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Factors Forecasting the Effect of Rapid Prototyping Technologies on Engineering Design Education.

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Factors Forecasting the Effect of Rapid Prototyping Technologies on Engineering Design Education: A Delphi Survey

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ABSTRACT

Factors Forecasting the Effect of Rapid Prototyping Technologies on
Engineering Design Education: A Delphi Survey

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This dissertation presents information gathered and analyzed through an electronic internet-based Delphi Survey process. The purpose of this study is to identify a consensus of factors that might forecast the future effects of Rapid Prototyping (RP) technology on engineering design education when used for the purpose of overcoming the limitations of 2D representation of 3D space. The identification of consensus was developed from the collection of opinions from a panel of experts in RP technology.

Early adopters of emerging technologies can reduce risk through careful research, but decisions must often be made before significant quantitative data are available. Expert subjective judgment may be a valuable source of information for making decisions. RP is just one of the tools used in engineering design education for visualization. This research should help to guide faculty members in making decisions regarding the use of RP technology in the curriculum.

The one consensus reached by the panel is that 3D CAD will replace 2D CAD as the default modeling tool in most product-design related curricula within 5 years. The general conclusion of the study is that the appropriate use of the technology in the curriculum is largely situational.

DEDICATION

On September 11, 2001, terrorists hijacked four commercial passenger aircraft. By all accounts one of these planes flew very near, if not directly over, my home in central Pennsylvania before crashing in the western part of the state. On board the plane several passengers apparently processed what little information they had about the other three hijackings and made the decision to confront the terrorists and try to take back control of the plane. Although individuals on the aircraft lost their lives in the struggle -- their actions based on the information they had -- almost certainly saved the lives of countless others.

For whatever reason you have found your way to this research, I assume that you too, have to make some sort of decision. Although your decision may not be as momentous as those made aboard the hijacked flight, in the spirit of the heroes of United Airlines Flight 93, make your decision, and “Let’s roll.”

CONTENTS

Chapter Page

Page

Chapter Page

Appendix Page

LIST OF TABLES

LIST OF FIGURES

Figure | Page

CHAPTER 1

INTRODUCTION

In a competitive world significant risks are associated with not recognizing the potential of an emerging technology and adopting it into practice. Early adopters of emerging technologies face significant risks that can be reduced through a blending of careful research and personal insight. The focus of this study is on an emerging technology, Rapid Prototyping (RP), for the purpose of forecasting the future impact of the technology on curricula related to engineering design education.

RP refers to a class of machines designed to rapidly print physical objects from three-dimensional (3D) computer aided design (CAD) data with little or no human intervention during the production process (Wohlers, 1998). RP is an additive process that forms a physical object by building thin layers upon layers in various specialized materials. As with many emerging technologies, some argument exists about what to call this particular class of technology. Some other terms used include Solid Free-form (SFF) fabrication, Desktop Manufacturing, or Layer Manufacturing Technologies (Kai & Fai, 1997).

A variety of product design-related curricula programs use RP technology. I have used the National Science Foundation (NSF) Engineering Design program definition to guide this research.

> In the context of the Engineering Design program, engineering design is defined broadly to include all activities related to the acts of conception and description of engineered products, systems, processes and services, including comparative analysis of alternatives and selection of a preferred alternative. It reaches into other areas, such as manufacture, use and disposal, to the extent necessary to ensure good design decision making. A key element of the program lies in the recognition of uncertainty and risk in the design decision making process and their accommodation through research on appropriate theories and methodologies. (Hazelrigg, 2002, p. 1)

A body of practice grounded in mathematics has evolved over time in the various fields of education related to engineering design. A recurring question in the literature is how much of the curriculum should be spent on descriptions of design problems, in terms of the mathematics versus studying problems in terms of applications. Obviously, there are limited hours available in a typical four-year baccalaureate program of study, so the curriculum is usually focused on a foundation of theoretical understanding that is transferable to a broad base of problem-solving techniques that the student will be able to apply upon graduation. Randy Maires, director of the Society of Manufacturing Engineers' Education Foundation stated, "The problem is that colleges and universities aren't doing enough to turn out students with applied knowledge of engineering" (Five Pittsburg, 2001, p. D2). A balance of theory and application must be achieved in the curriculum to provide students with long-term problem-solving skills, along with near-term employment skills. Ideal learning experiences satisfy both of these needs (Zawila, 2001b).

RP technology first became available in 1989. In 1995, the College of Engineering at Virginia Polytechnic Institute & State University (VPI & SU) offered the first RP course in the nation (Bohn, 1999). In 1998, Wohlers Associates, Inc. reported that academic institutions accounted for 6.9% of the use of RP technology (Wohlers, 1998). By 2002, this percentage had slipped to 6.7% (Wohlers, 2002a). To date, most of the research involving this technology has focused on developing the technology itself, with limited research being reported on factors of the technology affecting engineering design education or forecasting of future impact for the purpose of curriculum development.

Statement of the Problem

The problem addressed in this research is to attempt to identify factors forecasting the effect of RP technologies on engineering design education when used for the purpose of overcoming the limitations of 2D representation of 3D space. Traditional mechanical engineering or product design practice uses annotated two-dimensional (2D) orthogonal multi-view drawings for the purpose of conveying design parameters for manufacture. Advances in CAD software have made it possible for a designer to simulate the representation of 3D space in the 2D media of print and video. Additionally, significant research and development are currently underway to refine computer-generated Virtual Reality (VR) for the purpose of 3D visualization (Society of Manufacturing Engineers/Rapid Prototyping Association, 2000).

However, all of these technologies are methods of 2D representation of 3D space. Traditional prototyping techniques for producing physical 3D models require a high level of skill. Methods of RP were developed for the purpose of rapidly fabricating 3D prototype models to overcome the limitations of trying to represent 3D space in 2D media and the high level of skill required to make traditional prototypes. Various forms of the technology include stereolithography (SL), fused deposition modeling (FDM), selective laser sintering (SLS), laminated object manufacture (LOM), and 3D printing (3DP).

A number of colleges and universities have already gained experience in using RP technology in their engineering design curriculums, but there is a lack of information in the literature from users about their experiences in reference to the effects on the curriculum. The purpose of this study is to forecast the future effects of RP technology on engineering design education, through the collection of expert opinion from a panel of experts in RP technology.

Significance of the Study

Early adopters of emerging technologies can reduce risk through careful research, but decisions must often be made before significant quantitative data are available. Expert subjective judgment may be a valuable source of information for making decisions. RP is just one of the tools used in engineering design education for visualization. This research should help to guide faculty members in making decisions regarding the use of RP technology in the curriculum.

Research Questions - Round One

Based on a review of the literature and the statement of the problem, the following 10 broad-based questions were presented in round one of a Delphi method survey instrument:

1. What term do you prefer to use for "rapid prototyping technology" and why?
2. Do you think 3D CAD modeling will become the initial or default design tool in CAD-related education and if so why and by what year? Describe the role that you foresee for 3D CAD in engineering design curricula?
3. In your opinion, might Virtual Reality (VR) become a replacement for RP in engineering design curricula? If so, when and under what conditions?
4. Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students? If so, describe the differences.
5. Should students, a technician, or a faculty member run the machine, and under what conditions?
6. Do you expect the cost of RP technology to decrease dramatically in the near future? What would be the optimal cost for perceived benefit for introducing the technology into the curriculum? At an optimal cost/benefit would you expect the majority of schools and small to medium size companies will bring RP technology in-house?
7. List in order of importance, related to the use of RP in the curricula, the properties of: aesthetics, accuracy/repeatability, machine cost, material mechanical properties, speed, technical support, machine reliability, cost of raw material, ease of operation, cost of operation, or other. List the properties with the number 1 being the most important. Comment on reasoning where appropriate.
8. Assuming an RP model could have one property identical to the finished product, state the property that would be most important in an educational environment. Comment on reasoning where appropriate.
9. What machine (brand and model) would you currently recommend for purchase for use in a product design related curricula?
10. How will RP technology affect design education to the year 2010?

CHAPTER 2

REVIEW OF RELATED LITERATURE

The ability to visualize and communicate an engineering design in 2D and 3D is a critical skill that product design students need to develop. They should be able to communicate in the technical language of the field, as well as in non-technical language with other stakeholders. Several computer-based methods have replaced traditional drawing board and t-square drafting as the written language of communication for engineers, designers, draftsmen, and tradesmen. The computer-based tools are either required for, or supplement, RP technology. With the exception of RP, however, all of the tools represent 3D space in 2D media.

CAD

CAD is one of the computer-based tools has been developed to facilitate the 3D visualization process. However, most users of CAD use the technology as a direct 2D replacement for traditional drawing board drafting. Cyon Research found that as of 2001 fewer than 20% of mechanical CAD users were working in 3D solid modeling (Wohlers & Grimm, 2001). The development of downstream software applications that rely on 3D CAD output data as their input data is accelerating the change from 2D CAD to 3D CAD. Although more than 80% of users of CAD use it as a 2D tool, the use of 3D CAD tools is increasing (Jacobs, 1996). Also, companies are finding that they cannot design in 2D the kind of freeform products their customers are demanding (Zawila, 2001a). Figure 1 is an example of a typical engineering drawing based on American National Standards Institute (ANSI) standards for 3rd angle projection with 2D orthogonal views and dimensional annotation of the top, front, and right sides of an object (Giesecke, 2003).

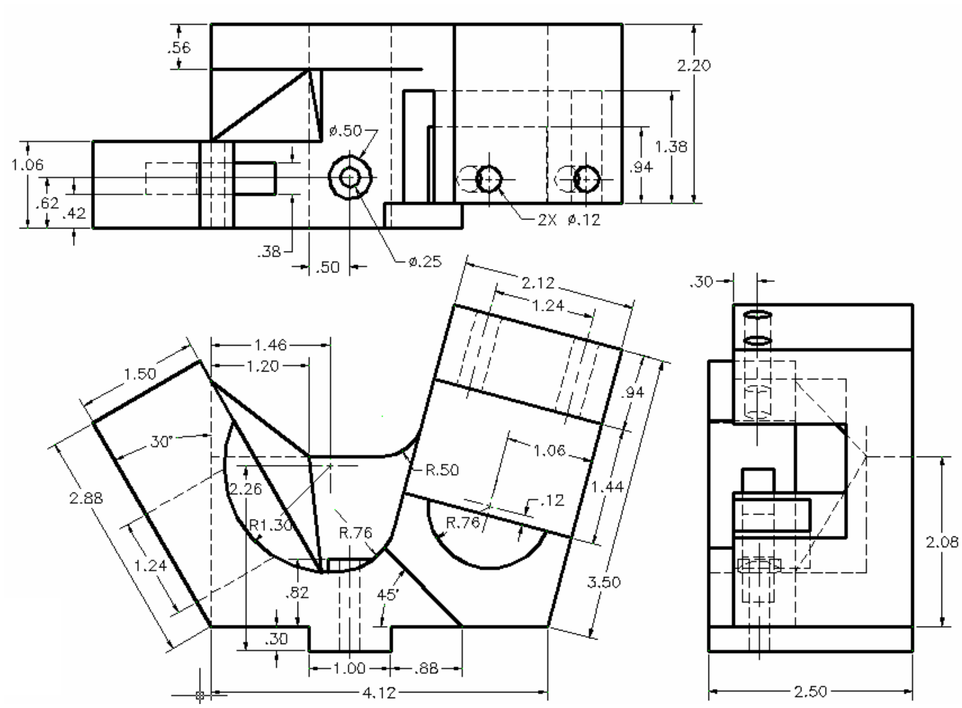

Figure 1. Orthogonal multi-view drawing (adapted from Giesecke, 2003).

The traditional orthographic projection method works well for depicting planar surfaces, cylinders, conic sections and prismatic geometries such as boxes and wedges. But it becomes quite complex when describing organic or freeform surfaces, such as airfoils, and ergonomic design. Metelnick (1991) has shown that in the 25 years preceding his study, products have increased in complexity of shape and form. Figure 2 is a partial representation of Non-uniform Rational Bezier-Spline (NURBS) surfaces of a product.

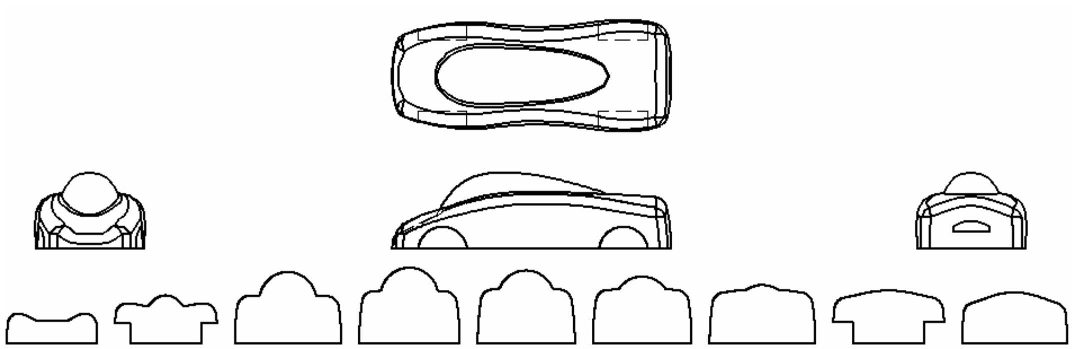

Figure 2. Partial representation of NURBS surfaces (adapted from Chu, Cheng, Tam, & Wong, 1998).

The lower portion of Figure 2 represents sliced profiles of the solid object about every 10% of the total length of the object. Actually, in order to make this object based on a traditional engineering drawing as depicted in Figure 1, hundreds of sections annotated with dimensions would be required. For untrained users, this method of communication gives very little information about the 3D parameters of the object. Even a skilled user of engineering drawings may take several minutes to several hours to fully understand a complex drawing. Stier and Brown (2000) stated that students often want to concentrate on 3D modeling and skip orthographic projection. A more natural way for them to communicate is in 3D. Another problem that arises with the traditional 2D practice is that key decision makers are often untrained in reading orthographic engineering drawings (Kai & Fai, 1997).

The chief technology officer at the CAD vendor, Autodesk®, reported that 3D CAD products are now becoming the method of choice for design tools in the manufacturing market, with new sales of software now 20% 2D CAD products and 80% 3D CAD products (Schnitger, 2002). Software for 3D CAD has been around for years, but the software and the hardware it required were relatively expensive. The widespread use of 3D CAD has also been delayed by the long history of traditional 2D practice that has worked well and will remain the predominant method of engineering communication into the foreseeable future. Compared to 2D, the use of 3D CAD tools offers several advantages in analyzing mass properties, design visualization, and in Computer-Aided Manufacture (CAM). With 3D, CAD designers must fundamentally change the design process and are forced to be more "realistic" (Connolly, 2001). On an internet RP mailing list one respondent with 10 years of RP experience in industry stated, "I'd like to see students having the opportunity to print out most of the solid models they create. It's the ultimate "hand-in" of their assignments" (Time-Compression Technologies, 1998, p. 12).

Figure 3 represents a 3D visualization of the same object depicted previously in Figure 1 as a traditional engineering drawing. But Figure 3, referred to as an isometric view, is not a true

3D image; it is a 2D depiction of a 3D image. A sheet of paper, a television, or computer monitors are all 2D media that are used to depict 3D images. This research is centered on the design visualization utility of the tools.

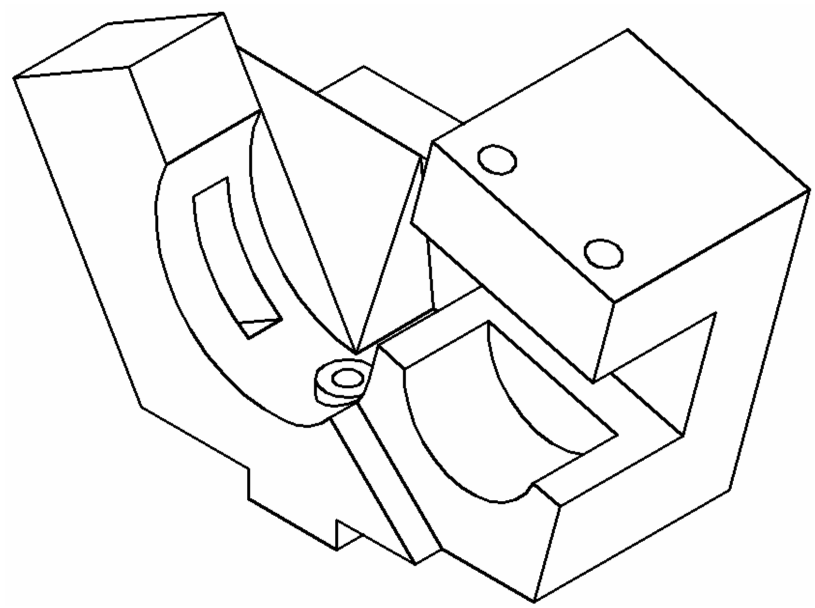

Figure 3. Representation of 3D with a 2D isometric.

The television screen and the computer monitor can also depict motion of a 3D object, which can give more information about the 3D space the object occupies. However the representation of true depth perception is not yet possible with these technologies.

Virtual Reality

Virtual Reality (VR) is a computer-based technology that uses 3D CAD to give the impression of depth perception. The computer generates slightly different individual images for each eye. The brain processes these stereoscopic images to produce a single coherent image with the illusion of depth perception. At the level of current technology, the illusion is instantly recognizable as such and does not provide the tactile feedback that a physical model would provide. There is considerable ongoing research to improve VR technology. The U.S. Army

Tank & Automotive Armaments Command (TACOM) is one of several users of Cave Automatic Virtual Environment (CAVE) technology that incorporates VR to try to reduce the need for costly prototypes (Elliot, 2003).

To overcome the limitations of representing 3D designs in 2D media and the current limitations of VR, several companies have developed technology that is capable of rapidly prototyping designs as physical 3D models. The fact that these companies sold 1,298 RP machines in 2001 for sales of an estimated $238.1 million indicates that there is a population of users (Ford used 35 RP machines in 2002) who think that the technology offers additional value beyond the use of 2D and 3D CAD, and/or VR for product design and visualization. Total expenditures on RP-related products and services were $538.2 million worldwide in 2001 (Wohlers, 2002a).

RP Processes

There are a number of processes that have been developed that fit under the category of RP technology. The common characteristic of these processes is that a 3D CAD model is mathematically sliced into very thin cross-sectional layers. The cross-section layers are then reconstructed in an additive process in some form of solid material by a computer-controlled machine. The different characteristics of these processes are found in the materials used to reconstruct the solid and in how these materials are bonded in the layers. An abbreviated description of some of the most common RP process follows.

Stereolithography Apparatus

With a stereolithography apparatus (SLA) process the mathematically sliced model is reconstructed by focusing a laser on a thin layer of photosensitive liquid polymer that hardens into a solid after exposure. As the laser draws each layer, the part is automatically lowered in the vat of liquid until another very thin layer of liquid covers the solidified surface area and succeeding layers are drawn. There are some environmental hazards associated with the laser energy and material toxicity. Materials used in SLA include acrylate and epoxy photopolymers.

Fused Deposition Modeling

In the fused deposition modeling (FDM) process each layer is built up by extruding very small drops or threads of molten material. As the material cools, it bonds to the previous layer and solidifies. Materials used in FDM include acrylonitrile butadiene styrene (ABS), wax, and nylon.

Selective Laser Sintering

A selective laser sintering (SLS) process is a powdered material-based process in which each layer of powder is melted by a laser. The resulting molten puddle then solidifies and bonds. The materials used in this process are steel, polycarbonate, nylon, and other polymers.

Laminated Object Manufacturing

The material in a laminated object manufacturing (LOM) process is in the form of a continuous thin sheet bonded by an adhesive deposited between the sheets. A laser cuts the profile of the object and then cuts unwanted areas of material into small squares that act as supports for the object until chipped away at the end of the build process. When paper sheet is used as the build material, the finished object looks, feels, and smells like wood.

3D Printing

With 3D printing (3DP) an ink-jet style of printing head is used to dispense a liquid binder over a layer of powder. As each layer is finished the object is lowered, and a new layer of powder is spread over the surface. Cornstarch is one of the materials used in a 3DP process to produce the solid model.

In *The Road to Manufacturing: 1998 Industrial Roadmap for the Rapid Prototyping Industry,* published by the National Center for Manufacturing Sciences (NCMS), the various RP technologies were divided into the following categories: 1) Design Verification Systems, 2) Bridge Technology Systems, and 3) Direct Manufacturing Systems (Cooper, 2001). Wohlers (2002) presented similar application segments: 1) Concept Modeling, 2) Rapid Prototyping, and 3) Rapid Manufacturing. The categories or segments were based on the application of the technology.

RP Applications

Applications of RP technology range from "look-and-feel" concept visualization models to limited functional components for testing fit, form, and properties, and to patterns for making casting molds. While the ultimate goal is to develop the technology to the point where products can be directly manufactured by RP, the current focus is to reduce the costs and time-to-market for conventional manufacturing processes. The cost of making an engineering change order (ECO) in a design increases after the design has been reviewed and approved. After the product is in production, the cost of making the same ECO increases dramatically. This relationship of ECOs to the cost of a new product is given by the *Westinghouse Curve,* which states that 70% of the cost of a product is determined in the design phase (Bralla, 1996). According to work by McKinsey & Co., a high-tech product that comes to market six months late will generate 33% less profit over a five-year period (Srinaman, 1996). *Visionary Manufacturing Challenges for 2020,* from the National Research Council (NRC), stated, "Rapid prototyping technologies have shortened product development times and improved the integration of product and process design" (1998, chap. 2, ¶ 11).

Visualization Models

Comenius a theologian educator in the sixteenth century, introduced the extensive use of pictures in education. Later, Maria Montessori promoted the use of physical objects in the educational process. Physical models help to convey more information in a short period of time than numbers, drawings, or pictures (Ozmon & Craver, 1999). In the process of gathering information about an object, children are often told to look, but do not touch. The natural inclination for most people is to manipulate an object as a form of gathering rich information about the object in a short period of time (Wohlers, 2002a). In one of the most significant discoveries in history, Watson and Crick used a model to help them visualize the 3D structure of DNA (Watson, 1968). Their simple double helix model was critical in formulating their discovery, and it helped to convey understanding of the complex building blocks of life, even to those who are not scientists.

Watson and Crick did not have RP technology to help them build their DNA model for visualization, but students at the Milwaukee School of Engineering have used RP to build 3D physical models of proteins, nucleic acids, and other bio-molecular structures (Herman, Patrick, & Roberts, 2001).

Duesbury and O'Neil (1996) found that physical manipulation of a model did not prove superior to virtual rotation on a computer screen in helping students learn orthographic projection. However, they did find that using some form of rotational component yielded superior results in their Test of Three-Dimensional Shape Visualization. Frey and Baird (2000) concluded that the use of Rapid Prototyping technology did not significantly improve student visualization skills, though they also noted that there is currently a lack of other research related to this question. Smith (2001) pointed out that unlike orthographic projection, prototypes represent a common language that puts engineers, managers, manufacturers, and marketers on equal footing in evaluating a design.

The prototype need be refined only enough to answer a specific question, for example fitted with another part, and then discarded. In his book, *Stereolithography and other RP&M Technologies*, Jacobs quoted Chrysler's Vern Schmidt, "The average life of an RP model is 10 minutes. After a few 'oh no's' it's back to the CAD tube" (Jacobs, 1996, p. 20). Wohlers (2001) compared the easy availability of RP models to conventional models with the notion of the "paperless office." Fast, cheap printers and an explosion of information technologies derailed this notion. Wohlers predicted that by 2006, a Fortune 500 company will enter the RP market and the technology will become a common tool in education.

Fit, Form, and Properties

RP models can be used to test the fit of assembled components. The models can be tested for ergonomic design. One unforeseen use of RP models was the use of the models for optical evaluation of stresses. Under certain lighting conditions, some plastics will exhibit banding of refracted light in stress conditions. The properties of the model will often correlate closely with the final product, allowing engineers to test the effects of design changes to areas of stress at the modeling stage (Kai & Fai, 1997).

RP Research

On March 5, 1997, Neal F. Lane, Director of the NSF, testified before the House Science Committee that advances in computer assisted design and rapid prototyping could be traced to years of sustained NSF investment (NSF, 1997). A search of NSF records for grant awards using the keyword phrase "rapid prototyping" returned 252 awards (NSF, 2002). Of those awards, I eliminated 115 as probably not related to RP technology as defined in this study. The remaining 137 grants totaled approximately $31 million. I grouped the remaining 137 in three general categories listed by the award date in Appendix A. The word "curriculum" was found in 30 of the award abstracts, although the area of curriculum development related to the use of RP technologies is, as yet, somewhat unexplored in the literature.

I calculated that as of August of 2002, the NSF awarded 80 of the 137 grants, for a total of $16.8 million, for basic research in RP technologies. Specific goals stated in the research proposals were to develop the mathematics, the computer software, the materials, and the processes in advancing the technology.

Because many objects cannot be described with planar geometry, more sophisticated mathematics for surface description, such as Coon's patches and NURBS surfaces, must be used (Lengyel, 2002; Piegl & Tiller, 1997; Rogers, 2000). For RP, the mathematics is further complicated by the need to slice the surfaces into thin layers for processing. A full treatment of the mathematics can be found in numerous sources and is outside the scope of this research. Indeed, the mathematics of computer-generated visualization may be of little interest to the CAD designer, as the user interface with the computer makes all of the mathematics transparent. Because the mathematics is transparent, even young children can quickly learn to draw geometrically accurate 3D objects with CAD software.

From NSF-funded and other basic research, several similar methodologies were developed that are referred to in general as RP technology. The general characteristic of RP technology is that arbitrarily complex parts can be produced layer-by-layer directly from CAD data, with minimal or no human intervention in the production process. The process begins by mathematically slicing a 3D CAD model into very thin horizontal cross-sections. Production of the physical model is then accomplished by reconstructing the sliced CAD model layer-by-layer in some type of material.

RP represents a discontinuous innovation in that it could replace traditional methods of prototyping. An example of a discontinuous technological innovation is the replacement of vinyl LP records by compact discs (CDs). Turntables for playing LPs cannot be used for playing CDs, and CD players are not backward compatible with LPs. A number of market forces and technological developments must come together for a discontinuous innovation to succeed.

The S-shaped life cycle curve of a successful product is well known. The slope of the curve starts off with slow sales that then increase sharply and eventually level off and then decline. In *Crossing the Chasm*, Moore (1999) presented a model of what he called the Technology Adoption Life Cycle (TALC), which tracks the evolution of discontinuous technologies in the market. By Moore's definition, RP is not yet a *whole product* because the technology is dependent on another technology, 3D CAD solid modeling, which is used by fewer than 25% of mechanical CAD users (Wohlers, 2001).

An examination of an adaptation of Moore's model in Figure 4 shows that 3D CAD, adopted by 20-25% of industry, has barely bridged the chasm to reach whole-product status. Adoption by the first 16% of potential users represents technological innovators and visionaries. Some products never successfully bridge the chasm to gain market acceptance by pragmatists and conservatives. The slope of the curve for adoption of 3D CAD is not known, but RP adoption can only follow 3D CAD adoption as the RP technology is dependent on 3D CAD data.

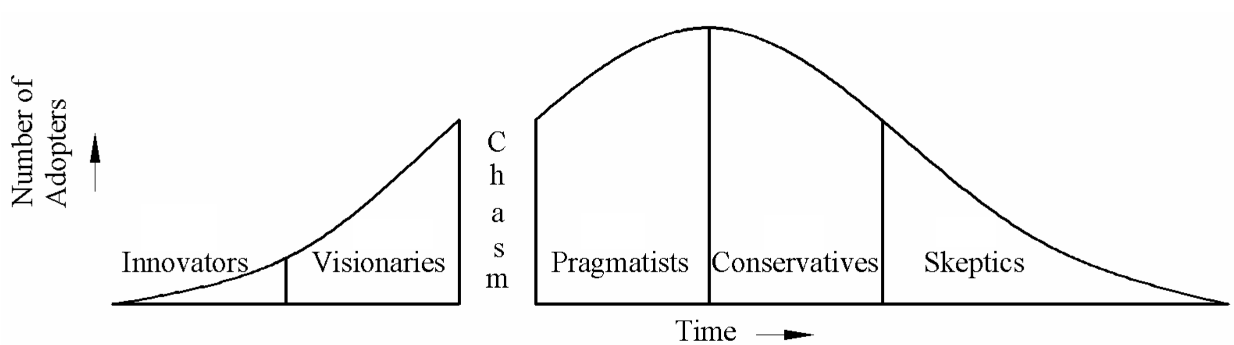

Figure 4. Technology adoption life cycle (adapted from Moore, 1999; Wohlers, 2002b).

Early adopters, or technology pioneers, might be willing to spend time and money on experimenting with a technology that does not yet represent whole-product status by Moore's definition (Wohlers, 2001). Some university research programs can justify this expenditure as an investment in the future. Other programs cannot afford what they might view as too much risk associated with an expensive and unproven technology that might be replaced by another discontinuous innovation in the near future. In forecasting the future of RP technology a time-dependant complexity arises because future events cannot be predicted *a priori* (Suh, 2001). If-then rules will not work because the problems of forecasting grow increasingly as the function of time into the future increases.

The cost of an RP machine is just one consideration in planning integration of the technology into the curriculum. The true cost of ownership also includes a number of hidden expenses. In their study titled *A Management-Support Technique for the Selection of Rapid Prototyping Technologies*, Braglia and Petroni (1999) identified a hierarchy of primary objectives influencing the selection process. The objectives were grouped into five categories: Office friendliness, material characteristics, machine price, operating costs, and process time. The selection of the wrong machine might not only result in costly problems, but could also drain resources from other parts of a curriculum.

Hidden costs include the following: The cost of materials tends to be relatively high, facility improvements including electrical and ventilation may be needed, and a specially trained technician may be needed. In addition to these hidden costs, there are significant risks associated with having students operate a $360,000 machine with a vat filled with $5,000 worth of photosensitive process liquid that is cured with a potentially hazardous laser (Wohlers & Grimm, 2002). The yearly service contract alone is $6,000 on one popular $57,000 machine, which is at the low end of the price range for the technology (Wohlers & Grimm, 2002).

There are considerable risks involved in adopting RP technology, given the costs, the questionable utility for teaching students (Duesbury & O'Neil, 1996; Frey & Baird, 2000), the status of the technology as lacking whole product status by Moore's definition (Wohlers, 2001), and the possibility that VR technology could represent another discontinuous innovation that could replace RP technology. Therefore, it would seem prudent for faculty considering integrating the technology into the curricula to attempt to identify, from the experts who are already using the technology, factors forecasting the effect of RP technologies on engineering design education for the purpose of overcoming the limitations of 2D representation of 3D space.

CHAPTER 3

METHODS AND PROCEDURES

A Delphi Survey method was used to gather data for this research. The Delphi method has previously been used by researchers for studies of technologies related to RP. In 1980, the Society of Manufacturing Engineers (SME) published the *CAD/CAM International Delphi Forecast* (Smith, Colwell, & Wilson, 1980) and two years later published a second study, *Industrial Robots: A Delphi Forecast of Markets and Technology* (Smith & Wilson, 1982). In a 1998 NRC study, *Visionary Manufacturing Challenges for 2020*, funded by the NSF under Grant No. DMI-9626585, RP was identified through a Delphi Survey as one technology area with potential to help meet some of the *Grand Challenges* described in the study (NRC, 1998). Levy and Nursanto (2002) carried out a Delphi Survey of small and medium enterprises using RP technology in Switzerland.

Delphi Survey

The Delphi Survey method was originally developed at the U.S. think tank, the RAND Corporation, out of research started in the early 1950s by Dalkey and Helmer (Linstone & Turoff, 1975). The Delphi method was designed for use with complex or ambiguous technology forecasting problems that exceed the capabilities of a single person. Linstone and Turoff defined the method by stating, “Delphi may be characterized as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem” (p. 3).

The method relies on anonymous or confidential surveys of experts and is inclusive of qualitative expert opinion as well as quantitative factors. The data collected are the opinions of the experts, and the validity of the judgment of the panel of experts is measured by consensus

(Linstone & Turoff, 1975). The philosophical basis of the Delphi method is that a hypothesis is not needed to collect data for a qualitative analysis of trends. The objective is to identify areas of consensus of opinion (Linstone & Turoff). The basic assumption is that expert opinion can be of value in making a decision in situations where knowledge or theory is incomplete. The Delphi method is an appropriate research method in the field of RP curriculum development because the field is too new to have adequate historical data.

The anonymous or confidential participation of panelists reduces or eliminates the occurrence of a charismatic or otherwise influential participant having an undue effect on the consensus outcome for reasons other than the validity and strength of arguments (Linstone & Turoff, 1975). Minority opinion holders are free to argue their positions as the participants move towards a consensus through the survey process.

The method is an iterative process requiring two or more (usually three or four) rounds of survey of the panel of experts. After each round, the data are compiled and used to generate the next iteration in the process. The process is continued until consensus is identified on factors related to the topic. Most Delphi Surveys reported in the literature ended after three rounds. Successive rounds tend to yield redundancy, with a serious diminishing of returns for substantial additional effort. Also, panelists will begin to exhaust their interest and drop out. To bind this research into a manageable time limit I restricted this Delphi Survey to three rounds.

In the first round a modified Delphi Survey was used, where, rather than starting from a *tabula rasa*, I developed the questions for the initial round based upon a review of the literature. Guidelines by Salancik, Wenger, and Helfer (1971) were considered in constructing the first round questions. The second round was used to rank a summary of factors identified from the first round. The third round was used to analyze consensus. Complete descriptions of the survey and the survey instrument may be found in Appendixes D through N. In response to critics of the Delphi method, Rieger (1986) called for users of the technique to be more careful in implementing quality control.

Critiques of the Method

In analyzing research guidelines for using the Delphi technique, Hasson, Keeny, and McKenna (2000) found, "An extensive review of the Delphi literature identified that no universal guidelines exist" (p. 1009). There may be researcher bias in designing the survey and in interpreting the data, particularly in the first round, where the initial questions are developed by the researcher and then the responses are categorized by the researcher for the second round (Woudenberg, 1991). Because of the iterative nature of Delphi Surveys, the experts have the opportunity to challenge and guide the research. However, Welty (1971) argued that the panel of experts could be manipulated.

Other challenges to the Delphi Survey method include: Experts usually expect to be compensated for their efforts, and the time needed to respond to multiple rounds of survey may lead to attrition. And the whole problem of identifying who is an "expert" leads to a somewhat arbitrary selection of panel members (Welty, 1973). Sackman (1974) made what is considered the historic critique of the Delphi. A year later Linstone and others provided a counterargument to Sackman (Lang, 1999; Linstone & Turoff, 1975; Reiger, 1986).

To address the criticisms regarding a lack of universal guidelines, researcher bias, arbitrary panel selection and panel manipulation, I used the Guba and Lincoln model of constructivist evaluation (or naturalistic inquiry) to guide this research (Lincoln & Guba, 1984: Guba & Lincoln, 1981, 1989). Along with the Guba and Lincoln model, I used Koen's (2003) definition of the engineering method as stated in *Discussion of the Method: Conducting the Engineer's Approach to Problem Solving*. By Koen's definition, "The engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources" (p. 94).

Constructivist Research Paradigm

In establishing tests of rigor for this research, I identified four basic concerns based on the constructivist research paradigm (Guba & Lincoln, 1981). These concerns were truth value, applicability, consistency, and neutrality. Each of the concerns was established at a particular point in the research and then recycled through successive rounds of the survey. The truth value was first established through the literature review. The applicability was established by selecting the Delphi Survey method of iterative rounds and especially in the first round, where the initial propositions were exposed for comment. The consistency was established in the second round with summarization that also exposed countervailing facts or assertions. And finally, neutrality was established in the third round with the verification of consensus propositions. A more complete description of each of the four concerns follows.

Truth Value

Guba and Lincoln (1981) presented two domains of knowledge as they relate to interviews or surveys: The propositional and the tacit. In the propositional domain the interviewer/researcher knows what he or she does not know, and therefore can form questions to try to fill in these knowledge gaps. This can be done through questionnaires. The first round of the Delphi Survey for this research is representative of the propositional domain, in which the initial questions were derived from a review of the literature. In the tacit domain, the interviewer/researcher does not know what he or she doesn't know, and therefore cannot form questions (Gall, Borg, & Gall, 1996). The first round of this survey included open-ended comments that allowed the experts to include information not directly asked. As the researcher classifies the first round responses and comments for subsequent rounds, the experts clarify the information and fill in additional knowledge gaps.

Applicability

In assuming the role of group communication facilitator in the Delphi Survey method, the researcher becomes part of the instrument (Guba & Lincoln, 1989). The role of the researcher as a part of the instrument raises methodological and reliability issues that you should recognize. In the traditional scientific research methodology the researcher in a role as part of the instrument might be termed both an independent variable and an interaction effect. The dialectic interaction available in a multi-round survey instrument like a Delphi Survey allows evaluative communication and helps ensure accuracy.

Immersion and experience in the field prepares the researcher to quickly identify what might emerge as an important issue in a dynamic group communication process. The researcher should use heuristics based on personal experience to quickly understand a problem (Koen, 2003). Investigation of these types of emergent issues would have to be ignored or delayed in other research paradigms that rely on *a priori* hypotheses. The use of heuristics is essential in uncovering the expert's tacit knowledge that would otherwise not be investigated because the researcher was not aware of what he/she did not know and could not form a question (Guba & Lincoln, 1981).

To help elicit this tacit knowledge, in round one I formulated exploratory questions that were broad-based, perhaps even complex or ambiguous. Rich, descriptive responses, incorporating both qualitative and quantitative information, were encouraged from the expert panel. The researcher as part of the instrument possesses a feature missing in other instruments, that is, judgment, and the flexibility to use it (Creswell, 1998; Denzin & Lincoln, 2000; Guba & Lincoln, 1989). While this constructivist research paradigm results in a loss of rigor, it gains flexibility. The design of subsequent rounds of the Delphi Survey emerges as the investigation proceeds.

Humans may be better than machines at recognizing patterns and establishing continuity between questions forming a complex and meaningful whole from the survey instrument. Koen

(2003) demonstrated that even with problems in which the solution can be precisely defined and described, such as those encountered in the game of chess, the human using heuristics to solve a problem can be much faster than programming a machine to solve the problem. The researcher might recognize patterns, even in otherwise chaotic systems that could be missed with other research methods. A particular pattern could form a boundary for the research. Two qualities of the human as instrument are the ability to change the direction of the inquiry based on heuristics and the immediate processing of the data (Guba & Lincoln, 1989). An expert in a particular technological field under investigation might have singular knowledge on a related issue, which allows reflexivity in response to changing conditions (Creswell, 1998; Gall et al., 1996). The Delphi Survey method is responsive, flexible and adaptive, and allows for clarification through continuing contact with the panel. Successive rounds serve as a credibility check through summarization of the collection and interpretation of the data. Multiple rounds allow the exploration of atypical responses that might not be explored in a scientific method inquiry but instead handled as a statistical deviation.

To ensure rigor the researcher must somehow derive a set of emergent categories within which the data can be classified. The construct or category is emergent if it is clear to others in the field that it was developed from the literature and the Delphi Survey, and not just from the researcher's biases (Gall et al., 1996). Rigor can be focused through a recycling process in the Delphi Survey method, which returns comments and summarizing statements or propositions to the expert panel for further evaluation and comment. This process helps establish a degree of structural corroboration and identifies and achieves convergence on the final boundaries of the research, limiting the inquiry to natural boundaries.

In round one the researcher begins in a discovery posture, the results of which he or she categorizes. The generation of emergent categories is obviously more a matter of art than science, but through recycling back to the expert panel the categories can be verified as representative of the expert opinion (Guba & Lincoln, 1989). In this research I used the heuristics representative of my personal knowledge to establish categories from the round one comments. Where I could not categorize the comments, I edited the questions to elicit Likert-type responses ranging from "strongly agree" to "strongly disagree" to my summarizations for round two.

Consistency

The researcher verifies his understanding by checking it against the experiences and understandings of the expert panel (Guba & Lincoln, 1989). Starting from baseline knowledge gathered through experience and a review of the literature, the researcher corroborates propositions through a method involving checking the propositions through the expert panel. With this method, the uncertainty of interpretation is greatly reduced. A final check involves presenting the inquirer's constructed reality to the panel to identify consensus. For this check the results of round two were analyzed using heuristics and presented as consensus propositions in round three. The third round identification of consensus (or lack of consensus) provides an agenda for negotiation of those issues that have not been resolved, in the hermeneutic dialectic exchanges of a future Delphi Survey, as this survey was limited to three rounds *a priori*.

Neutrality

It is the obligation of the users of the information presented in this research to establish external validity or transferability of this research in their particular setting. The researcher's obligation is to provide the descriptive and values database that will make the user's judgment process possible. The burden of proof of validity or transferability lies less with the researcher than with the decision maker who is seeking to apply the information elsewhere (Lincoln & Guba, 1989).

The presentation of the responses, analysis, and comments from each round formulates an audit trail for the research. The information gathered from round one was categorized based on identifiable issues. From these emergent categories, value judgments of utility or importance were rendered, depicted, or characterized to refine the initial questions for subsequent rounds. In round two the refined questions emergent from the analysis of round one were presented for verification. Finally, in round three the inquiry was bounded with consensus agreement or disagreement, with the intent to provide knowledge to decision makers. Where no consensus was identified further rounds could be used to negotiate consensus that honors individual values (Guba & Lincoln, 1989). The need of such reiteration in responsive evaluations are typical as they are never really complete but are ended for logistical reasons. The test or proof of the value of the information is left to the decision maker. In this research no effort was made to negotiate common ground that might render consensus, but rather the effort was made to identify emergent consensus.

Definition of Consensus

This research used the Baldrige National Quality Award program (BNQA) definition of consensus (A. Czuchry, personal communication, March 28, 2003). The BNQA program is administered under the National Institute of Standards and Technology (NIST). The Baldridge Education Criteria are used by many educational organizations to improve their performance (Baldrige National Quality Award, 2003).

According to the BNQA definition, consensus is a proposition acceptable enough that all members can support it; no member opposes it. Consensus is not a unanimous vote - consensus may not represent everyone's first priorities. Consensus is not a majority vote - in a majority vote, only the majority gets something they are happy with. People in the minority may get something they do not want at all. Consensus is not a situation in which everyone is totally satisfied.

Delphi Panel Selection

Following approval of the research by the East Tennessee State University - Institutional Review Board (ETSU-IRB), Appendix B, the panel members were selected based on their expertise as evidenced by identification as principal investigators (PI) for NSF grants, journal publications, membership in the Rapid Prototyping Association of the Society of Manufacturing Engineers (RPA/SME), or nomination by peers. A letter explaining the research was e-mailed to each of the panel members (Appendix C). Panel members responded with a yes as an answer to at least one of the experiences listed in the Pre-Delphi Questionnaire in Appendix D. While some of the literature suggests that there is no limit to the upper size of a panel, Delbecq, Van deVen, and Gufstafson (1975) recommended a panel size of 15 to 30 members, with little improvement achieved with panels of a larger size. In emergent constructivist research the selection of the expert panel is not based on a random sample. The aim of the researcher is to optimize learning through selection of a purposeful sample (Gall et al., 1996; Guba & Lincoln, 1989).

For this research an effort was made in the selection process to identify those individuals with the most experience and active involvement in research and publication in the RP field. Additionally, the panel was comprised of male and female participants, and included two independent experts not employed by educational institutions, as well as two artists/educators. The names of panel members who elected to be identified in publication of this research are listed in Appendix O.

Survey Instrument Design

Following the Dalkey (1973, 1975) restrictions for the group estimation process the types of data expected to be collected by a Delphi Survey are dates, costs, probability of events, and performance expectations for the technology. In light of several internet-based Delphi Survey software programs being developed and tested, Twining (2000) found renewed interest in the

Delphi method. Twining described the internet-based Delphi method as a platform for a "collaboratory" – a term the NRC synthesized from the words "collaboration" and "laboratory" (Twining). On any particular topic there is information available to the researcher through a review of the literature. With this collaboratory method additional information is developed through survey of the panel of experts. Figure 5 is a representation of the domain of collaboratory research adapted from Twining with Guba and Lincoln's (1981) propositional and tacit domains. The goal of the researcher is to elicit and develop the tacit knowledge that has not appeared in the literature.

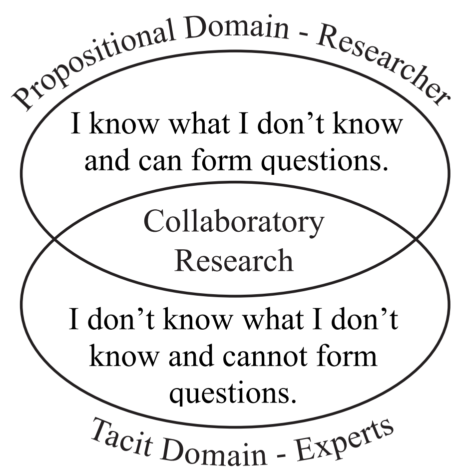

Figure 5. Collaboratory diagram (adapted from Guba & Lincoln, 1981; Twining, 2000).

The method of this research was based on the assumption that knowledge is a social construct and collaborative learning processes can take place between researchers and experts as a group. By forming propositions about issues developed from the review of the literature, I was able to elicit multiple responses or opinions from the experts on each question. These responses or expert opinions might otherwise have remained unspoken and unpublished in the literature. The internet provided the platform for this collaboratory.

Each panel member logged onto an internet web site to view and complete the instrument on-line. The instrument was produced in Microsoft FrontPage® with the use of the FrontPage

Extensions® forms tools. When each panelist completed each round of the survey, the data were submitted in coded format to a FrontPage® forms-results file available only to the researcher conducting this study. Categorized panelist comments and data analysis were returned to the panel after the first and second rounds. Figure 6 is a block diagram of the Delphi Survey process used in this research.

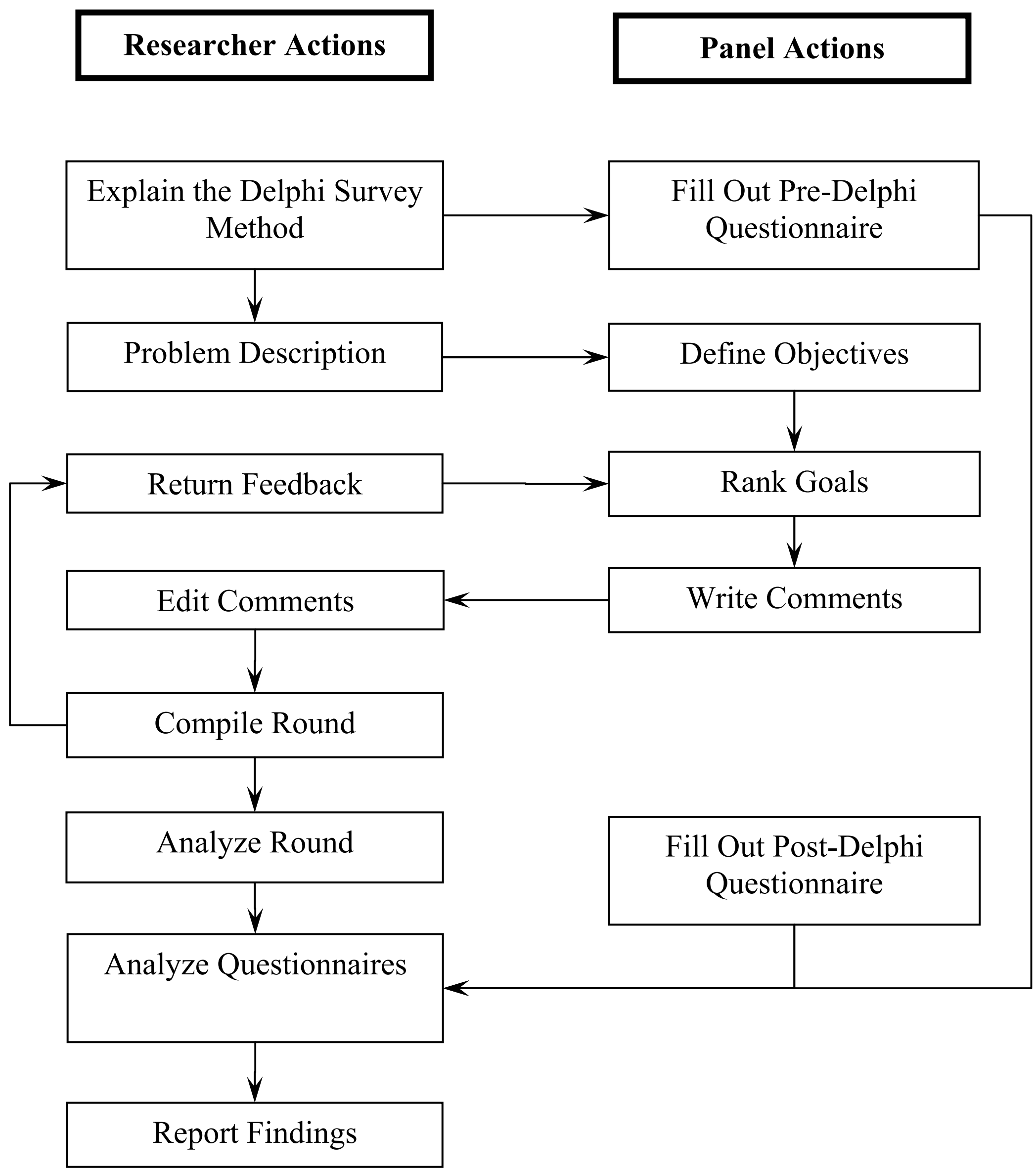

Figure 6. Block diagram of the Delphi Survey iterations

The figure provides a process flow to guide the researcher's and the panel's actions. Appendix E contains complete descriptions of the blocks.

In summary of the constructivist paradigm used for this research, rather than prematurely setting *a priori* hypothesis for this research, for the initial questions I composed open-ended questions from the literature to allow the questions to develop in subsequent rounds in an emergent format. This approach/strategy allowed pluralism in opinion from experts who use the technology in a variety of environments. I treated individual differences as important findings rather than categorizing them as outliers and discarding them as statistical anomalies, as other research paradigms might do.

CHAPTER 4

FINDINGS AND ANALYSIS

This chapter contains information on the demographics of the panel, the distribution of the Delphi questionnaires, the response rate, and a summary of each of the three rounds of the survey. Round one was constructed from a review of the literature, while rounds two and three were of an emergent design developed from their predecessors. The panel was instructed that the declarative nature of the survey questions was not intended to imply an opinion or degree of certainty on the part of the researcher.

Demographics of the Panel

The selection of the Delphi panel of experts began in January 2003. An exhaustive attempt was made to identify the entire population of experts in the field (limited to the United States) who had published papers or obtained funded grants related to the topic of the study. Approximately 100 individuals were identified. From this population a purposeful sample of about 50 individuals was contacted about participating in this study. Several individuals suggested other experts whom I had not identified. The selection process identified those individuals with the most experience and active involvement in research and publication in the field. Twenty-one individuals agreed to participate in the study. The panel was composed of a mix of male/female participants, including two independent experts not employed by educational institutions, and two artists/educators.

Survey Distribution and Response Rate

Panel members were notified by e-mail before each round began. In the first round 21 panelists responded, in the second round 18 (86%) responded, and in the third round 15 (71%) responded. Many panelists completed the first round within hours. Despite an effort to test and retest the electronic internet-based Delphi Survey instrument during a pilot test and before each round, several unforeseen problems arose at the beginning of round two. Almost immediately one panelist reported a problem that I traced to hypertext markup language (html) code that worked in Microsoft Internet Explorer® but was incompatible with the Netscape® internet browser. A second panelist reported security problems related to internet firewall electronic protection software at his location. In the process of fixing these problems I discovered a third problem: Participants could inadvertently delete their responses and possibly not notice the deletion. To fix the problems, I temporarily blocked access to the website for one day. During this time several panelists reported by e-mail that they had attempted to complete the survey but could not access the blocked website. Upon correcting the difficulties, I e-mailed each panel member explaining the problem. After two weeks, when most of the panel members had not completed round two, I phoned all of the non-responding panel members to request their continued participation in the survey. Two panelists declined, one indicated that he might not have the time, and the remaining agreed to continue. In contrast with the problems experienced in the second round, the third round was completed almost overnight, with one panelist declining with reason (confidential) and two other panelists declining without further comment.

Construction and Methodology of Response Analysis: Round One Questionnaire

Round one was constructed from information culled from a review of the literature. No definition of prototype was presented *a priori*, in recognition of the pluralistic use of the word in different environments. For example, an industrial designer might consider an original model cut from foam by hand in a few minutes to be the prototype on which the final product is patterned. On the other hand, a manufacturing engineer might label a first full-scale and functional form of a new type or design as a prototype. A continuum of definitions also exists between these two. The responses to the round one broad-based and perhaps ambiguous questions were categorized for formulation of the round two summarizing statements. Where I was unable to categorize the comments, I edited the round two questions to elicit a Likert-type response. The comments and the categories in which I placed them may be found in Appendix H for audit. The round one comments were also returned to the panel in round two.

Research Question Q1

"What term do you prefer to use for 'rapid prototyping technology' and why?" Five different terms were identified as preferred, indicating that the technology is not a "whole product" by Moore's definition. The term "RP" was cited most often as the preferred term, but the full term "Rapid Prototyping" presents some problems, as it is also commonly used in electronics circuit design and in computer programming. The other four terms categorized were Computer Aided Additive Manufacturing (CAMM), Solid Modeling (SM), Solid Freeform Fabrication (SFF), and Layered Manufacturing (LM).

Research Question Q2

"Do you think 3D CAD modeling will become the initial or default design tool in CAD-related education and if so why and by what year? Describe the role that you foresee for 3D CAD in engineering design curricula?" The preponderance of responses indicated that 3D CAD is now the default tool or soon will be in engineering design-related curricula. The comments generally indicated that 2D CAD is an outdated technology. One respondent wrote, "2-D drafting, even on a computer, is already an outdated paradigm. Professors who still use it are just simply outdated and not ready to upgrade to 3-D." However, another respondent wrote, "…we have a bit of the "chicken and the egg." Approximately 25% of industry uses 3D CAD (solid modeling)…." Clearly, curriculum and industry are at a transition point in moving away from one technology (2D CAD) and adopting a new technology (3D CAD).

Research Question Q3

"In your opinion, might Virtual Reality (VR) become a replacement for RP in engineering design curricula? If so, when and under what conditions?" The general opinion indicated that VR and RP are complementary technologies and that one technology is unlikely to replace the other.

Research Question Q4

"Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students? If so, describe the differences." Many of the respondents to this question stated either that they didn't know or that there were no differences. Several respondents cited a history of male dominance in the field that could be affected by use of the technology.

Research Question Q5

"Should students, a technician, or a faculty member run the machine, and under what conditions?" There was a wide variety of opinion on this question. The responses indicated that the answer to the question is situational dependent. One respondent wrote, "This is a foolish question..." Some responded that the technology was too expensive or complicated to have students run the machine. However, others responded that they had neither the money (budget) to hire a technician, nor the time (as faculty) to run the machine. One respondent wrote, "…[the machines] should not be used by students without faculty or staff supervision. When machines exist that are akin to printers next to a PC, then that will be different."

Research Question Q6

"Do you expect the cost of RP technology to decrease dramatically in the near future? What would be the optimal cost for perceived benefit for introducing the technology into the curriculum? At an optimal cost/benefit would you expect that the majority of schools and small to medium size companies will bring RP technology in-house?" From the responses it might be concluded that this question is actually three questions and also is too ambiguous. For example, how does one measure a "dramatic" decrease in cost?

Research Question Q7

"List in order of importance, related to the use of RP in the curricula, the properties of: aesthetics, accuracy/repeatability, machine cost, material mechanical properties, speed, technical support, machine reliability, cost of raw material, ease of operation, cost of operation, other. List properties with the number 1 being the most important. Comment on reasoning where appropriate." Machine cost, cost of raw material, and cost of operation were most often listed one, two, or three in order of importance. For round two these three parameters were combined into the category "Total Cost of Operation."

Research Question Q8

"Assuming a RP model could have ONE property identical to the finished product, state the property that would be most important in an educational environment. Comment on reasoning where appropriate." Based on the comments the general categories of Geometric Accuracy, Mechanical Properties, Appearance, Other, and No Opinion were formulated for rating in round two.

Research Question Q9

"What machine (brand and model) would you currently recommend for purchase for use in a product design related curricula?" Based on the comments the general categories of Too Many Factors, Z-Corp® 3D Printer, Stratasys Demension®, 3D Systems Thermojet®, 3D Systems SLA®, No Opinion, and Other were formulated for rating in round 3.

Research Question Q10

"How will RP technology affect design education to the year 2010?" Based on the comments to this question and the previous nine questions, the question was revised in round two to reflect the opinion that RP might be considered a tool rather than a field of study. The revised question was formulated to attempt to clarify the opinion of the panel of experts. For round two the categories of study of RP, 3D-Printer/Concept Modeler, Rapid Manufacture were proposed.

Summary of Round One

I began round one in a discovery posture, having read the related literature and formed 10 questions to explore in the collaboratory environment of the Delphi Survey. To ensure rigor, I derived emergent categories from the responses to more clearly focus the questions through a recycling process in succeeding rounds for the purposes of determining applicability to the statement of the problem and ultimately identifying areas of consensus. The summary statements developed from round one were verified for consistency in round two.

Construction and Methodology of Content Analysis: Round Two Questionnaire

The questions were revised for round two based on the comments from round one. The round one comments are listed in Appendix H. To test consistency and validate the applicability of the questions to the statement of the problem, I edited the questions to request selections of preferences or level of agreement on a Likert-type scale. Before choosing preferences or levels of agreement in round two, the panelists could view the comments from the first round and make additional comments.

The suffix letter "a" was added to the revised questions for round two. For example, research question Q1 from round one became research question Q1a in round two. The revised round two questions and responses follow.

Research Question Q1a

"What term do you prefer to use for 'rapid prototyping technology'?" From the results of round one, six options were presented in round two. Table 1 shows the responses to the round two question.

Table 1. Research Question Q1a Results.

CAAM	SM	RP	SFF	LM	Other
Computer Aided Additive Manufacturing 0.0%	Solid Modeling 5.6%	Rapid Prototyping 66.7%	Solid Freeform Fabrication 22.2%	Layered Manufacturing 0.0%	5.6%
n=18					

Research Question Q2a

"Do you think 3D CAD modeling will become the initial or default design tool in the majority of CAD-related curriculums and if so why and by what year?" From the results of round one, five options were presented in round two. Table 2 shows the responses to the round two question.

Table 2. Research Question Q2a Results.

3D CAD is current default design tool	Within 5 years	5-10 years	Other Opinion	No Opinion
38.9%	44.4%	11.1%	0.0%	5.6%
n=18				

Research Question Q3a

"In your opinion, might Virtual Reality (VR) become a replacement for RP in engineering design curricula when the VR technology improves?" From the results of round one, five options were presented in round two. Table 3 shows the responses to the round two question.

Table 3. Research Question Q3a Results

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
0.0%	38.9%	11.1%	44.4%	5.6%
n=18				

Research Question Q4a

"Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students?" From the results of round one, five options were presented in round two. Table 4 shows the responses to the round two question.

Table 4. Research Question Q4a Results

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
5.6%	5.6%	22.2%	55.6%	11.1%
n=18				

Research Question Q5a

"In your opinion, in most circumstances where RP is used in engineering design curricula should students, a technician, or a faculty member run the machine?" From the results of round one, five options were presented in round two. Table 5 shows the responses to the round two question.

Table 5. Research Question Q5a Results

Students	Technician	Faculty	Other	No Opinion
27.8%	27.8%	22.2%	16.7%	5.6%
n=18				

Research Question Q6a

"The total cost of operation of RP technology will decrease dramatically in the next 5-10 years?" From the results of round one, five options were presented in round two. Table 6 shows the responses to the round two question.

Table 6. Research Question Q6a Results

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
16.7%	55.6%	5.6%	22.2%	0.0%
n=18				

Research Question Q7a

"Total cost of operation is the most important factor related to the use of RP in the curricula?" From the results of round one, five options were presented in round two. Table 7 shows the responses to the round two question.

Table 7. Research Question Q7a Results

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
27.8%	50.0%	0.0%	16.7%	5.6%
n=18				

Research Question Q8a

"Assuming a RP model could have ONE property identical to the finished product from the list: Geometric accuracy, Mechanical properties, Appearance, which property is the most important in an educational environment?" From the results of round one, five options were presented in round two. Table 8 shows the responses to the round two question.

Table 8. Research Question Q8a Results

Geometric accuracy	Mechanical properties	Appearance	Other	No Opinion
44.4%	22.2%	33.3%	0.0%	0.0%
n=18				

Research Question Q9a

"What RP machine would you currently recommend for purchase as appropriate in the majority of product design-related curriculums?" From the results of round one, seven options were presented in round two. Table 9 shows the responses to the round two question.

Table 9. Research Question Q9a Results

Too many factors	Z-Corp 3D Printer	Stratasys Dimension	3D Systems Thermojet	3D Systems SLA	No Opinion	Other
16.7%	22.2%	33.3%	11.1%	5.6%	5.6%	0.0%
n=18						

Research Question Q10a

"Based on the panel comments to questions 1-10 is it your opinion that future research of the effects of "RP technology" using the Delphi method should be subdivided into the categories: RP, 3D-Printer/Concept Modeler, Rapid Manufacturing?" From the results of round one, five options were presented in round two. Table 10 shows the responses to the round two question.

Table 10. Research Question Q10a Results

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
5.6%	22.2%	27.8%	38.9%	5.6%
n=18				

Summary of Round Two

The results of round two reflect the pluralistic environments in which the different experts use RP technology. The results were consistent with the review of the literature, establishing the truth value and applicability of the questions with regard to the problem statement. The panel comments and results of round two were made available to the panel for round three.

Construction and Methodology of Content Analysis: Round Three Questionnaire

Based on the results of the literature review, round one, and round two, the summarizing statements were revised for round three to identify areas of consensus. With the definition of consensus used for this research, only two options were given, "agree" or "disagree", but the panel could add final comments.

The suffix letter "b" was added to the revised questions for round three. For example, research question Q1a from round two became research question Q1b in round three. The revised round three questions and responses follow.

Research Question Q1b

"Given the definition of consensus for this research, I accept Rapid Prototyping (RP) as the consensus term for 'rapid prototyping technology'?" From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 86.7% giving the 'agree' response and 13.3% the 'disagree' response.

Research Question Q2b

"Given the definition of consensus for this research, I accept as consensus the projection that 3D CAD modeling will be the initial or default design tool in the majority of CAD-related curriculums within 5 years." From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 100.0% giving the 'agree' response and 0.0% the 'disagree' response.

Research Question Q3b

"Given the definition of consensus for this research, I accept as consensus the projection that Virtual Reality will not become a replacement for RP in engineering design curricula." From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 80.0% giving the 'agree' response and 20.0% the 'disagree' response.

Research Question Q4b

"Given the definition of consensus for this research, I accept as consensus the proposition that the inclusion of RP technology into the engineering design curricula does not have different effects on male and female students." From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 93.3% giving the ‘agree’ response and 6.7% the ‘disagree’ response.

Research Question Q5b

“Given the definition of consensus for this research, I accept as consensus the proposition that in most circumstances where RP is used in engineering design related curricula a technician or faculty member is more likely than a student to run the machine.” From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 80.0% giving the ‘agree’ response and 20.0% the ‘disagree’ response.

Research Question Q6b

“Given the definition of consensus for this research, I accept as consensus the projection that the total cost of operation of RP technology will decrease dramatically in the next 5-10 years.” From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 93.3% giving the ‘agree’ response and 6.7% the ‘disagree’ response.

Research Question Q7b

“Given the definition of consensus for this research, I accept as consensus the proposition that the total cost of operation is the most important factor related to the use of RP in the curricula.” From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 93.3% giving the ‘agree’ response and 6.7% the ‘disagree’ response.

Research Question Q8b

"Given the definition of consensus for this research, I accept as consensus the proposition that, assuming a RP model could have one property identical to the finished product, that geometric accuracy is the property that is the most important in an educational environment." From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 93.3% giving the 'agree' response and 6.7% the 'disagree' response.

Research Question Q9b

"Given the definition of consensus for this research, I accept as consensus the proposition that the currently available RP machine most appropriate for the majority of product design-related curriculums is the Stratasys Dimension." From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 73.3% giving the 'agree' response and 26.7% the 'disagree' response.

Research Question Q10b

"Given the definition of consensus for this research, I accept as consensus the proposition that future research of the effects of 'RP technology' using the Delphi method should not be subdivided into the categories: RP, 3D-Printer/Concept Modeler, and Rapid Manufacturing." From the results of round two, the question was edited to identify consensus and presented in round three. Fifteen panelists responded in round three with 86.7% giving the 'agree' response and 13.3% the 'disagree' response.

Summary of Round Three

The only question for which consensus was identified in this survey was question number two, dealing with the curriculum transition from 2D CAD to 3D CAD. The percentage of panelists who agreed or disagreed should not be construed as a measure of the closeness to consensus as defined for this research. However, the results form a basis for future negotiation to identify consensus that might best be carried out in a collaboratory format. The final comments to round three are included in Appendix K. Chapters 1 through 4 and the appendixes provide an audit trail for the interested researcher. I have completed my obligation to provide information that will allow users to judge external validity in application as a decision-making aid for curriculum development related to the use of RP technology in their particular settings. Table 11 shows a summary of the results. My interpretation, conclusions, and recommendations based on these results appear in Chapter 5.

Table 11. Summarizing Statement Results

Question	Summarizing Statement	Agree	Disagree
Q1b	Given the definition of consensus for this research, I accept Rapid Prototyping (RP) as the consensus term for ‘rapid prototyping technology’?	86.7%	13.3%
Q2b	Given the definition of consensus for this research, I accept as consensus the projection that 3D CAD modeling will be the initial or default design tool in the majority of CAD-related curriculums within 5 years.	100.0%	0.0%
Q3b	Given the definition of consensus for this research, I accept as consensus the projection that Virtual Reality will not become a replacement for RP in engineering design curricula.	80.0%	20.0%
Q4b	Given the definition of consensus for this research, I accept as consensus the proposition that the inclusion of RP technology into the engineering design curricula does not have different effects on male and female students.	93.3%	6.7%
Q5b	Given the definition of consensus for this research, I accept as consensus the proposition that in most circumstances where RP is used in engineering design related curricula a technician or faculty member is more likely than a student to run the machine.	80.0%	20.0%
Q6b	Given the definition of consensus for this research, I accept as consensus the projection that the total cost of operation of RP technology will decrease dramatically in the next 5-10 years.	93.3%	6.7%
Q7b	Given the definition of consensus for this research, I accept as consensus the proposition that the total cost of operation is the most important factor related to the use of RP in the curricula.	93.3%	6.7%
Q8b	Given the definition of consensus for this research, I accept as consensus the proposition that, assuming a RP model could have one property identical to the finished product, that geometric accuracy is the property that is the most important in an educational environment.	93.3%	6.7%
Q9b	Given the definition of consensus for this research, I accept as consensus the proposition that the currently available RP machine most appropriate for the majority of product design-related curriculums is the Stratasys Dimension.	73.3%	26.7%
Q10b	Given the definition of consensus for this research, I accept as consensus the proposition that future research of the effects of ‘RP technology’ using the Delphi method should not be subdivided into the categories: RP, 3D-Printer/Concept Modeler, and Rapid Manufacturing.	86.7%	13.3%
n=15			

CHAPTER 5

INTERPRETATION, CONCLUSIONS, AND RECOMMENDATIONS

Review of the Study

In Chapter 1, I introduced the purpose of this study as a decision-making aid in curriculum development related to the use of RP technology. The chapter introduced 10 initial research questions to be developed throughout the study. In Chapter 2, I reviewed the literature in the field of RP technology as used in classroom and laboratory instruction. In Chapter 3, the Delphi Survey method was presented as an appropriate method for gathering information on complex or ambiguous technology forecasting problems that exceed the capabilities of a single person. Then, in Chapter 4, in an attempt to identify areas of consensus of opinion, I reported the development of the round one initial research questions through two additional iterations.

In round one of the Delphi Survey I introduced a broad series of statements or questions culled from the literature and asked the expert panel to make comments. The responses from round one were used to narrow the broad statements or questions into more specific selections in round two. The selections and comments from round two were used to formulate statements to identify areas of consensus of opinion in round three.

This chapter develops those expert opinions into conclusions and recommendations using the 10 research questions and the definition for consensus taken from the BNQA process. In keeping with the "collaboratory" nature and constructivist paradigm of this research the interpretations, conclusions, and recommendations are presented as a source of qualitative information rather than the empirical evidence that the reader might hope to find to support a decision. Each reader should carefully examine this research and construct their own analysis as to the applicability of the information presented to their particular decision needs.

In comparing their own analysis to the conclusions presented here, readers should recognize that qualitative research cannot be separated from the researcher's experiences and biases. I am currently preparing specifications for the approved purchase of a fourth RP machine at my campus. I have primary access to an FDM (just across the hall from my office) and secondary access (through colleagues on campus in another building) to an STL machine and a BPM machine.

Research Question Q1b Conclusions

"Given the definition of consensus for this research, I accept Rapid Prototyping (RP) as the consensus term for 'rapid prototyping technology'?" The panel did not reach consensus on this statement. A search on the internet using the keyword phrase "rapid prototyping" revealed that this term is also used in electronics circuit design and in software design, which might lead to confusion. From the comments of the experts the term may be considered either too broad or too limiting. However, the term is understood by all in the field and probably will continue as the most often used. As one panelist commented, "We all know what it means… so let's get on with it!"

Research Question Q2b Conclusions

"Given the definition of consensus for this research, I accept as consensus the projection that 3D CAD modeling will be the initial or default design tool in the majority of CAD-related curriculums within 5 years." The panel reached consensus on this statement. It should be noted that 3D CAD modeling is a prerequisite for RP, and therefore the experts on this panel may have more experience with 3D CAD than most users of 2D CAD. Given the estimate that 75-80% of industry has not yet upgraded to 3D CAD, this consensus result has very significant implications for curriculum development and faculty training. An indication of resistance to change from 2D to 3D CAD might be the basis behind one panelist's comments that, "3-D CAD is already the default starting point for engineering design education. 2-D drafting, even on a computer, is already an outdated paradigm. Professors who still use it are just simply outdated and not ready to upgrade to 3-D [sic]."

Research Question Q3b Conclusions

"Given the definition of consensus for this research, I accept as consensus the projection that Virtual Reality will not become a replacement for RP in engineering design curricula." The panel did not reach consensus on this statement. The most common opinion was that VR is more likely to compliment rather than replace RP technology. The panel's comments suggest that the experts consider VR technology less mature than RP. The recent improvements in the 3D visualization tools in the software allowing real-time rotation and relative movement of CAD models and assemblies, as computers (PCs) have gotten faster and less expensive, might already have reduced, but not replaced, the need for RP models. Future development in VR technology might have significant effects on the engineering design curriculum and should be investigated, but as one panelist commented, "Difficult to answer. VR is very powerful in several ways, but needs a lot of development. It will be easier to answer this question 5 years later. [sic]"

Research Question Q4b Conclusions

"Given the definition of consensus for this research, I accept as consensus the proposition that the inclusion of RP technology into the engineering design curricula does not have different effects on male and female students." The panel did not reach consensus on this statement. The comments revealed a wide range of opinions on this question. Several panelists responded that in their experience there were no differences, with one commenting, "I do not see why? [sic] I fail to understand this question!" Many panelists responded that they were undecided or didn't know if there were any differences. Others commented on the historical domination of males in the field and offered the opinion that the technology might draw more females into the field.

One panelist asserted that gender doesn't matter as far as curriculum development is concerned and responded, "No decisions about curriculum should be based on any minority status. Curriculum decisions should be based on industry needs. Not on how it will affect any minority. [sic]"

Research Question Q5b Conclusions

"Given the definition of consensus for this research, I accept as consensus the proposition that in most circumstances where RP is used in engineering design related curricula a technician or faculty member is more likely than a student to run the machine." The panel did not reach consensus on this statement. From the comments of the experts, one can surmise that the question of who will run the machine is situational. The implications are very important, as there is evidence that erroneous information might lead a potential user of the technology to believe that it is as easy to print a 3D model using RP technology as it is to print a traditional 2D drawing of the model on paper with a laser printer or plotter. The level of training and skill needed to operate the machines varies among the different machines. Generally the least expensive machines are the easiest to operate. Even the fastest machine may take several hours to produce a model. A decision must be made about whether unattended operation will be allowed. Safety is a concern with some of the equipment restricting or precluding student operation of the machine. The cost of the person to operate or to supervise the machine operation should be considered before including the technology in the curriculum. The curriculum goals of how the technology could provide the most benefit to the students should also be considered.

Research Question Q6b Conclusions

"Given the definition of consensus for this research, I accept as consensus the projection that the total cost of operation of RP technology will decrease dramatically in the next 5-10 years." The panel did not reach consensus on this statement. At least one panelist cited that there was no clear definition of the word "dramatically" and that the technology could improve while the cost remains relatively unchanged. Two of the pioneer manufacturers of RP machines have gone out of business in recent years. In addition, at the time I was concluding this research the largest manufacturer, 3D Systems, was experiencing financial difficulty and potential delisting from the Nasdaq stock exchange (CAD/CAM Publishing, 2003a). For some research institutions the cost of the technology is not a barrier, while for other institutions it is.

Research Question Q7b Conclusions

"Given the definition of consensus for this research, I accept as consensus the proposition that the total cost of operation is the most important factor related to the use of RP in the curricula." The panel did not reach consensus on this statement. The original question listed several properties of the models produced by RP technology, in addition to technical support and properties of the machines. In making the decision to purchase one of the machines, individuals would be prudent to list the expectations of the product of the machine, that is, the model properties. For many of the panelists the cost of the technology seemed to be an overriding concern related to several of the research questions. As one panelist noted, however, "It is a shame that educators place cost above learning. The purpose of using RP equipment in a school is not to use RP equipment, [sic] the purpose should only be to learn…" In contrast, another panelist commented, "You must have dollars for this technology!" The benefit of using the technology in the curriculum should be considered in relation to the cost.

Research Question Q8b Conclusions

"Given the definition of consensus for this research, I accept as consensus the proposition that, assuming a RP model could have one property identical to the finished product, that geometric accuracy is the property that is the most important in an educational environment."

The panel did not reach consensus on this statement. The various machines included under the umbrella term “RP” are best at mimicking one or several properties of a finished product manufactured with standard technology, but no one RP technology is yet capable of reproducing all properties. The decision of which property is most important will vary, based on particular curriculum goals. For example, in an industrial design-based curriculum aesthetic appearance might be the most important property, while in a mechanics based curriculum the strength of the material might be the most important property identical to the finished product.

Research Question Q9b Conclusions

“Given the definition of consensus for this research, I accept as consensus the proposition that the currently available RP machine most appropriate for the majority of product design-related curriculums is the Stratasys Dimension.” The panel did not reach consensus on this statement. Different curricula emphasize different properties in the finished RP model, so it is not surprising that given that no RP machine is yet capable of producing models with properties identical to conventional manufacturing processes, there is no consensus of opinion as to one most appropriate machine.

Research Question Q10b Conclusions

“Given the definition of consensus for this research, I accept as consensus the proposition that future research of the effects of ‘RP technology’ using the Delphi method should not be subdivided into the categories: RP, 3D-Printer/Concept Modeler, and Rapid Manufacturing.” The panel did not reach consensus on this statement. From the review of the literature and from comments to questions 1-9 in the first two rounds, there seems to be an inferred but unstated continuum of sophistication of the technology with 3D-Printing/Concept modeler occupying the position as least sophisticated to RP as the state-of-the-art occupying a separate category from the former, and with Rapid Manufacturing based on RP technology as the ultimate goal of the future. The NCMS document *The Road to Manufacturing: 1998 Industrial Roadmap for the Rapid Prototyping Industry* and Wohlers in the *Wohlers Report* proposed similar categories. According to Wohlers, in 2002 virtually all of the increase in sales of the technology was in the low-priced concept modeler category (CAD/CAM Publishing, 2003b).

Implications of the Study

Based on a review of the literature, 10 questions were developed for this research. The importance of the implications of each of these questions will vary among curriculum programs. In the spirit of a collaboratory research effort, the procedure was to ask questions about what is known and what is unknown, and then to collect information that aids in the decision-making process.

The first question, relating to the preferred term for “RP,” illustrates the lack of “whole product” status by Moore’s definition, but is probably a moot concern at this point, as the term RP has been used often enough that it is not likely to be replaced. Throughout this research I have generally referred to RP as though it were, in fact, a consensus term.

The second question, relating to 3D CAD, might represent a revolutionary change when considering what will have to occur in order for the consensus opinion to prevail. If the measure of penetration of 3D CAD in education mirrors the industry use, programs that have already migrated to 3D CAD as the default design tool are probably ahead of the curve at this time. If most educational programs will have made the change within 5 years, as forecast by the panel of experts, the corollary is that industry must also make this change, or graduates’ skills will not match the required skills in the field. Therein lays the real challenge, and what might represent the most significant finding of this study.

In the third question, VR technology has probably not yet matured enough to be considered as a replacement to RP. There may need to be some clarification in continuing research over the purpose of a prototype and a “real part”. Indicators within the comments of many of the experts imply that what they really want from the technology is a real part, not a prototype. If VR technology ever improves enough, both through visual feedback and perhaps even through haptic or tactile feedback, the need for most physical prototypes might be eliminated. The ultimate goal is rapid manufacturing of real parts, not prototypes.

The responses to the fourth question, about possible gender issues related to the use of the technology, appears to be either a non-issue in reality or one that few people have considered. This issue might be more likely examined from a historical perspective 10 years from now, rather than as a directed effort in the present.

The fifth question, about who will run the machine, is probably a neglected question until after the purchase is made. It might be interesting to gather data on the number of hours currently installed machines are used, along with data on who is actually operating which machines and how the use relates to curriculum goals. In round one of the Delphi Survey a panelist commented on the question of who should run the machine, "This is a foolish question. Activities should be chosen based on learning objectives. A rigorous adherence to any of the above three seems to be a managerial decision, and I have seen all three work successfully. I really hope this Delphi process does not result in any of the three being recommended over the others."

Questions six through nine could probably be rendered down to the basic question of cost. The ideal machine would print a real product with all the desired properties. It would cost no more than the conventional manufacturing processes used to create the real product, and it would be as easy to operate as an office laser printer. Each decision-maker must evaluate what he or she expects from the technology in terms of these four questions.

Question ten relates to all of the previous questions in terms of a prototype's definition. For this research, I did not present a definition and none was offered by the panel. Yet clearly the most basic question that should be answered before deciding whether or how to include the technology in the curriculum should be this: For the purpose of defining our curriculum goals, what is a prototype, and can this technology help us reach those goals?

Recommendations for Further Research

Each of the 10 questions has implications for future curriculum development. However, question two, the single question for which consensus was identified, probably presents the most immediate need for further research and development of an action plan. In the remaining nine questions, future research in a collaboratory environment might be able to identify negotiable consensus. In four of these remaining nine questions in which consensus was not identified only one panelist, (not always the same panelist), disagreed with the summarizing statement. This could indicate that a fourth round or future research replicating this study might result in refinement to the statements that could identify emergent consensus. In an intact work-group, for example an engineering design program at a particular university, consensus on these research questions might be negotiated for the purpose of making decisions.

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APPENDIXES

Appendix A

NSF RP Grant Awards

Categorized NSF RP Grant Awards	
NSF RP Grants Categorized as Applied Research Funding	13,781,183.00
NSF RP Grants Categorized as Basic Research Funding	16,801,653.00
NSF RP Grants Categorized as Conference or Seminar Funding	428,110.00
	$31,010,946.00

NSF RP Grants Categorized as Applied Research Funding						
Grant	Amount	Start Date		Grant	Amount	Start Date
9150291	60,708.00	8/31/1991		9724528	103,993.00	8/31/1997
9121978	79,870.00	5/31/1992		9724186	280,000.00	10/1/1997
9251834	47,900.00	6/30/1992		9851495	15,037.00	5/31/1998
9250614	45,000.00	7/31/1992		9850498	53,450.00	5/31/1998
9213083	50,000.00	8/14/1992		9732046	397,848.00	6/1/1998
9415345	320,374.00	6/30/1994		9851314	57,584.00	6/30/1998
9451371	99,900.00	9/14/1994		9851200	55,000.00	7/31/1998
9420397	1,394,893.00	11/14/1994		9850574	30,365.00	8/14/1998
9552248	69,500.00	5/14/1995		9874965	200,000.00	6/30/1999
9552288	53,851.00	5/31/1995		9905140	1,000,000.00	8/1/1999
9551741	40,634.00	5/31/1995		9950816	100,000.00	9/1/1999
9420396	1,519,670.00	5/31/1995		9984051	260,008.00	4/15/2000
9550953	70,316.00	6/30/1995		9952364	80,322.00	4/15/2000
9551467	49,882.00	8/31/1995		79397	340,500.00	7/14/2000
9553038	375,000.00	10/31/1995		86065	2,296,599.00	8/31/2000
9529530	76,918.00	2/14/1996		88315	96,962.00	12/31/2000
9650653	47,040.00	6/30/1996		90422	599,898.00	2/14/2001
9650418	46,000.00	6/30/1996		88669	414,301.00	2/14/2001
9650013	85,000.00	7/14/1996		101633	540,725.00	7/1/2001
9650800	51,338.00	7/14/1996		88064	399,998.00	7/14/2001
9610289	204,560.00	3/31/1997		114309	418,641.00	9/1/2001
9751482	47,150.00	5/31/1997		202256	346,146.00	4/15/2002
9752021	600,000.00	6/14/1997		127397	74,778.00	4/15/2002
9750961	31,500.00	6/30/1997		127081	87,299.00	5/31/2002
9750743	64,725.00	8/14/1997				
	$5,531,729.00				$8,249,454.00	
					$13,781,183.00	

NSF RP Grants Categorized as Basic Research Funding										
Grant	Amount	Start Date		Grant	Amount	Start Date		Grant	Amount	Start Date
9122123	189,708.00	8/31/1992		9625752	410,176.00	7/31/1996		9860948	100,000.00	12/31/1998
9311345	13,000.00	3/31/1993		9622220	42,266.00	7/31/1996		9860606	100,000.00	12/31/1998
9312603	15,000.00	5/31/1993		9632345	451,052.00	8/14/1996		9861182	100,000.00	12/31/1998
9312932	255,668.00	9/14/1993		9530741	126,030.00	8/31/1996		9860883	99,988.00	12/31/1998
9361795	65,000.00	1/14/1994		9634393	159,355.00	8/31/1996		9860715	93,965.00	12/31/1998
9361426	64,463.00	2/14/1994		9661204	74,407.00	12/31/1996		9902340	109,483.00	5/31/1999
9457205	303,795.00	8/31/1994		9622400	304,644.00	1/31/1997		9874971	260,000.00	6/1/1999
9457206	275,000.00	9/14/1994		9628968	300,000.00	1/31/1997		9875445	210,000.00	7/31/1999
9414793	236,972.00	9/30/1994		9612676	0.00	2/28/1997		9975961	160,125.00	8/15/1999
9420099	1,024,595.0	11/14/1994		9796186	240,029.00	2/28/1997		9908249	359,904.00	8/31/1999
9413026	75,000.00	12/14/1994		9634962	271,863.00	3/1/1997		9902669	262,523.00	9/1/1999
9420356	300,000.00	12/31/1994		9634931	299,981.00	4/30/1997		9901827	400,000.00	9/14/1999
9415001	247,800.00	12/31/1994		9618034	435,561.00	6/14/1997		9960925	99,600.00	12/31/1999
9420386	375,000.00	1/14/1995		9700007	297,140.00	8/1/1997		9980795	373,554.00	12/31/1999
9420357	1,055,003.00	1/14/1995		9724357	198,766.00	9/14/1997		9982010	370,000.00	3/31/2000
9461693	74,927.00	1/31/1995		9713913	154,270.00	9/30/1997		9988664	282,939.00	8/1/2000
9420373	306,992.00	3/14/1995		9760607	100,000.00	12/31/1997		70429	374,850.00	8/14/2000
9500545	60,185.00	4/30/1995		9760545	100,000.00	12/31/1997		78990	135,000.00	8/31/2000
9502728	310,000.00	5/31/1995		9760459	99,999.00	12/31/1997		76498	301,500.00	9/30/2000
9528579	50,000.00	8/31/1995		9760429	99,568.00	12/31/1997		60707	99,937.00	12/31/2000
9522982	100,000.00	9/30/1995		9896394	140,771.00	1/31/1998		60046	99,976.00	12/31/2000
9512296	300,000.00	12/31/1995		9732848	210,000.00	4/15/1998		97521	348,948.00	5/1/2001
9529346	61,334.00	2/14/1996		9800187	185,000.00	6/14/1998		110486	500,000.00	8/31/2001
9561315	75,000.00	2/29/1996		9800493	99,999.00	7/31/1998		115091	252,021.00	9/1/2001
9633108	36,858.00	5/31/1996		9996045	56,318.00	7/31/1998		116753	149,711.00	10/1/2001
9625816	46,200.00	6/14/1996		9813042	65,441.00	8/15/1998		140625	80,000.00	6/15/2002
9529921	182,493.00	6/30/1996		9809198	55,000.00	9/1/1998				
	$6,099,993.00				$4,977,636.00				$5,724,024.00	
									$16,801,653.00	

NSF RP Grants Categorized as Conference or Seminar Funding		
Grant	Amount	Start Date
9055157	131,326.00	2/14/1991
9455076	95,284.00	1/14/1995
9614807	25,000.00	8/31/1996
9752015	100,000.00	7/31/1997
9812084	5,000.00	4/30/1998
9806467	5,000.00	7/14/1998
9820812	61,500.00	11/30/1998
9909127	5,000.00	8/31/1999
	$428,110.00	

Appendix B

ETSU Institutional Review Board

ETSU Campus Institutional Review Board
ETSU Institutional Review Board
Johnson City, TN

IRB APPROVAL - EXEMPT APPROVAL

Date: January 13, 2003
From: James J. Fox, III, Ph.D., Chairperson
Investigator: **Jeffrey D. Mather**
Protocol: Factors Forecasting the Effect of Rapid Prototyping Technologies on Engineering Design Education: A Delphi Survey
ID: 03063 Prom#: N/A Protocol#: c03-063c

The following items were reviewed and approved :

- **Letter to Delphi Panel (01/13/2003)**
- **Questionnaire / Survey - Pre-Delphia Questionnaire (01/13/2003)**
- **Questionnaire / Survey - Post-Delphi (12/08/2002)**
- **Questionnaire / Survey - Round One (12/08/2002)**
- **Questionnaire / Survey - Round Three (12/08/2002)**
- **Questionnaire / Survey - Round Two (12/08/2002)**
- **Narrative (01/13/2003)**
- **Form 103 (12/08/2002)**

I reviewed the above-referenced study and find that it qualifies as exempt from coverage under the federal guidelines for the protection of human subjects as referenced as Title 45—Part 46.101. The changes requested have been received. Your approval is acknowledged by this office as of January 13, 2003.

If you feel it is necessary to call further IRB attention to any aspects of this study, please refer to the above-titled project and IRB number. I appreciate your bringing this project before the IRB for its concurrence of exempt status.

Exemption Reference: 45CRF46.101(2)(b)(2)

The ETSU IRB is not connected with, has no authority over, and is not responsible for human research conducted at any other institution, except where a Memorandum of Understanding specifies otherwise. Separate consent forms, initial reviews, continuing reviews, amendments, and reporting of serious adverse events are required if the same study is conducted at multiple institutions.

Appendix C

Letter to the Delphi Panel

Hello,

I am a doctoral student at East Tennessee State University. The title of my dissertation is *Factors Forecasting the Effect of Rapid Prototyping Technologies on Engineering Design Education: A Delphi Survey*. I am currently employed as Assistant Professor, CAD and Product Design, Pennsylvania College of Technology, in Williamsport, PA. I have eight years of experience teaching at the collegiate level. Prior to entering the teaching profession I gained 15+ years of experience in manufacturing including positions as; Journeyman Machinist, Industrial Engineering Technician, and Research and Development Technician.

You have been selected, based on your experience, to participate as a panel member on this Rapid Prototyping research. Complete information regarding the survey can be found at: http://students.etsu.edu/mather/rp-survey/

This Delphi survey will run for three rounds spread over 7-14 weeks depending on response times by the panel of experts. It is expected that an average of one hour per round will be required to complete the survey.

At no time will any particular response to this survey be attributed to a particular panel member. Panel members will not be identified to others until the survey is complete and at that time they must elect to be identified; otherwise their participation will remain confidential.

Thank You,
J.D. Mather

Please feel free to contact me if you have any questions.

J.D. Mather
DIF 77
Pennsylvania College of Technology
One College Avenue
Williamsport, PA 17701
570 326-3761 ext. 7847
jmather@pct.edu

Doctoral Committee Chair
Dr. Terrence Tollefson
East Tennessee State University
Johnson City, TN
423 439-7617
tollefst@etsu.edu

Appendix D

Pre-Delphi Questionnaire

You have been selected for participation in a survey on Rapid Prototyping technology. Panel members were selected based on their expertise as evidenced by NSF Grants, journal publications, membership in SME/RPA, or nomination by peers. I developed this internet administered survey instrument based on the Delphi Method to take advantage of the "collaboratory" (collaboration + laboratory) nature of the world wide web in facilitating a group communication process.

All responses in a Delphi Survey are confidential. However, at the completion of the survey you may elect to be recognized for your participation on this panel. At no time will any individual response be associated with a particular panel member.

For this research the topic is:

Factors Forecasting the Effect of Rapid Prototyping on Engineering Design Education

If you have any questions please contact me:

J.D. Mather
Assistant Professor, CAD & Product Design
Pennsylvania College of Technology
DIF 77
One College Avenue
Williamsport, PA 17701
(570) 326-3761 ext. 7847
jmather@pct.edu

Please provide a unique Delphi panel member identification that you will use throughout the survey:

User Name

Title
Affiliation
Address
Phone
Email

I have at least one of the following experiences with Rapid Prototyping technology.

Grant	Publication	Applied or Basic Research	Utilization in Curriculum
Yes	Yes	Yes	Yes
No	No	No	No

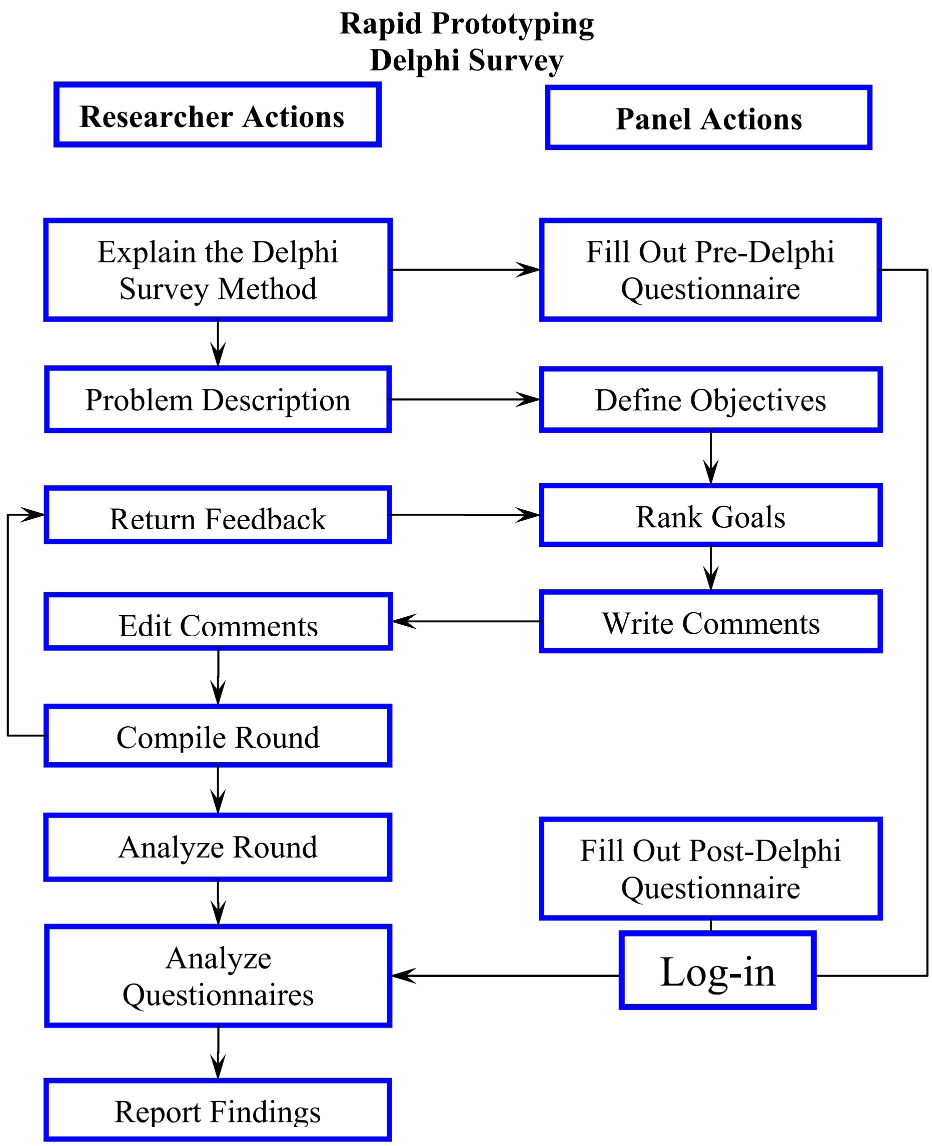
I would like to nominate the following person to participate on the Delphi panel.

Submit Form Reset Form

Thanks for completing the Pre-Delphi questionnaire.
Delphi Survey

Appendix E

On-line Delphi Method Description



For a complete description of each step in the Delphi Survey process click on the appropriate button, otherwise click on the Log-in button when you are ready to begin the survey.

Researcher Actions
The Delphi Survey method is a group communication process. The researcher acts as a facilitator for the group. For this research the topic: Factors Forecasting the Effect of Rapid Prototyping on Engineering Design Education has been selected. Each of the entries in the Research Actions column of the Delphi Survey Flowchart is hyper-linked to a complete description.
HOME Log-In

Delphi Survey Method

The Delphi Survey method was originally developed at the U.S. intelligence think-tank, the Rand Corporation, out of research started in the early 1950s by Norman Dalkey and Olaf Helmer (Linstone & Turoff, 1975). It was designed for use with complex or ambiguous technology forecasting problems that exceed the capabilities of a single person. The method relies on anonymous surveys of experts and is inclusive of qualitative expert opinion as well as quantitative factors. The Delphi method is described as a pure Lockean procedure because, starting from a blank slate, the data are the opinions of the experts and the validity of the judgment of the panel is measured by consensus (Linstone & Turoff, 1975). The philosophical basis is that an *a priori* hypothesis is not needed to collect data for a qualitative analysis of trends. The objective is to identify consensus of opinion (Linstone & Turoff, 1975). The basic assumption is that expert opinion can be of value in making a decision in situations where knowledge or theory is incomplete.

The method is an iterative process requiring two or more (usually three) rounds of survey of the panel of experts. This survey will last three rounds. In Round One the open-ended questions were developed from a review of the literature. The Second Round will be used to rank a summary of factors identified from Round One. Round Three will be used to analyzed consensus.

The anonymous participation of panelists reduces or eliminates the occurrence of a charismatic or otherwise influential participant from unduly influencing the consensus outcome for reasons other than the validity and strength of their arguments (Linstone & Turoff, 1975). Minority opinion holders are free to argue their positions as the participants move towards consensus through the iterative process.

The panel of experts were selected by first, identifying key faculty members at universities that use RP technology identified from published research, and second, by nominations by the faculty members previously identified and by the Rapid Prototyping Association of the Society of Manufacturing Engineers (RPA/SME).

Following the Dalkey (1975) restrictions for the group estimation process, the types of data expected to be collected by this survey are: dates, costs, probability of events, and performance expectations for the technology. The survey will be administered over the Internet. Each panel member will log onto a World Wide Web site to view and complete the instrument on-line.

HOME Log-In

Problem Description

For this research the topic: Factors Forecasting the Effect of Rapid Prototyping on Engineering Design Education has been selected. A review of the literature reveals that there are a number of factors involved with the use of Rapid Prototyping technology which may impact curriculum design.

The primary sources of questions for the first round of this Delphi Survey were: National Science Foundation grant awards, the National Research Commission publication - *Visionary Manufacturing Challenges for 2020*, *Rapid Prototyping Industry Trends*, Volume 1, published by the Rapid Prototyping Association of the Society of Manufacturing Engineers, and the *Journal of Industrial Technology*.

HOME Log-In

Return Feedback
The researcher’s actions are to return the results of the previous round to the panel along with indications of panel consensus to further identify areas of consensus where appropriate.
HOME Log-In

Edit Comments
The researcher's actions are to categorize responses eliminating multiple equivalent responses. Spelling errors are also corrected for publication.
HOME Log-In

Compile Round
The researcher's actions are to run statistical tests of Median, as a measure of central tendency, and Interquartile Range, as a measure of dispersion where appropriate. Qualitative interpretation by the researcher as facilitator is used to refine the summary statements for validation or rejection in subsequent rounds by the expert panel.
HOME Log-In

Analyze Round
The researcher's actions are to analyze each round for the purpose of reporting the findings back to the panel and ultimately to a wider audience.
HOME Log-In

Analyze Questionnaires
Pre and post Delphi questionnaires are analyzed for the purpose of describing the panel and the utility of the Delphi Survey.
HOME Log-In

Report Findings
The researcher's actions are to report the findings of this research to the panelists and to the wider audience interested in the topic.
HOME Log-In

Panel Actions
The Delphi Survey method is a group communication process. The panel of experts responds to a series of questions which identify areas of consensus and digression of opinion.
HOME Log-In

Pre-Delphi Questionnaire
Panelist will give demographic information describing their expertise relative to the survey topic. In a Delphi Survey panelists remain anonymous to each other throughout the duration of the survey. When the survey is completed individual members may elect to be identified as participants. At no time will individual responses be identified with any particular panel member.
HOME Log-In
Pre-Delphi Questionnaire

Define Objectives
In Round One of the Delphi Survey the panelist will identify factors forecasting the effect of Rapid Prototyping technologies on design education by responding to the questions posed by the researcher. Qualitative as well as quantitative data are sought in Round One. The panelist should respond with thick descriptive narrative where appropriate.
HOME Log-In

Rank Goals
The panelist may choose to rank goals in Round One. In Round Two a summary of factors identified from Round One is submitted to the panel for validation, in some cases in a Likert scale type format for the purpose of ranking and identifying areas of consensus. Round Three is used to analyze consensus, rate probability factors, rate confidence, and to identify those areas where consensus may not be possible. The findings are then analyzed and reported.
HOME Log-In

Write Comments
In a group communication process thick descriptive comments are valuable in qualitatively describing a problem. With a Delphi Survey anonymous panel members are not influenced by group dynamics such as charismatic or otherwise powerful individuals. Panelists can respond simultaneously which would be impractical in a face-to-face meeting. Panelists may be widely dispersed geographically. Panelists may have more time to reflect on their comments as well as the comments of others.
HOME Log-In

Post-Delphi Questionnaire
The panelists are asked to comment on the Delphi Survey.
HOME Log-In
Post-Delphi Questionnaire

Appendix F

Delphi Survey Round One

For this research the topic is:

Factors Forecasting the Effect of Rapid Prototyping on Engineering Design Education

A review of the literature reveals that there are a number of factors that may impact the effect of RP technology on design education. The purpose of this study is to identify the factors that experts in the field rank as predictive, so that interested parties can research the factors for the purpose of making curriculum decisions.

The primary sources of questions for the first round of this Delphi Survey were: National Science Foundation grant awards, the National Research Commission publication - *Visionary Manufacturing Challenges for 2020*, *Rapid Prototyping Industry Trends*, Volume 1, published by the Rapid Prototyping Association of the Society of Manufacturing Engineers, and the *Journal of Industrial Technology*.

Instructions:
The survey instrument for Round One consists of a series of statements or questions for which you are requested to respond. To avoid overlap read through the entire survey before beginning as some of the statements or questions may have very similar wording or meaning but are intended to address subtle differences.

All responses in a Delphi Survey are anonymous to the panel. Your name is required by the researcher only for necessary logistics in administering a multi-part survey. Please complete the Round One survey within 14 days of notification by e-mail that the round has begun. The Round One responses from the panel will be categorized and compiled into summarizing statements for Round Two. You will be notified by e-mail when the Round Two survey is ready. A copy of the findings of this research will be provided to all participants.

If you have any questions please contact me:

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Pennsylvania College of Technology
DIF 77
One College Avenue
Williamsport, PA 17701
(570) 326-3761 ext 7847
jmather@pct.edu

Round One - Questions 1-3

Please provide your unique Delphi panel member identification:

User Name

In round one please provide a narrative or short-answer response to each of the questions. Answer the questions fully, providing rich descriptive data if possible. The declarative nature of the questions is not intended to imply an opinion. The questions are merely a starting point for the group communication process.

Q1. What term do you prefer to use for "rapid prototyping technology" and why?
Comments:

Q2. Do you think 3D CAD modeling will become the initial or default design tool in CAD-related education and if so why and by what year? Describe the role that you foresee for 3D CAD in engineering design curricula?
Comments:

Q3. In your opinion, might Virtual Reality (VR) become a replacement for RP in engineering design curricula? If so, when and under what conditions?
Comments:

Round One - Questions 4-7

Q4. Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students? If so, describe the differences.
Comments:

Q5. Should students, a technician, or a faculty member run the machine, and under what conditions?
Comments:

Q6. Do you expect the cost of RP technology to decrease dramatically in the near future? What would be the optimal cost for perceived benefit for introducing the technology into the curriculum? At an optimal cost/benefit would you expect that the majority of schools and small to medium size companies will bring RP technology in-house?
Comments:

Q7. List in order of importance, related to the use of RP in the curricula, the properties of: aesthetics, accuracy/repeatability, machine cost, material mechanical properties, speed, technical support, machine reliability, cost of raw material, ease of operation, cost of operation, or other. List the properties with the number 1 being the most important. Comment on reasoning where appropriate.
Comments:

Round One - Questions 8-10

Q8. Assuming an RP model could have ONE property identical to the finished product, state the property that would be most important in an educational environment. Comment on reasoning where appropriate.
Comments:

Q9. What machine (brand and model) would you currently recommend for purchase for use in a product design related curricula?
Comments:

Q10. How will RP technology affect design education to the year 2010?
Comments:

Submit Form   Reset Form

J.D. Mather

Return Confirmation - Round One
Thank you for participating in Round One of this survey. You will be notified by e-mail when Round Two is ready. This survey will run three rounds.

Appendix G

Delphi Survey Round Two

For this research the topic is:

Factors Forecasting the Effect of Rapid Prototyping on Engineering Design Education

The source of questions for the second round of this Delphi Survey was the compilation of responses of the panel to Round One.

Instructions:

The survey instrument for Round Two consists of a series of statements or questions which you are requested to select a summarizing response. You may also choose to respond with additional comments after reflecting on Round One. To avoid overlap read through the entire survey before beginning as some of the statements or questions may have very similar wording or meaning but are intended to address subtle differences.

All responses in a Delphi Survey are anonymous to the panel. Your name is required by the researcher only for necessary logistics in administering a multi-part survey. Please complete the Round Two survey within 14 days of notification by e-mail that the round has begun. The Round Two responses from the panel will be analyzed for identification of areas of possible consensus. The analysis of Round Two will be returned to the panel for final identification of consensus in Round Three. Copies of this research will be provided to all participants.

If you have any questions please contact me:

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jmather@pct.edu

Begin Round 2

Rating of Summarizing Statements

Delphi Survey Round Two

In Round Two please select a summarizing response to each of the summary forecast statements. The declarative format of the statements is not intended to imply a degree of certainty. Each statement includes a hyperlink to compiled comments from Round One. Each statement includes space for additional comments.

Please provide your unique Delphi panel member identification:
User Name: [ ]

Q1a. What term do you prefer to use for "rapid prototyping technology"?

Read compiled comments from Round One Q1.

CAAM	SM	RP	SFF	LM	Other
Computer Aided Additive Manufacturing	Solid Modeling	Rapid Prototyping	Solid Freeform Fabrication	Layered Manufacturing	
○	○	○	○	○	○

Comments:

Q2a. Do you think 3D CAD modeling will become the initial or default design tool in the majority of CAD-related curriculums and if so why and by what year?

Read compiled comments from Round One Q2.

3D CAD is current default design tool	Within 5 years	5-10 years	Other Opinion	No Opinion
○	○	○	○	○

Comments:

Round Two – Questions 3-5

Q3a. In your opinion, Virtual Reality (VR) might become a replacement for RP in engineering design curricula when the VR technology improves?

Read compiled comments from Round One Q3.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

Comments:

Q4a. Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students?

Read compiled comments from Round One Q4.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

Comments:

Q5a. In your opinion, in most circumstances where RP is used in engineering design curricula should students, a technician, or a faculty member run the machine?

Read compiled comments from Round One Q5.

Students	Technician	Faculty	Other	No Opinion
☐	☐	☐	☐	☐

Comments:

Round Two – Questions 6-8

Q6a. The total cost of operation of RP technology will decrease dramatically in the next 5-10 years?

Read compiled comments from Round One Q6.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

Comments:

Q7a. Total cost of operation is the most important factor related to the use of RP in the curricula?

Read compiled comments from Round One Q7.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

Comments:

Q8a. Assuming a RP model could have ONE property identical to the finished product from the list: Geometric accuracy, Mechanical properties, Appearance, which property is the most important in an educational environment?

Read compiled comments from Round One Q8.

Geometric accuracy	Mechanical properties	Appearance	Other	No Opinion
☐	☐	☐	☐	☐

Comments:

Round Two – Questions 9-10

Q9a. What RP machine would you currently recommend for purchase as appropriate in the majority of product design-related curriculums?

Read compiled comments from Round One Q9.

Too many factors	Z-Corp 3D Printer	Stratasys Dimension	3D Systems Thermojet	3D Systems SLA	No Opinion	Other
◯	◯	◯	◯	◯	◯	◯

Comments:

Q10a. Based on the panel comments to questions 1-10 is it your opinion that future research of the effects of "RP technology" using the Delphi method should be subdivided into the categories: RP, 3D-Printer/Concept Modeler, Rapid Manufacturing?

Read compiled comments from Round One Q10.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
◯	◯	◯	◯	◯

Comments:

Submit Form

Appendix H

Delphi Survey Round One - Comments

Q1. What term do you prefer to use for "rapid prototyping technology" and why?

Return to Question Q1a.

CAMM

I do not like prototyping since it is not necessarily the only product, I do not like rapid, since it is not that fast, it is computer aided, it is additive and sometimes subtractive manufacturing, it is free form, so I guess I would coin the name: CAAM computer aided additive manufacturing or fabrication. I would also go along with SFF for solid freeform fabrication, even though i do not think it really represent the technology, and have used RP instead of rapid prototyping. Thus: 1st choice: CAAM Computer aided additive manufacturing 2nd choice: SFF Solid freeform fabrication 3rd choice: RP.

SM

I prefer to use the term "Solid Modeling", as rapid prototyping is just one application as a subset of the technology of solid modeling. As technology increases, and new materials are discovered, this will be even more important, as we will then be in other areas such as "direct manufacturing".

SFF

Solid Freeform Fabrication. "Rapid prototyping" is limiting in the sense that the technology actually is not all that rapid, and an important part of the technologies' future lies in rapid manufacturing rather than prototyping. The SFF term is not limited to just prototyping.

Solid freeform fabrication. This is a broader terminology, that I think will better describe this technology over a longer period of time.

LM

LM Layered manufacturing, as it covers the solid freeform fabrication in a broad sense.

RP

Rapid Prototyping is the term I use since it is the most appropriate. However, in education, 3-D printing may actually become more viable and popular.

This is a tough question. I prefer to use "rapid prototyping" even though the term has lost its true meaning. Everything from machining to rubber molding has been described as a rapid prototyping technology.

RP, it's short and to the point.

For the general field either rapid prototyping or RP. From there you can use slang terms for the processes.

Rapid Prototyping. It is a general term that describes the process

I personally prefer "rapid prototyping technology", partly from habit (10 years in the business) and partly for the name association that goes with it. I tend to tailor my description to the audience, sometimes tossing out some of the other terms as well.

Rapid prototyping because it is the most commonly used and understood term.

I like to distinguish between additive rapid prototyping technologies and subtractive ones. I use "rapid prototyping" typically to describe the former. Sometimes I say RP technologies.

I prefer to use the term "RP". It is the term I became most acquainted with during my thesis research in graduate school. It is also the term I have experienced most often when speaking to various service bureaus.

RP or SFF. SFF is more academic term, but RP is a more applied term.

RP It is understood by all in the field.

I use the term "rapid prototyping" to represent all of the activities involved in the process. I don't know of another term that would be as descriptive.

RP is fine but layered manufacturing might be slightly better. I understand that prototype has some issues but ....

Other

The industry needs a new term, but one has yet to develop.

Return to Question Q1a.

Q2. Do you think 3D CAD modeling will become the initial or default design tool in CAD-related education and if so why and by what year? Describe the role that you foresee for 3D CAD in engineering design curricula?

Return to Question Q2a.

Current default

3D cad modeling is already here and the mainstay of educational design. Employers drive the educational market; we are still 5-8 years away for employers embracing the technology as the default platform.

Yes, I think 3D CAD is absolutely necessary. We have been educating students in this mode for well over 5 years. It is our default. Boeing made it their default with the 777 design. 3D CAD is as necessary in the design curriculum as being able to use a spreadsheet tool.

We have used 3D modeling as the default way to do Mechanical engineering design since 1980. It is the default design tool. It is the only way to view complex parts and assembles. It allows "what ifs' to be visualized, support down stream applications such as dimensioned drawing, fixturing, NC machining and mfg process simulation.

Yes, already is. Students need to be exposed to 3D CAD, and to features, parametrics early on. They pick up these tools in industry during their coop, and they could use the tools to represent designs, especially in the advanced senior design capstone classes. They can also use them in lab sequences that promote design and manufacture, tying CAD to SFF. From this, the students should appreciate tolerance issues, manufacturability issues, possibly use these methods to do design of experiments, robustness, etc.

Yes, I think 3D modeling has already become the initial and default design tool. It has at my institution in the lab outside my office. Beginning with 3D virtual models rather than with 2D CAD or 2D drafting has different cognitive implications for the learner and instruction, requiring different types of thought processes. I see the role of 3D CAD becoming less in future years. 3D CAD skills can be acquired by middle schoolers - let's hope that undergraduate and graduate education in engineering concentrates on the critical aspects of the job, rather than technical skills of using CAD software.

We have used (parametric 3D software) as our CAD modeling platform for past ten years or more.

I believe that it is now the default CAD tool for design. It produces files with far more useful information. Besides allowing better visualization it allows for RP to produce tangible objects.

I think that 3D CAD is already the default design tool (at least at our University).

RE the role: First, every design/engineering student should be given at least a moderate degree of education on 3D CAD. To send them out to industry is a disservice. This education should start in the freshman year, and possible continue into later years with advanced courses. After the first taste of 3D CAD education, all future design related projects/courses should demand its use.

3-D CAD is already the default starting point for engineering design education. 2-D drafting, even on a computer, is already an outdated paradigm. Professors who still use it are just simply outdated and not ready to upgrade to 3-D.

3-D CAD begins the building of a 3-D digital database that can be applied to all phases of design analysis, simulation, manufacturing, and documentation. This should be the current and near-future paradigm for initial engineering design education at all schools in the U.S.

<u>Within 5 years</u>

3D CAD is quickly becoming the default tool. It will replace 2D CAD and design in 5 years. Student computer skills and the ease of software use will drive the change. 3D CAD will provide the visualization and design skills needed in engineering. It speeds the Art to Part concept. Educational institutions will teach design, build and testing with more ease and understanding. 3D data will be used for analysis and inspection purposes on only critical characteristic will be defined. Design and engineering skills and standards will still need to be taught.

It will always be important to understand 2D drawings, although I do feel that most of the curriculum will need to be focused on 3D CAD in order to keep up with the manufacturing industry, perhaps within the next 5 years. 3D design and analysis will be core for Mechanical, Aerospace and Manufacturing engineering students, and will bleed over Industrial Systems, Architectural, Biomedical. It will help students understand mechanical systems and how they work.

3D CAD (solid modeling) will very soon be the process of choice for product design. As in many things in education university education will take a while to make the change. Estimate 5 years.

Yes, by the freshman year. 3D modeling is intuitive and produces results that are easy to conceptualize and visualize, especially for newer students. I think 3D modeling will be the basic, beginning design tool for all mechanical design in the next 5 years, both in education and in industry.

Yes, it will. In some cases, it has already become that way.

I believe it will become default design tool in CAD related education because of the immense complication in the development of the technology. In my field--apparel & textile design--it is much more complicated to accomplish 3D modeling successfully. To date, no one system is even really close. I believe that once the systems have been refined and can be run without a room full of computers, 3D CAD will be integrated into the curricula. I expect that it will be 5 years, at least before we see true success in the software that can demonstrate the drape of any fabric, using any grainline, and any human body.

5-10 years

Yes, 3D CAD will become the default design tool. However, we have a bit of the "chicken and the egg". Approximately 25% of industry uses 3D CAD (solid modeling)...this may not warrant its instruction in a design curriculum. Yet, without graduates hitting the street with 3D CAD under their belt, industry's adoption may be slowed.

I think 3D CAD modeling will be the default design tool within the next 10 years for a number of reasons. 1) Time from to design to market is decreasing. Students must be prepared to meet these challenges. 2) Visualization - 3D often makes learning easier, students grasp concepts easier 3) Geography - we have a world economy. We design in one country and produce products in another country, shipping computer files via digital communication lines. Visualization helps communication between the multiple locations. 4) Its more fun.

Yes I do. Not necessarily to the point of producing the solid model, as expense plays a role at this point. But in the design area, I believe that this will become the basic design tool, and used with increased standardization for rapid manufacturing applications as well as direct manufacturing. I believe that all higher ed institutions must incorporate 3D CAD design into the curriculum, it is the tool that all design engineers will need to have in their bag.

This should be the default for all curricula today. But, I expect it to take 5-7 years for it to reach this point.

Other opinion

Not for materials-related courses unless it can handle multiple materials and feed into FEA.

No opinion

Return to Question Q2a.

Q3. In your opinion, might Virtual Reality (VR) become a replacement for RP in engineering design curricula? If so, when and under what conditions?

Return to Question Q3a

Another point. A definition of VR is required. Some believe FEA to be VR. Others think in terms of immersive, digital environments.

I foresee VR replacing RP in the future. When VR is more widely used and accepted by industry as an engineering and design tool. I would estimate in 10 years the software and hardware will be sophisticated and affordable for Engineering Institutions.

VR will partially replace hands-on RP technology experiences for students, due to the costs and availability of each. However, if RP refers to a "study of rapid prototyping technology" rather than "use of rapid prototyping equipment," then VR is just one part of studying RP - not a replacement of it.

Difficult to answer. VR is very powerful in several ways, but needs a lot of development. It will be easier to answer this question 5 years later.

VR and RP go hand in hand. Need VR to get RP and need RP to true sense of ergonomics and aesthetics, form, and fit.

No, it should complement, not replace.

I really don't think VR will overtake RP. First VR is still really expensive whereas RP is now down in the $30K range. VR has its place especially in larger system but nothing is better than giving the customer an RP part. In my experience putting RP parts on the meeting table is often a meeting stopping event (especially if it wasn't a pre-planned activity). Humans like to physically hold / touch things.

It may at some time in the future when a VR workstation can be purchased for <$5K.

Virtual reality is tool only in our field. It might enable one to repair scale of a design or shape of a garment, however, almost all will require actual production for a decision to be made. An exception to this might be when changes in a product are very subtle--such as solid colors, color shapes, etc.

It is possible that Virtual Reality could replace RP, "if" Virtual Reality ever becomes user-friendly. My limited experience tells me that it is still a somewhat "bulky" process with limited user satisfaction (e.g. has to wear glasses or helmet, limited peripheral vision, muscle fatigue, etc.)

I do not know enough about VR to comment on this question.

Possibly, when it can be done for less than $5K per seat.

Unless VR figures out how to demonstrate different material properties, stiffness, surface roughness, etc, it will not be useful in this technology.

I don't think so. The first go around of VR was too video game like. The application seemed better for situational training.

As VR develops, it should be included in the students' education. The key message being that there are both electronic and physical means to validate a design. Help them to understand when it is beneficial to apply each.

It might. I think architectural engineering is one application this could be used. An architect/structural engineer/civil engineer could design a building, bridge, etc. Virtual Reality may enhance how we visualize the model before lots of money is spent building smaller models, doing testing, and building large structures.

Not anytime soon. It is difficult to replace the "feel" of a part, although with haptic feedback systems and the new line of 3D monitors coming out soon, it could eventually play a competitive role. Mostly it will remain supplementary.

Not at this time, as the technology does not lend itself other applications in the manufacturing process. It also is not advanced enough to save time in the process of manufacturing. The area I believe that it could/and will play a role is in the design of assembled manufactured products such as, automobiles.

Probably not. In order for VR to provide the same "touch and feel" as a physical prototype, computer workstations that are equipped with the VR gear would be needed. I think that RP technology will evolve within 10 years to the point where low-end machines are as commonplace as printers. Students will always take pride in designing something, making it, and then taking it home and setting it on their shelf so that others can see it. VR will certainly have its role in the early iterative design stages and in the design of larger systems that cannot feasibly be prototyped though.

VR is still too much in its infancy to become a replacement for RP at this time. With major technological advancements in the field it is possible VR could replace RP. However, there seems to be major differences in the paradigms of thought related to both technologies. VR is still perceived as gaming in both industry and education.

Return to Question Q3a.

Q4. Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students? If so, describe the differences.

Return to Question Q4a.

I do not see why? I fail to understand this question!

No decisions about curriculum should be based on any minority status. Curriculum decisions must be based on industry needs. Not on how it will effect any minority.

Yes. In many countries and for centuries, the use of specialized industrial manufacturing equipment has been male-dominated. RP technology allows individuals to bypass much of the need for machine tool skills, empowering people to design and create prototypes that would exceed their ability to manufacture by other means. I believe that the disservice done to females in engineering and pre-engineering education is brought to a more level field by RP technology.

Yes, I believe it will draw more females into the design engineering arena as it will be perceived more as an artistic field and therefore appeal to a wider audience.

Not sure about this. We have historically seen that male students are less reluctant to get their hands dirty in the manufacturing labs. Conversely, the RP course that we teach is surprisingly balanced (male/female) considering that it is a manufacturing elective course. RP machines are typically kept in a separate lab from the main manufacturing labs, so perhaps the female students don't perceive it as being similar to the male dominated low tech metal shop.

I have no opinion, but I guess it would be minimal difference. It produces a model in some fashion that should be equally pleasing to males and females.

Undecided.

Don't know.

I don't see male or female students benefiting differently. Today, both male and female students are about equal in mechanical experience. In the past males were more apt to fix, destroy and repair equipment. With todays throw away society all student are about equal. Academic strength and desire is the key to either ones success.

No -- students seem to have similar effects. The visualization capabilities are what both sexes are looking for.

Not particularly. Just give all students a feeling of accomplishment since they can create an artifact and have it in their hand.

I have been teaching an RP class for over 5 years which includes RTV tooling and hand poured castings. I have seen no gender issues either positive or negative. Students are just excited about being able to understand and use this technology.

I have not seen a difference. I typically deal with 50% men and 50% women. They are all thrilled to use RP and have used it for many different engineering applications.

I don't think so. Beginning engineers and technologists of both genders have visualization problems.

I do not feel that the inclusion of RP technology into engineering design curricula will have different effects on male and female students. In fact, due to the nature and environment of CAD and the anonymity of the internet gender will continue to be less of a factor in the field. CAD as a new media within the design field will begin to form a new history, which will slowly dissolve the stereotypes and notions of any dominant gender.

Return to Question Q4a.

Q5. Should students, a technician, or a faculty member run the machine, and under what conditions?

Return to Question Q5a.

Other

This is a foolish question. Activities should be chosen based on learning objectives. A rigorous adherence to any of the above three seems to be a managerial decision, and I have seen all three work successfully. I really hope this Delphi process does not result in any of the three being recommended over the others.

This depends on the machine. We have two RP machines that cost more than $100,000 each, and they should not be used by students without faculty or staff supervision. When machines exist that are akin to printers next to a PC, then that will be different.

Students

Students should run the RP printer!

Students. Technician or graduate assistant support. They will be engineers; they better learn and use these machines.

I have a grad student with full time technician to back him/her up.

It would depend on the machine that you were talking about. There is not just one machine used to enable rapid prototyping in my field. I believe that students should be allowed and encouraged to run the machines, to every extent that is possible. Sometimes there is a cost associated with the use of a machine, which might require greater control through a technician or a faculty member.

Students can run the machine and processes once a formal training session is completed. It is supervised by a technician.

We have Z-corp machines and I tried having students run the machines. I have had good success. But lately, I've been pushing the students to design more interesting items and as a result parts take more time to build. Hence, I have my TA pack the build space to make the machine more productive. We have a new Stratasys machine and two new CNC mills which I have yet to use in class. So time will tell... Also, as a public university we do not have money for classroom/lab technicians.

Machines are still very expensive and the service contracts are difficult to maintain in an academic setting. That is why a technician or professors sometime run machines, as opposed to students. In my opinion, students should operate after proper training.

Depends on the situation. 1. If the course is for "design to manufacture", I think the student needs to have a hand on the machine, post processing, etc. in order to realize that it is not "instant" prototyping and that there is touch labor involved. It will also let them see the results of decision they make in the design. 2. If the students are merely using it as a tool, say to indirectly make parts for a design project; it may be OK to have a technician do it. 3. The faculty should have training on the machine regardless, to know what they can expect from the students or technician that runs it. Also, if time is limited in the class, the faculty could "demonstrate" the steps involved properly without having each student participate.

I believe that students should be taught to run the machine under the supervision/guidance of a lab technician. The lab technician will be more aware of the nuances of the modeling equipment, and be of better technical assistance to the students.

University students should run the RP machine. It's the best way for most technology students, to learn. The learning styles of our students primarily fit into the visual and haptic styles.

Well trained students can run the RP machine. The student should be at least a sophomore to run the machines and should be provided with either a monetary or tuition reward. A well prepared plan should be in place with defined documentation.

Technician/Faculty

I think technicians are the best personnel to operate machines. In order to take the best advantage of this expensive equipment and produce the best quality parts there is a need for consistent use and maintenance. I doubt a faculty member would be able to make this time commitment. Faculty members also cost more than technicians. We've found that students are great machine operators if they can give at least a two year commitment to the rapid prototyping center. Too much personnel turnover leads to poor part quality, inferior machine operation, lack of machine knowledge and inadequate machine maintenance.

Faculty or technicians unless the machines are very easy to operate.

A technician because usage for courses will be very sporadic.

A technician (or trained faculty) should run it, with health and safety as the highest concerns.

No. Not necessary. All students should know how to create solid model, build model and how to do post-fabrication cleaning and smoothing. The hardware has specific settings, let a technician or selected graduate and/or undergraduate handle the actual fabrication. This way, it is efficient financially and time wise.

Due to the cost and maintenance of RP machines it is my belief that only trained technicians and faculty members should be allowed to operate them. Students should be present during the setup and file transfer of their models so that they may become acquainted with the procedure. Machines, accessories, and material should be stored in a secure place.

It depends on the vision of the course. If a university's manufacturing curriculum has students running CNCs, then the students should operate the RP device. If not, leave it up to a technician. Very few students will actually run an RP system (at least until it becomes a printer-like peripheral). So, there is no direct benefit in having students run the equipment. That is unless the philosophy is that you learn more by doing than by having others do for you.

No Opinion

Return to Question Q5a.

Q6. Do you expect the cost of RP technology to decrease dramatically in the near future? What would be the optimal cost for perceived benefit for introducing the technology into the curriculum? At an optimal cost/benefit would you expect that the majority of schools and small to medium size companies will bring RP technology in-house?

Return to Question Q6a.

No. I do not see the cost going down. The RP-technology industries are in profit oriented business, they are not in charity or not-for-profit business. I do not know the optimal cost.

RP technology is currently included in many university programs already. Therefore, this question is moot.

RP technology has always been affordable. The JP5 costs $4-5K. We first introduced students to layered manufacture by having them cut out Styrofoam cross-sections and glue them together. Now the bottom end of RP machines cost $30K. This is an OK price point. High schools in our city are starting to purchase Z-corps and Stratasys Dimension Printers. Both cost less then $35K ready to run. At that cost, the machine time cost is about $25 / hour plus materials. This is way less than technician time.

I do not foresee the cost of RP technology to decrease dramatically. As this technology matures the work horse machines may decrease in cost but I think we will look for new features to add to machines. I also think we will require new materials - more metal, stronger plastics, more color, which will keep costs relatively stable. Increased competition among manufacturers and a greater selection of material and maintenance suppliers would help decrease cost. No, I think many schools and small/medium businesses will have more concept modelers rather than full fledge RP machines.

I have seen a slow decline in prices. If a 3D printer could be purchased for <$10K we could place them in all CAD labs. This would bring the RP used for design development in-house. Final prototypes may still go to service bureaus that have cutting edge technology.

Yes the costs should come down. 3D color plastic printers are affordable now. What we really need is RP made of metal for functional and performance testing. These are expensive now. $50K for metals would be great.

The cost of RP technology is currently decreasing and high schools and career centers are buying machines. 10 t0 20K is optimal range and I would expect the majority of the schools and companies will take advantage of the opportunity.

In a materials curriculum it would need to be $10K. For use with multiple courses there would need to be flexibility.

The cost of systems and accessories should drop, with lower end systems becoming more "mass produced". Also, a lot of the patents on build materials are expiring and breaking up the monopolies, so for example, "resin wars" between new third party vendors can bring the costs down. It is hard to quantify the cost/benefit in a curriculum, but for small companies I think a 1:1 ROI within the first six months is not unheard of in the industry.

Yes, I believe that the cost of RP technology will be decreasing in the future, particularly in the lower end technology. This is the end of RP technology that is best suited for infusion into the curriculum at this point. Schools will bring in the RP technology when the material cost is low enough for all design students to model their projects. It must also be affordable students as an additional lab fee for material cost. In terms of small business, it will be brought in as the advantages of the technology are known, and the cost is less than the cost of outsourcing the modeling and design work. They must be able to keep the process in-house so they can control the platform of design, own the design and insure that it is digital.

When RP concept modelers cost under $5,000 and small models cost no more than a few dollars each to build, then I think pretty much everyone will bring the technology in house.

Yes, I expect RP costs to drop somewhat. However, I do not understand what the question implies as an "optimal cost for perceived benefit for introducing the technology into the curriculum." The costs of RP technology are not determined by educational benefit - RP technology cost is more closely geared to the costs to develop and produce the equipment and materials and to the price industry can bear, not schools. Secondly, you note, "the majority of schools," and here I suppose you are referring to colleges and universities with baccalaureate programs in engineering. But then again, some high schools use RP technologies, and so do 2-year colleges. So please clarify. Also, since rapid prototypers have been offered for prices below $50,000US, I do not believe your question would be appropriate for universities, which typically spend much greater amounts on technical equipment for engineering students.

The cost of RP technology since I began using it for my work has dropped dramatically. I believe it will continue to do so. As machines begin to scale down in size and raw material cost schools and companies will be looking to bring more technology in-house. When the machines begin to price comparably to a small computer lab, or printing center many administrations will be more supportive to their purchase.

Drop dramatically No, drop in cost yes. Technology will always lead to a lowering of cost. We have seen a large decrease in RP machine costs already. If RP machines were in the $15-25K range that would provide a decent return on investment.

It is already quite affordable $30-50K machines. This is an acceptable cost. What needs to come down is the maintenance fees on these machines and the material costs.

Yes, prices will drop in the near future. (near being 1 to 5 years). An optimal cost (in terms of departmental budgets) would be $5000.00. But, the optimal cost in terms of value to the student is <$50,000.00, and there are already systems at this price. While price plays a role in industry's adoption of the technology, it is not the only factor. So, price alone will not do it. Many believe that we have an issue with awareness and education. And that the industry must get the technology in the hands of the students.

Yes, of course the technology will decrease in cost as it becomes used more. It is easy to demonstrate to students the cost savings when using the technology. As far as the optimal cost for perceived benefit--it would certainly depend on the type of technology that you are talking about. We bring all of it in-house, but the cost is too high for most small companies to bring it in-house. Our job as a research institution is to help develop the technology so that it is more affordable by industry.

My opinion is that eventually everyone will want to print in 3-D. That broad customer based will drive the price down to, say, less than $2000 per machine. That will not yield the same quality needed for RP, but it will open up the industry to new users, and education is one customer.

I hope so. An RP machine should not cost more than $15,000. There should be high-end machines, but there needs to be low end machines as well.

I hope so. I think less than $10K per machine will be needed for widespread use. The materials must come down as well.

Return to Question Q6a.

Q7. List in order of importance, related to the use of RP in the curricula, the properties of: aesthetics, accuracy/repeatability, machine cost, material mechanical properties, speed, technical support, machine reliability, cost of raw material, ease of operation, cost of operation, other. List properties with the number 1 being the most important. Comment on reasoning where appropriate.

Return to Question Q7a.

Machine cost, cost of operation, accuracy of parts, machine reliability

1. Cost of operation 2. Cost of raw materials 3. Material properties 4. Ease of operation 5. Speed 6. Machine reliability 7. Machine cost 8. Accuracy/repeatability 9. Aesthetics 10.Technical support (if you purchased a reliable machine)

1.) Total cost of operation (i.e. per part cost or cost per student) 2.) Machine reliability. 3.) Tech. Support 4.) Speed 4.) Nature of Materials (whether they are toxic). I can not deal with anything that is toxic.

1) function 2) form and Aesthetics 3) fit- assembly issues 4) features 5) finance

1. machine cost 1. cost of operation 1. cost of raw material 3. accuracy/repeatability 2. speed 3. reliability 4. ease of operation

1 - machine cost; if we can't afford it, all else does not matter! 2 - cost of raw material; see above. 3 - machine reliability; if we can't depend on it, we won't buy it. 4 - ease of operation; if it is too complicated, students will avoid it. 5 - cost of operation; if it is too expensive, we won't use it. 6 - aesthetics; this is important but we may be willing to compromise 7 - technical support; if all of the above are in place, we won't need technical support! 8 - material mechanical properties; for design development, mechanical properties may be sacrificed. 9 - accuracy/repeatability; see above. 10 - speed; in the classroom slower speed may be tolerated.

1. aesthetics 2. machine reliability 3. cost of raw materials 4. accuracy/repeatability, 5. ease of operation 6. cost of operation 7. technical support 8. material mechanical properties 9 machine cost

1. machine cost 2. cost of operation 3. technical support 4. ease of operation 5. cost of raw material 6. machine reliability 7. material mechanical properties 8. aesthetics

1. machine cost (got to have one first) 2. cost of raw material and cost of operation(re-curing costs) 3. safety, ease of operation, and technical support 4. accuracy/repeatability/reliability 5. mechanical properties of the output 6. speed and aesthetics

Machine reliability, cost of raw material, Technical support, accurate process information, cost of operation, accurate and complete information on material properties and the relation to technical process.

For the use of RP in the curricula: 1. speed, for use in coursework or labs 2. machine cost, for school-size budgets 3. material mechanical properties for handling or testing 4. cost of operation, again it needs to be affordable for student use 5. cost of raw material, 6-9. aesthetics, machine reliability, accuracy/repeatability, , technical support, 10. ease of operation, If it is too easy, they'll never learn how it actually works...just like you never give the shortcut formula until they've learned how to derive it...

1. Cost of raw material and cost of operation - while schools can often get grants to pay for equipment, it is nearly impossible to get money to operate the machine. (Most) schools are not service bureaus, so the machines do not generate revenue. The cost of consumables is therefore a major issue if the machine is used on a regular basis. 2. Machine reliability - schools do not have maintenance staffs 3. Ease of operation - unlike service bureaus where one or two experts run the machines, the machines at schools are used by many people that are novices. Machines that require "voodoo magic" to make them run are just too complex for the occasional user. 4. Accuracy - when students make parts that must be assembled, accuracy becomes an issue. 5. Aesthetics - The models need to look good enough to get the students excited about what they are doing. 6. Mechanical properties - Parts need to be strong enough that they don't disintegrate during normal handling, but they don't need to be much stronger than that for concept modeling. 7. Speed - Schools don't earn their livelihoods from these machines, a so slower speed in exchange for a lower purchase price is an acceptable tradeoff.

cost reliability material cost speed accuracy material properties

The priority list is: accuracy/repeatability, material mechanical properties, aesthetics, speed, cost of raw material, ease of operation, cost of operation, technical support, machine reliability, machine cost.

1. Material mechanical properties- What can the students do with this "thing" they just built. This is the reason why we did not purchase a Z-Corp. printer. 2. Machine cost 3. Machine reliability 4. aesthetics- I am currently teaching CAD to both engineers and art students. The qualities of the material are very important to me, as many of my students and I are using the prototype material as the final object and not a prototype. 5. Cost of raw material 6. Ease of operation 7. accuracy/repeatability 8. speed - all pretty similar these days 9. Tech support 10. cost of operation

Machine cost, Mechanical properties, Surface finish.

1. accuracy 2. reliability 3. support 4. cost of material 5. cost of machine 6. speed 7. ease of operation 8. cost of operation

Let's assume you are talking about undergraduate engineering curriculum, which is a big assumption. 1. A critical comparison among the types of RP technology regarding principles of operation, requirements and limitations, and for selected RP technologies: procedures. Those particular parameters you've listed are rather picky. 2. safety and environmental issues. 3. ease of operation. (This should be reworded principles and procedure of operation. 4. accuracy / reliability (this should be reworded to include the parameters of the output, which includes size, material type, and many other properties, thus material mechanical properties is a factory in accuracy, and should be included here.) 5. costs, including initial investment, set up costs, operating costs, material costs, maintenance, and replacement.

1. Machine reliability 2. Flexibility of materials can more than one be used in the machine 3. Application or use of the RP part 4. Material mechanical properties 5. Accuracy and repeatability 6. Cost of the machine 7. Cost of the material 8. Speed 9. ease of operation and post processing 10. Machine reliability 11. Technical support 12. Cost of operation.

Return to Question Q7a.

Q8. Assuming a RP model could have ONE property identical to the finished product, state the property that would be most important in an educational environment. Comment on reasoning where appropriate.

Return to Question Q8a.

Geometric accuracy

The RP part needs to have dimensional accuracy because we are going to use it to generate RTV tooling. We use RP to produce forms to make molds.

The shape of the object produced should be identical to the shape of the finished product. (Isn't that the point?) Scale could be different, materials could be different, etc.

Accuracy of the part size.

Geometric accuracy and high resolution, also full-size replication. This is what the student wants to see derived from the computer model.

Geometry - Realistic design exercises involve assemblies of multiple parts. Those parts must fit together properly, and students need to know how to design for assembly. If the RP system is not accurate enough to allow them to successfully assemble the parts, then they'll limit themselves to designing individual parts in a vacuum.

Size, so accurate investment castings can be made.

Accuracy/repeatability

Mechanical Properties

Correct material properties - everything else will follow

Metallurgical property. Testing, machining and fit/function would be useful

Durability; this would allow us to retain samples for didactic purposes.

Material mechanical properties because it is really nice to be able to test the piece you are modeling. If you want to use the model in a focus group, do fluid flow testing, carry it to a meeting you want to have a piece that is going to be strong and handle the test you are completing.

Strength.

Mechanical properties, part that comes out of the machine needs to look act like the one they designed. This allows for not only getting a model but actually implementing it into a piece of hardware.

I feel it is very important for the material to have a similar strength and structure to the "finished product" if the product was in fact to be made of another material. If the material is so fragile that the students cannot grab their model and measure where something may see to thin then they are not able to experience and learn from the process. They need to be able to really handle the model without a great hesitancy.

Durability. The models produced will be stuffed in a backpack to be taken to the next class. Students will not have the luxury of time to invest in delicate work to "post process" their models. Easily broken models will have two negative results: 1) Increase system use with associated increase in operational/material expense. 2) Frustration on the part of the student. A job well done, only to break the model and have to rebuild.

Appearance

Surface finish.

Color--Much of textile and apparel design centers around color of the final product. What we produce in RP must be as close as humanly possible to what will be produced in Mass production.

Other

For a concept modeler-appearance for a production modeler- physical properties.

Shape and tolerances.

No Opinion

Return to Question Q8a.

Q9. What machine (brand and model) would you currently recommend for purchase for use in a product design related curricula?

Return to Question Q9a.

Too many factors

Several have properties good for different situations. Too many factors play a part to identify one machine for all situations.

Z-Corp 3D Printer

Purchase something with low purchase price, low operating expense and ease of use. Two come to mind: Z Corporation's 3D Printing systems and Stratays' Dimension. Both can be purchased for $30,000. Both are easy to use. And neither require extensive amounts of supporting equipment.

Z-Corp ZPrinter 310

Either Z-corp (fastest) or Stratasys Dimension (cost). They both seem to work. BUT the other big winner is small 3/4-axis CNC mills which cost $2-3K. One can produce metal parts on the CNC mill. There is a software produce called DESKPROTO which reads STL files and outputs G-code for many CNC mills. It is all wizard driven and makes a CNC mill behave much like an RP machine.

Currently, the best for a lab for teaching, while keeping cost of operation in mind would be the Z-Corp. Following that, if budget and program dictate, - the Thermo Jet Also depending on program focus, the Stratasys system - for durability of RP model and architectural application.

ZCorp Z402

Stratasys Dimension

We use a 1)FDM 3000 from Stratasys, outsource to 3D systems job shop and we hope to get a Zcorp 3D color printer. Materials Dept has a LENSE 3D metal RP for R&D

Stratasys either the low cost model or the mid range model

FDM and the use of ABS plastics is the easiest, closest to industry material application, cost effective and less post processing. Stratsys Dimension

Stratasys's low end machines.

Right now we are running a Stratasys Dimension which we are very happy with. We have produced approx. 30 models and we are very pleased with the consistency as well as the low maintenance it requires to operate smoothly. The models are durable and can be post processed to adapt in many ways (drilled, tapped, sanded, painted etc.)We are currently running white ABS plastic, but are considering ordering some colors- as it is one of the major requests of the students.

Actua, Objet, Stratasys

3D Systems Thermojet

I'd recommend the 3D Systems Solid Object Printer because it is low-cost, has low risk for the worker and environment, and can produce low-cost models quickly, quietly, and in an office environment. (I wish we had one.)

3-D Systems new tabletop machine or maybe Z-Corp's modeling machine.

3D Systems Thermojet with reservations - too expensive, material too expensive.

3D Systems SLA

SLA - 5000, 3D Systems

SLA Viper or FDM 3000.

No opinion

Other

Return to Question Q9a.

Q10. How will RP technology affect design education to the year 2010?

Return to Question Q10a.

It will show the student how a 3-D computer model can be transformed into a physical prototype that they can hold in their hand. All happens in an automated fashion (like overnight, cool!)

I would expect real metal parts. I would hope for multi-material parts are well. Both at the $35K price range. It should work like a star trek replicator.... Think about ...

By 2010, I hope that RP has become an invisible peripheral to the design process. Something akin to an ink-jet printer. With this in mind, teaching RP may not be wise. All that may be required is an introduction to RP as one tool available to the designer.

It will be common practice.

Materials design: it will still be just beginning.

It will increase the numbers of new designs put into production, shortening the seasons so that new product introduction will be a continuous process rather than 4-5 times a year.

I think computer labs will be full of 3D CAD software attached to a concept modeler. Students will print an actual model instead of a design on a piece of paper.

If it continues to be enhanced and refined it will become Rapid Manufacture and the students will be able to produce their designs in their materials of choice. Parts will be produced that are ready to market.

The concept model viewing is already on the rise, and will free up the designers to make more iterations and learn how to design things right early on. The more functional models will allow the designers to actually apply their designs real time, so there may be a merging of design and analysis courses.

I do not believe that we will have any viable programs that do not utilize RP technology. RP and its relationship to future direct manufacturing process (along with the advent of new materials), will be the face of manufacturing in the year 2010

It will significantly increase the student's awareness and understanding of usability and ergonomics. With low-cost RP systems, students will be able to build and physically evaluate their design for comfort and usability.

Solid modeling and RP will become the standard with typical 2D drafting relegated to the rank of secondary technology, much as board drafting is today.

In 2010 it is my hope that students will be very used to the idea of thinking in 3D space. They will design "in the round" with the help of the many tools in their CAD packages. Their objects will begin to use a different design vocabulary and will therefore appear as new geometry, and new form. The RP technology will have sped up enough that from their seats they will be able to hold their piece prior to the end of the day, or maybe even the end of the class period. Students will learn to brainstorm physically while they build the ideas they see in their imaginations, rather than altering them to fit an established archaic criteria. RP technology will give greater fluidity and freedom to the students of 2010.

Making complex functional design faster and accurately.

Not much. RP is just a tool, like a lathe or a pencil or a CAD program. The essence of design education is not the mastering of that tool, or let's at least hope it is not.

Students will have a better understanding of design and applications with the use of RP. RP is only one tool of many that can be used in education. It won't make a drastic change in design and engineering education.

It will still be used as a tool for part visualization, the use of 3D modeling to develop it will be more common.

Bring back manufacturing to the forefront, and open up new design and manufacturing paradigms.

Return to Question Q10a.

Return Confirmation - Round Two
Thank you for participating in Round Two of this survey. You will be notified by e-mail when Round Three is ready. This Delphi survey will run three rounds.

Appendix I

Delphi Survey Round Three

For this research the topic is:

Factors Forecasting the Effect of Rapid Prototyping on Engineering Design Education

The source of questions for the Third Round of this Delphi Survey was the summarizing selections and comments of the panel from Round Two.

Instructions:
The survey instrument for Round Three consists of a series of statements or questions for which you are requested to agree or disagree that the statement or question represents consensus opinion. You may also choose to respond with additional comments after reflecting on Round Two. To avoid overlap read through the entire survey before beginning as some of the statements or questions may have very similar wording or meaning but are intended to address subtle differences.

All responses in a Delphi Survey are anonymous to the panel. Your name is required by the researcher only for necessary logistics in administering a multi-part survey. Please complete the Round Three survey within 14 days of notification by e-mail that the round has begun. The Round Three responses from the panel will be analyzed and a copy of the findings of this research will be provided to all participants.

If you have any questions please contact me:

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Begin Round 3

Summarizing Statements

Delphi Survey Round Three

In Round Two please provide an agreement or disagreement response to each of the summary forecast statements. The declarative format of the statements is not intended to imply a degree of certainty. Each statement includes a hyper link to compiled comments from Round Two. Each statement includes space for final comments.
Please provide your unique Delphi panel member identification: User Name:

Definition of Consensus for this Research

Consensus is:

For this research consensus is defined as: A proposition acceptable enough that all members can support it; no member opposes it. (Baldrige National Quality Award Process)

Consensus is not:

1. A unanimous vote - consensus may not represent everyone's first priorities.
2. A majority vote- in a majority vote, only the majority gets something they are happy with. People in the minority may get something they do not want at all, which is not what consensus is all about.
3. Everyone is totally satisfied.

From Round Two **Q1a.** What term do you prefer to use for "rapid prototyping technology"?

Read compiled comments from Round Two Q1a.

CAAM	SM	RP	SFF	LM	Other
Computer Aided Additive Manufacturing 0%	Solid Modeling 5.6%	Rapid Prototyping 67%	Solid Freeform Fabrication 22%	Layered Manufacturing 0%	5.6%
Round Two Responses n=18					

Q1b. Given the definition of consensus for this research, I accept Rapid Prototyping (RP) as the consensus term for "rapid prototyping technology"?

Agree	Disagree
◻	◻

Final comments:

From Round Two **Q2a.** Do you think 3D CAD modeling will become the initial or default design tool in the majority of CAD-related curriculums and if so why and by what year?

Read compiled comments from Round Two Q2a.

3D CAD is current default design tool 39%	Within 5 years 44%	5-10 years 11%	Other Opinion 0%	No Opinion 5.6%
Round Two Responses n=18				

Q2b. Given the definition of consensus for this research, I accept as consensus the projection that 3D CAD modeling will be the initial or default design tool in the majority of CAD-related curriculums within 5 years.

Agree	Disagree
☐	☐

Final comments:

From Round Two **Q3a.** In your opinion, Virtual Reality (VR) might become a replacement for RP in engineering design curricula when the VR technology improves?

Read compiled comments from Round Two Q3a.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
0%	39%	11%	44%	5.6%
Round Two Responses n=18				

Q3b. Given the definition of consensus for this research, I accept as consensus the projection that Virtual Reality will not become a replacement for RP in engineering design curricula.

Agree	Disagree
◯	◯

Final comments:

From Round Two **Q4a.** Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students?

Read compiled comments from Round Two Q4a.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
5.6%	5.6%	22%	56%	11%
Round Two Responses n=18				

Q4b. Given the definition of consensus for this research, I accept as consensus the proposition that the inclusion of RP technology into the engineering design curricula does not have different effects on male and female students.

Agree	Disagree
◯	◯

Final comments:

From Round Two **Q5a**. In your opinion, in most circumstances where RP is used in engineering design curricula should students, a technician, or a faculty member run the machine?

Read compiled comments from Round Two Q5a.

Students	Technician	Faculty	Other	No Opinion
28%	28%	22%	17%	5.6%
Round Two Responses n=18				

Q5b. Given the definition of consensus for this research, I accept as consensus the proposition that in most circumstances where RP is used in engineering design related curricula a technician or faculty member is more likely than a student to run the machine.

Agree	Disagree
☐	☐

Final comments:

From Round Two **Q6a.** The total cost of operation of RP technology will decrease dramatically in the next 5-10 years?

Read compiled comments from Round Two Q6a.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
17%	56%	5.6%	22%	0%
Round Two Responses n=18				

Q6b. Given the definition of consensus for this research, I accept as consensus the projection that the total cost of operation of RP technology will decrease dramatically in the next 5-10 years.

Agree	Disagree
☐	☐

Final comments:

From Round Two **Q7a.** Total cost of operation is the most important factor related to the use of RP in the curricula?

Read compiled comments from Round Two Q7a.

Strongly Agree 28%	Agree 50%	No Opinion 0%	Disagree 17%	Strongly Disagree 5.6%
Round Two Responses n=18				

Q7b. Given the definition of consensus for this research, I accept as consensus the proposition that the total cost of operation is the most important factor related to the use of RP in the curricula.

Agree	Disagree
○	○

Final comments:

From Round Two **Q8a.** Assuming a RP model could have ONE property identical to the finished product from the list: Geometric accuracy, Mechanical properties, Appearance, which property is the most important in an educational environment?

Read compiled comments from Round Two Q8a.

Geometric accuracy 44%	Mechanical properties 22%	Appearance 33%	Other 0%	No Opinion 0%
Round Two Responses n=18				

Q8b. Given the definition of consensus for this research, I accept as consensus the proposition that, assuming a RP model could have one property identical to the finished product, that geometric accuracy is the property that is the most important in an educational environment.

Agree	Disagree
◯	◯

Final comments:

From Round Two **Q9a.** What RP machine would you currently recommend for purchase as appropriate in the majority of product design-related curriculums?

Read compiled comments from Round Two Q9a.

Too many factors 17%	Z-Corp 3D Printer 22%	Stratasys Dimension 33%	3D Systems Thermojet 11%	3D Systems SLA 5.6%	No Opinion 5.6%	Other 0%
Round Two Responses n=18						

Q9b. Given the definition of consensus for this research, I accept as consensus the proposition that the currently available RP machine most appropriate for the majority of product design-related curriculums is the Stratasys Dimension.

Agree	Disagree
○	○

Final comments:

From Round Two **Q10a.** Based on the panel comments to questions 1-10 is it your opinion that future research of the effects of "RP technology" using the Delphi method should be subdivided into the categories: RP, 3D-Printer/Concept Modeler, Rapid Manufacturing?

Read compiled comments from Round Two Q10a.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
5.6%	22%	28%	39%	5.6%
Round Two Responses n=18				

Q10b. Given the definition of consensus for this research, I accept as consensus the proposition that future research of the effects of "RP technology" using the Delphi method should not be subdivided into the categories: RP, 3D-Printer/Concept Modeler, and Rapid Manufacturing.

Agree	Disagree
◯	◯

Final comments:

Submit Form   Reset Form

Appendix J

Delphi Survey Round Two - Comments

Q1a. What term do you prefer to use for "rapid prototyping technology"?

We all know what it means... so let's get on with it!

Concept modeling

Solid modeling is a subset of RP

Return to Question Q1b.

Q2a. Do you think 3D CAD modeling will become the initial or default design tool in the majority of CAD-related curriculums and if so why and by what year?

Until something better comes along!

Companies still use 2D. As more of our students get into decision making areas of business, will we see 3D used more.

The ease of use and interest it generates.

The key term here is "design tool" CAD will remain the drafting tool.

Return to Question Q2b.

Q3a. In your opinion, Virtual Reality (VR) might become a replacement for RP in engineering design curricula when the VR technology improves?

I think VR will compliment RP.

We will still need models for ergonomics.

Maybe as a supplement. VR tools are still a ways away.

Will always need a physical mock up to touch, feel, manipulate and integrate into a larger assembly.

I see it as an addition, rather than a replacement. They compliment one another.

Not entirely. VR and RP will complement each other.

VR might be used to teach about RP, it is incorrect to say that it will replace it. VR could be used to teach about a number of non-virtual topics.

Return to Question Q3b.

Q4a. Is the inclusion of RP technology into the engineering design curricula likely to have different effects on male and female students?

RP technology really is only a tool. Based on industry needs, the curriculum is the key.

Yes, it is bringing more females into the field.

Return to Question Q4b.

Q5a. In your opinion, in most circumstances where RP is used in engineering design curricula should students, a technician, or a faculty member run the machine?

A tech or faculty member who is trained- not students.

As the technology matures, students should run it.

All of them should run it for different reasons at different times. This answer might default to "students" in your analysis.

Mix of all three.

I think having a technician operate the machine is the most cost effective approach. To use a machine well you need to know how it operates, provide consistent maintenance, understand the pros and cons of materials, etc. Faculty does not have the time to do this. Students can help, if they can make a long term time commitment.

If students run the machine it must be very closely supervised.

Curriculum drives the needs. The technician only maintains the machine.

Faculty will need to monitor the operation but I would prefer a paid part time support person to run the machine.

Students should run the 3D printers. More complex RP requires faculty/technician supervision.

Return to Question Q5b.

Q6a. The total cost of operation of RP technology will decrease dramatically in the next 5-10 years?

Dramatically NO!. Companies still charge too much for the machine, materials and maintenance contracts. It will drop SOME!

It will continue to decline in the future but not dramatically. It depends of the process and material being used.

I expect high quality 3D printers to cost <15K in the next 5 years.

If it were not for the word, "dramatically," I'd have agreed.

Return to Question Q6b.

Q7a. Total cost of operation is the most important factor related to the use of RP in the curricula?

The initial cost of the machine is the determining factor.

Curriculum should NEVER be dictated by equipment cost.

You must have the dollars for this technology!

Return to Question Q7b.

Q8a. Assuming a RP model could have ONE property identical to the finished product from the list: Geometric accuracy, Mechanical properties, Appearance, which property is the most important in an educational environment?

I'll bet that those who originally selected material properties, surface characteristics, etc., were assuming geometric accuracy as a given.

The accuracy is the key. Everything else falls into place after the model is built.

Return to Question Q8b.

Q9a. What RP machine would you currently recommend for purchase as appropriate in the majority of product design-related curriculums?

Cost is the factor. Must schools will go with what cost the cheapest. For DESIGN-related curriculums, Z-Corps, Stratasys and Thermojet are the best choices. The others machines just cost to much overall. ROI is hard to justify.

My 2nd choice is the Dimension.

Return to Question Q9b.

Q10a. Based on the panel comments to questions 1-10 is it your opinion that future research of the effects of "RP technology" using the Delphi method should be subdivided into the categories: RP, 3D-Printer/Concept Modeler, Rapid Manufacturing?

Maybe in 5 years we can subdivide. Not enough schools use this technology.

Return to Question Q10b.

Return Confirmation - Round Three

Thank you for participating in Round Three of this survey.
A report of the findings of this research in pdf format will be e-mailed to you.

Please take a few minutes to fill out a short Post-Delphi questionnaire.

Post-Delphi Questionnaire

Appendix K

Delphi Survey Round Three – Comments

Q1b. Given the definition of consensus for this research, I accept Rapid Prototyping (RP) as the consensus term for “rapid prototyping technology”?

My only major issue with the term is that it is used in the software industry and will lead to confusion.

Rapid Prototyping is currently a very accurate and standard term. In the long hall however, it is limiting to the potential of the technology. There are currently uses for modeling of characters for the entertainment industry (animation) and uses in direct manufacturing. As different materials are developed, more direct manufacturing will occur as well as different applications that go beyond prototyping.

Q2b. Given the definition of consensus for this research, I accept as consensus the projection that 3D CAD modeling will be the initial or default design tool in the majority of CAD-related curriculums within 5 years.

It already is the default tool to start design in our graphics curriculum.

Q3b. Given the definition of consensus for this research, I accept as consensus the projection that Virtual Reality will not become a replacement for RP in engineering design curricula.

Not a replacement, an add-on.

At least not in the near 5-8 year future.

Q4b. Given the definition of consensus for this research, I accept as consensus the proposition that the inclusion of RP technology into the engineering design curricula does not have different effects on male and female students.

I would guess that those who forwarded the proposition that RP technology in engineering design doesn't effect male and female students differently tend to: 1. have many more male students than female students; and 2. have female students who are gender-atypical related to their engineering interests. I would therefore be suspect of their ability to speak to the larger population of potential female students.

Q5b. Given the definition of consensus for this research, I accept as consensus the proposition that in most circumstances where RP is used in engineering design related curricula a technician or faculty member is more likely than a student to run the machine.

No longer the case with the newer office machines.

Safety is a major concern.

As the technology evolves, it becomes easier to operate. The difficult part is learning which technology to use for each application and the material to be used. Also important in the learning process is finishing the model for presentation. I see not reason that the student cannot "push" the button once the design and build decisions are made with the oversight of the instructor and lab tech.

Q6b. Given the definition of consensus for this research, I accept as consensus the projection that the total cost of operation of RP technology will decrease dramatically in the next 5-10 years.

As soon as the numbers of users get up significantly, then the cost will decrease.

Q7b. Given the definition of consensus for this research, I accept as consensus the proposition that the total cost of operation is the most important factor related to the use of RP in the curricula.

It is a shame that educators place cost above learning. The purpose of using RP equipment in a school is not to use RP equipment, the purpose should only be to learn. Learning can be facilitated in ways that do not require the purchase of costly equipment.

With office machines, the operating cost is very manageable, and can be covered by lab fees.

It is what is keeping us from going to a better machine.

Q8b. Given the definition of consensus for this research, I accept as consensus the proposition that, assuming a RP model could have one property identical to the finished product, that geometric accuracy is the property that is the most important in an educational environment.

As a first step. This will soon become the norm, then material properties will be next.

Q9b. Given the definition of consensus for this research, I accept as consensus the proposition that the currently available RP machine most appropriate for the majority of product design-related curriculums is the Stratasys Dimension.

For small classes maybe. For larger classes, the Thermoject can build more parts quicker.

Q10b. Given the definition of consensus for this research, I accept as consensus the proposition that future research of the effects of "RP technology" using the Delphi method should not be subdivided into the categories: RP, 3D-Printer/Concept Modeler, and Rapid Manufacturing.

Please send us each an Email letting us know where the final report from this study is published. Keep up the good work.

Thanks for your participation in this Delphi Survey. A copy of the survey results in pdf file format will be e-mailed to you upon completion.

J.D. Mather

Appendix L

Post-Delphi Questionnaire

Thank you for participating in this Delphi Survey. I developed this internet-based survey to take advantage of the "collaboratory" (collaboration + laboratory) nature of the world wide web in facilitating a group communication process. Please answer a few questions about your experience with this survey instrument format.

Finally, all responses in a Delphi Survey are confidential. At no time will any individual response be associated with a particular panel member. However you may elect to be recognized for your participation on this panel.

If you have any questions please contact me:

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Please provide your unique Delphi panel member identification:
User Name: ______________________

☐ I elect to be recognized in publication for my participation on this panel.

☐ I elect to remain anonymous in publication.

1. I feel satisfied with this Delphi survey format in general.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

2. I learned from the feedback.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

3. I could express my ideas in this format.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

4. I feel a face-to-face meeting would have worked better than this format.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

5. I think the survey in this format went too fast.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

6. I think the survey in this format went too slow.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

7. General comments

Submit Form   Reset Form

Appendix M

Post Delphi Questionnaire - Results

1. I feel satisfied with this Delphi survey format in general.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
42%	50%	8%	0%	0%
n=12				

2. I learned from the feedback.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
25%	67%	8%	0%	0%
n =12				

3. I could express my ideas in this format.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
50%	33%	17%	0%	0%
n =12				

4. I feel a face-to-face meeting would have worked better than this format.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
8%	0%	17%	58%	17%
n =12				

5. I think the survey in this format went too fast.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
0%	8%	8%	58%	25%
n =12				

6. I think the survey in this format went too slow.

Strongly Agree	Agree	No Opinion	Disagree	Strongly Disagree
0%	17%	17%	42%	25%
n =12				

7. General comments from the Post Delphi can be found in Appendix N.

Appendix N

Post Delphi Questionnaire - Comments

Great job. I've seen consensus building botched by many researchers and leaders in a field, but you are to be commended on doing a fine job.
It went just fine, not too fast and not too slow. Good job. Send me the results.
The system seemed to work well.
Thank you for the opportunity to participate. It is nice to see the interest in the RP process and the educational perspective.
I am looking forward to the complete data and the form in which it will be presented. I hope to be of assistance in the future if I can. Thanks

Appendix O

Delphi Panel Members

The following panel members elected to be recognized in publication for their participation on this survey.

David Baird Associate Professor Southeast Missouri State University	Todd Grimm President, T.A. Grimm & Associates Edgewood, Kentucky
Ronald E. Barr Professor, Mechanical Engineering University of Texas at Austin	James B. Higley Professor of Mechanical Engineering Technology Purdue University
Bob Chalou Academic Specialist, Engineering Department Michigan State University	Ken Patton Dean, Business Science, Vocational Education, Economic Development Saddleback College Mission Viejo, California
Richard Eldridge Assistant Professor, CAD Drafting and Tool Design and Department Chair Ferris State University	Rebecca Strzelec Assistant Professor of Visual Arts Penn State University-Altoona College
James C Flowers Professor, Director of Online Education Industry & Technology Ball State University	The rest of the panel members elected to keep their participation confidential.

VITA

Jeffrey D. Mather

Personal Data: Date of Birth: June 22, 1957
Place of Birth: Alliance, Ohio

Education: Public Schools, Hollywood, Florida, 1975
John Tyler Community College, Richmond, Virginia
Industrial Engineering Technology, A.A.S., 1983
Virginia Polytechnic Institute & State University, Blacksburg, Virginia;
Technology Education, B.S., 1993
East Tennessee State University, Johnson City, Tennessee;
Engineering Technology, M.S., 1994
East Tennessee State University, Johnson City, Tennessee;
Educational Leadership and Policy Analysis, Ed.D., 2003

Professional Experience: 15 years Industrial Experience including the positions:
Industrial Engineering Technician
Research and Development Technician
Journeyman Machinist
Graduate Assistant, East Tennessee State University, Department of Technology, Johnson City, Tennessee, 1992 – 1993
Assistant Professor, East Tennessee State University, Department of Technology, Johnson City, Tennessee, 1993 – 1999
Assistant Professor, Pennsylvania College of Technology, School of Construction and Design, Williamsport, Pennsylvania, 1999 - present

Grants: Principal Investigator for $517,391 grant titled, *Fleet Logistics Management*, US Army Tank & Automotive Armaments Command, 1997.

Awards: Innovative Excellence in Teaching, Learning and Technology, 2003. 14th International Conference on College Teaching and Learning.