d Printing" and Customization	1976 to Present	7-30-2013	16
"3d Printing" and "Reverse Engineering"	1976 to Present	7-30-2013	3
"3d Printing" and Size	1976 to Present	7-30-2013	263

The patent responses from the above queries were then placed in the following table and analyzed with respect to the entire data set. The patent prioirty was established by dividing the keyword search by the total number of 3D printing patents. The patent priotity was then normalized by taking each patent priority and dividing it by the summation of all of the patent priorities from the data set. The following tables and expressions identify the results and formulas utilized for this analysis.

Table A.II: Patent Search Results

	Patent Search Keyword										
	Cost	Software	Time	Quality	Design	Safety	Material	On Demand	Customization	Reverse Engineering	Size
Number of Patents "Keyword"	168	159	312	193	260	31	315	66	16	3	263
Total Patents "3D Printing"	349	349	349	349	349	349	349	349	349	349	349
Patent Priority	0.481	0.456	0.894	0.553	0.745	0.089	0.903	0.189	0.046	0.009	0.754
Normalized Value	0.094	0.089	0.175	0.108	0.146	0.017	0.176	0.037	0.009	0.002	0.147

ExpressionA.1: Patent Priority Formula

$$P_i = \frac{K_i}{T}$$

Where:

P_i: $Patent\ Priority\ (Percentage)$for feature i

K_i: $Keyword\ search\ appearance\ count$for feature i

T: $Total\ number\ of\ patents\ searched\ (i.e.349)$

i: $Product\ feature\ of\ interest\ (i.e.Cost, Software)$

ExpressionA.2: Normalized Value Formula

$$NV_i = \frac{K_i}{\sum_1^N P_j}$$

Where:

NV_i: $Patent\ Priority\ (Percentage)\ for\ feature\ i$

K_i: $Keyword\ search\ appearance\ count\ for\ feature\ i$

P_j: $Patent\ prioirity\ for\ feature\ j$

N: $Total\ number\ of\ prodcut\ features\ (i.e.Cost, Software)$

Appendix B – Technology Assessment Tables

Industrial													
Spro 230	Spro 60 HD	Spro 60 SD	Phenix PXL	Phenix PXM	Phenix PXS	Spro 125 Direct Metal	Spro 250 Direct Metal	VX1000	VX500	Fortus 250mc	Fortus 360mc	Fortus 400mc	Fortus 900mc
3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	3D Systems	Stratsys	Stratsys	Stratsys	Stratsys
8	8	8	0	0	0	0	0	1	1	1	3	9	9
No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
No	No	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes
No	No	No	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes
0.051	0.015	0.015	-	-	-	0.000338	0.000338	0.389	0.389	-	-	-	-
-	-	-	-	-	-	-	-	600	600	-	-	-	-
-	-	-	-	-	-	-	-	600	600	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.0031	0.0031	0.0031	0.0008	0.0008	0.0008	0.0008	0.0008	0.0039	0.0031	0.0070	0.0050	0.0050	0.0070
-	-	-	-	-	-	-	-	-	-	1	1	1	1
Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No
2.00	15.00	-	9.84	5.51	3.93	4.92	9.84	41.73	19.68	10.00	16.00	16.00	36.00
2.00	13.00	-	9.84	5.51	3.93	4.92	9.84	23.62	15.74	10.00	14.00	14.00	24.00
30.00	18.00	-	11.81	3.93	3.14	4.92	12.60	19.68	11.81	12.00	16.00	16.00	36.00
520.00	3510.00	-	1143.51	119.32	48.50	119.10	1220.00	19397.84	3658.30	1200.00	3584.00	3584.00	31104.00
No	No	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes

Personal									
									Project 260C
									Syste
									1
Materials	Metal	No	No	No	No	No	No	No	No
	Support	No	No	No	No	No	No	No	No
Software	Bundle	Yes	Yes	Yes	Yes	No	No	No	No
Speed	in^3/s	-	0.000915	0.000915	0.000915	.5 in/hr	.8 in/hr	.8 in/hr	.8 in/hr
	X (DPI)	-	-	-	-	1024	1024	300	300
	Y (DPI)	-	-	-	-	768	768	450	450
Surface Finish	Z (DPI)	-	-	-	-	-	-	-	-
	Layer Thickness (in)	0.0079	0.0039	0.0039	0.0039	0.0040	0.0040	0.0039	0.0039
	Colors	1	1	2	3	1	6	1	Basic CM
Scanning Ability	Bundle	No	No	No	No	No	No	No	No
Print Envelope	X (in)	5.50	10.75	9.00	7.30	6.75	6.75	9.30	9.30
	Y (in)	5.50	10.75	10.75	10.75	9.00	9.00	7.30	7.30
	Z (in)	5.50	9.50	9.50	9.50	8.00	8.00	5.00	5.00
	Volume (in^3)	166.38	1097.84	919.13	745.51	486.00	486.00	339.45	339.45
Safety	Certification	No	No	No	No	Yes	Yes	Yes	Yes

Key	
-	Info Not Available

Professional											
ProJet 3510DP	Objet24	Objet30 Pro	Objet Eden 260V	Object Eden350V	Objet Eden500V	Objet 260Connex	Objet350 Connex	Objet500 Connex	Objet1000	Dimension 1200es	Dimension Elite
3D Systems	Stratsys	Stratsys	Stratsys	Stratsys	Stratsys	Stratsys	Stratsys	Stratsys	Stratsys	Stratsys	Stratsys
2	1	7	6	6	6	10	10	10	100	1	1
No	No	No	No	No	No	No	No	No	No	No	No
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
-	-	-	-	-	-	-	-	-	-	-	-
375	-	600	600	600	600	600	600	600	600	-	-
375	-	600	600	600	600	600	600	600	600	-	-
790	-	900	1600	1600	1600	1600	1600	1600	1600	-	-
-	0.0011	0.0011	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0100	0.0070
	2	2	8	8	8	8	8	8	8	10	10
No	No	No	No	No	No	No	No	No	No	No	No
11.75	9.21	11.57	10.00	13.40	19.30	10.00	13.40	19.30	39.30	10.00	10.00
7.30	7.55	7.55	9.90	13.40	15.35	9.90	13.40	15.40	31.40	10.00	8.00
8.00	5.85	5.85	7.90	7.90	7.90	7.90	7.90	7.90	19.60	12.00	12.00
686.20	406.78	511.02	782.10	1418.52	2340.41	782.10	1418.52	2348.04	24186.79	1200.00	768.00
Yes	Yes	Yes	No	No	No	No	No	No	No	Yes	Yes

Professional
ProJet 7000SD
3D Systems
6
No
No
Yes
-
-
-
-
0.0049
No
15.00
15.00
10.00
2250.00
Yes

Product Features

Software: Support, Bundle

Speed: in³/s

Surface Finish: X (DPI), Y (DPI), Z (DPI), Layer Thickness (in), Colors

Scanning Ability: Bundle

Print Envelope: X (in), Y (in), Z (in), Volume (in³)

Safety: Certification

Key: Info Not Available

Appendix C – Quality Functional Deployment and Product Feature Prioritization

A QFD matrix was completed to transpose the market driver priorities to the product feature priorities. This was completed by assigning numerical values to the correlations between market drivers and product features, a 1=strong, 0=No Relationship, or -1=inverse relationship. The market drivers were transposed by multiplying the correlations by the market driver normalized values and summing them across all of the market drivers. The product feature priotity was then normalized by taking each patent priority and dividing it by the summation of all of the priorities from the data set.The following table identifies the populated matrix and final results from the analysis.

Table C.I: Product Feature Prioritization

			Patent Search Keyword												
			Cost	Software	Time	Quality	Design	Safety	Material	On Demand	Customization	Reverse Engineering	Size		
	Normalized Value		0.094	0.089	0.175	0.108	0.146	0.017	0.176	0.037	0.009	0.002	0.147	Product Feature Priority	Normalized Value
Product Features	Materials	PF1	-1	0	1	1	1	1	1	1	1	1	0	3.91	0.172
	Software	PF2	-1	1	1	0	1	0	0	1	1	1	0	2.82	0.124
	Speed	PF3	-1	1	1	1	0	0	0	1	0	0	1	3.33	0.147
	Resolution	PF4	-1	0	1	1	0	0	0	0	1	1	0	1.98	0.087
	Surface Finish	PF5	-1	0	1	1	0	1	1	0	1	1	1	3.73	0.164
	Scanning	PF6	-1	1	0	0	-1	0	0	1	1	1	1	2.68	0.118
	Print Envelope	PF7	-1	0	1	1	1	0	0	1	1	1	1	3.67	0.162
	Safety	PF8	-1	0	0	0	0	1	0	0	0	0	0	0.57	0.025

Fig C.1: Product Feature Priority Formula

Product Feature Priority =(((Cost^2)*Cost Normalized Value)+((Software^2)* Software Normalized Value)+((Time^2)*Time Normalized Value)+((Quality^2)Quality Normalized Value)+((Design^2)*Design Normalized Value)+((Safety^2)*Safety Normalized Value)+((Material^2)*Material Normalized Value)+((On Demand^2)*On Demand Normalized Value)+((Customization^2)*Customization Normalized Value)+((Reverse Engineering^2)*Reverse Engineering Normalized Value)+((Size^2)*Size Normalized Value))

Fig C.2: Normalized Value Formula

Normalized Value = Product Feature Priority / Sum of Product Feature Priorities “Materials, Software…Safety”