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Development of Functional Rapid Prototyping for the Production of Near Shape Castings and Its Applications for Concurrent Engineering in the Metal Casting Industry

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DEVELOPMENT OF FUNCTIONAL RAPID PROTOTYPING FOR THE PRODUCTION OF NEAR SHAPE CASTINGS AND ITS APPLICATIONS FOR CONCURRENT ENGINEERING IN THE METAL CASTING INDUSTRY

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CHAPTER 1

Introduction

The strategic goal of any competitive manufacturing organization is to cut lead time and increase productivity in an effort to reduce costs in getting their product to the customer. As companies strive to reach this goal they are constantly looking for technologies and processes to improve there competitive edge.

In recent years manufacturing companies have been in fast paced competition and have been trying to adopt the latest trends in management and quality programs. One such trend to "get" Total Quality, has driven companies to implement the latest CAD software, adopt Self Directed Work Teams, empower the workforce or embrace concurrent engineering (CE), thinking that these techniques would provide the way to achieve market dominance (Gee, 1994).

The increased use of rapid prototyping technologies, subtractive, additive, and hybrid (APPENDIX A), as a supplemental tool to concurrent engineering strategy, has developed into a viable developmental resource for making fully informed decisions in the planning stage and during the development process. The benefit of rapid prototyping lies in its use in advanced engineering technologies and concurrent design methodology to effectively execute the product solutions.

Purpose of Research

The purpose of this research was to determine the increased role that rapid prototyping has taken in the metal casting industry for the production of near-net shape castings as well as reducing the new product lead time essential in concurrent engineering cycles. Additionally, research will (1) assess associated costs for product development, (2) determine time percentages procured for each level of development and manufacture and determine the stages where Rapid Prototyping can effectively aid in time reduction and engineering changes, (3) and the trends that the cast metals industry is trying to achieve through use of this technology.

Statement of the Problem

The problem of this study was to determine the methods used in the conceptual phases of producing a three dimensional prototypes for the casting of a metal part. Additionally, this study was conducted to ascertain the roles that current rapid prototyping systems have taken in product development and how engineers are looking to increase the use of this technology as a means to reduce lead times and tooling costs over conventional tooling. Presently, from the industrial outlook, little is known about the full market potential for rapid prototyping, it's niche and what it can achieve. Costs, availability, and its operational effectiveness have driven the foundry and manufacturing industry as a whole to challenge its practical role in their productivity plans for the future.

Statement of Need

In today's competitive market, successfully launching a new product depends on quick and efficient product development, coupled with flexible manufacturing processes. Timing is essential, delays of relatively short periods of time may result in a significant loss of market share.

Dr. David Cole (1994), Director of OSAT at the University of Michigan's Transportation Institute, in a keynote address given at the April, 1994 Rapid Prototyping and Manufacturing Conference, concurred that the current average lead time for U.S. automakers is 52 weeks compared to the competitor's at 40 weeks. In the year 2003, this lead time is expected decrease to 38 weeks and 34 respectively. The competitors nature is relentless and unforgiving. In order to regain the competitive advantage industry must reduce leadtime, improve sales and service to the customer, and increase the awareness of technological change in the industrial climate.

"In order for foundrymen to be competitive," according to Paul Mikkola an engineering authority using rapid prototyping to produce experimental prototypes at GM's Powertrain Division, maintained, "It is necessary to become aggressive, producing castings of near-net shape, thus diminishing or eliminating machining of a particular part which reduces the overhead costs of production. Rapid prototyping has proven that it has the potential for reaching this achievement in the casting industry" (personal communication, November, 1993).

Don Sabin, a design engineer for John Deere Product Engineering Center, Waterloo, stated, "There is a need to incorporate a fast way to produce functional prototypes to be used to view, or to be used as a pattern in making castings. There are many advantages in producing CAD based prototypes over conventional CNC prototypes, which is still predominately used today. These advantages save the engineer time from designing the part, to saving the tooling engineer time in changes after the master pattern has been produced" (personal communication, October, 1993). In later communication, Sabin further explained that, "Currently, the time required for us to introduced a new tractor on the market is nearly five years. We would like to see this time reduced to under three. We need to be looking harder at what rapid prototyping can do to possibly impact that time to market" (personal communication, March 1994).

Yehoram Uziel, CEO of Soligen, Inc. (1993), relayed this message about being competitive, "In today's marketplace, companies introducing new products must achieve a combination of concurrent engineering, good design, and Just-In-Time (J-I-T) production. Once a prototype of a new design or test part has been approved, the race is on to deliver it to the market before the competition shows up."

David Bank, SPE (1994), when addressing what is really needed in making America a globally competitive economy at the recently held SME's Rapid Prototyping Conference, had this to say about rapid prototyping.

> "America is not creating new products fast enough to compete in a global economy. We are delivering products that do not meet customer needs, wants and perceived value. We are not establishing strategic networking relationships augmenting our internal capabilities to make full informed decisions in the planning stages and during development processes. We lag in the innovative use of advanced manufacturing technologies and use of concurrent design methodology to effectively execute the product solution. Rapid prototyping is one of the hottest subjects in the product development circles today as one solution to shortening the product timeline to market"

Research Questions

The specific questions that will aid in determining industrial need to what is available in this research study are:

1. How do engineers in the cast metals industry currently generate prototypes for casting of parts?

2. Is the process of rapid prototyping a cost effective way to produce 3-D prototypes?

3. What is the current applied percent usage for these types of technologies used? How is this going to change in the near future?

4. What are the costs of change associated in the design, manufacturing, and production stages?

5. What options does rapid prototyping offer to the conceptual engineer in application design engineering?

6. What effect does rapid prototyping have on product quality, design optimization, and time to market?

7. What are the achievable tolerances associated with the technologies being considered and are they within the desired allowances for cast to size castings?

8. What are the engineering advantages that rapid prototyping has in comparison to that of conventional methods of CNC machining?

Assumptions

In pursuit of this study, the following assumptions were made:

1. Suitable technologies exist (APPENDIX B).

2. All data that has been collected on each system considered is for small prototype parts and has been used for applications in the metal casting industry.

3. The foundries that will be involved are assumed to represent the typical ferrous/nonferrous foundry and its technological needs in this area.

4. It is assumed that all the processes considered for this study will be classified as additive, subtractive, or hybrid technologies (APPENDIX A).

Delimitations

The limitations pertaining to this study were:

1. The number and size of the foundries to be surveyed for current usage will be medium to large ferrous/nonferrous foundries, to exceed 20 for a sampling size.

2. Due to the focus of the study, the field will be based on companies that are considered to be technology leaders covering the general types for each solid modeling technology that will be researched. They are based on the availability of information and are listed as follows:

1. Stereolithography (SLA)

2. Laminated Object Manufacturing (LOM)
3. Fused Deposition Modeling (FDM)
4. Direct Shell Production Casting (DSPC)
5. Selective Laser Sintering (SLS)
6. Solid Ground Curing (SGC)

3.) Travel to observe each type of technology will be limited, therefore much of the research will be descriptive in nature.

Definition of Terms

The following terms are defined to clarify their use in the context of the study (additional terms in APPENDIX D):

Stereolithography. A combining form of a solid, firm three dimensional object produced by functions of layering material (RP Report, October, 1994).

Near-Shape Casting. Producing an as-cast part of near or exact dimensions that require minimal to virtually no machining operations.

Computer-Aided-Design. The use of computer generated geometry of an object for 2-D or 3-D form.

Concept model. Three-dimensional model having relatively loose accuracy requirements, intended for evaluation of appearance and form and similar characteristics (RP Report, October, 1994).

CAD Casting/3D Printing. A casting process where the ceramic mold is created directly from a CAD model with no intermediate steps. CAD Casting is accomplished using Three Dimensional Printing, a Manufacturing technology creates ceramic parts by printing them in layers.

Desktop manufacturing. A synonym for rapid prototyping (RP Report, October, 1994).

Epoxy molding. Part replication technique in which an original part, or pattern, is surrounded by an epoxy resin, which then sets. The pattern is then removed to leave behind a mold cavity (RP Report, October, 1994).

Free-form manufacturing. Yet another synonym for rapid prototyping (RP Report, October, 1994).

Fused deposition modeling. Rapid prototyping technology in which a thermoplastic material is extruded by a moving orifice and hardens to form a layer (RP Report, October, 1994).

Hard tooling. Tooling suitable for producing large numbers of parts in production.

Laminated object manufacturing. Rapid prototyping technology in which part layers are cut form sheet material using a laser, and laminated together through heat and pressure to form a three-dimensional structure (RP Report, October, 1994).

Photopolymerization. Chemical process in which monomers and other small molecules combine to form complex molecules while producing solidification of the material (RP Report, October, 1994).

Post processing. One or more procedures occurring after a part is built, including stripping, post-curing, support removal, sanding, and painting (RP Report, October, 1994).

Prototype. Representation of a functional 3-D part that can be used as a visual representation or for use in fit or form experimentation.

Rapid prototyping. Fabrication of a physical, three-dimensional part of arbitrary shape directly from a numerical description (typically a CAD model) by a quick, highly automated and totally flexible process (RP Report, October, 1994).

Rubber molding. Similar to epoxy molding, but using silicone rubber as the mold material (RP Report, October, 1994).

RTV Molding. (Room temperature vulcanization or silicone-rubber molding). This is a process in which silicone-rubber is poured around a master produced by rapid prototyping to create a mold into which urethane or epoxy resins are then cast (RP Report, October, 1994).

Selective laser sintering. Rapid prototyping technology in which a laser draws the pattern of a layer onto a thin layer of thermoplastic powder, causing localized sintering of particles into a solid mass and adhesion to the underlying layer(RP Report, October, 1994).

Soft tooling. Tooling capable of producing a limited number of parts.

Solid ground curing. Rapid prototyping technology in which unexposed liquid photopolymer resin is removed from each layer and replaced by wax, after which the resin and wax layer is milled to the correct thickness before a new layer is added (RP Report, October, 1994).

Solid model. A CAD model which is represented as a three-dimensional volume having all points on or internal to the surfaces defined.

Spray metallization. Method of creating a mold cavity in which molten metal is sprayed to form a rigid shell over a pattern which is subsequently removed (RP Report, October, 1994).

Stereolithography. Rapid prototyping technology in which an ultraviolet laser is used to draw successive cross-sectional patterns on the surface of a photopolymer resin. The resin solidifies where illuminated, generating layers which adhere to one another to form a three-dimensional part (RP Report, October, 1994).

.StL file. Data file of a specific format originally developed by 3D Systems in which the surfaces of a CAD model are represented by a set of triangular facets (RP Report, October, 1994).

Surface finish. Smoothness of a surface, usually expressed in microinches.

Surface model. A CAD representation of a three-dimensional object in which all the points on the surface are defined (RP Report, October, 1994).

Thermo-plastic composite tooling (TPC). TPC is a composite injection molded process which rapidly reproduces highly defined three dimensional parts. It is used to reduce tooling time by 55% and cost by 35%. The tool consists of a composite material core and cavity that allows duplicate parts to be shot with the selected production material (Griffin & Foley, 1994).

CHAPTER II

Review of Literature

The body of information available on this topic of technology is considerable, however the degree of maturity in this emerging technology makes it difficult to ascertain reliable characteristic data. Therefore the review will be limited to studies dealing with product development and proposed use in concurrent engineering cycles.

Manufacturing the 90's is driven by a cycle time world. According to Davis (1993), a consultant for Metalcast Engineering which has performed extensive research into prototype technologies,

> "Customers are forced to market quicker, in order to grab diminishing market share in a world where the life span of many products lasts only 18 months. From the design and engineering side, major cycle time reduction has taken place by the use of solid model CAD tools, like Pro/E (ProEngineer-a solid modeling software system). From the foundry side, the use of new rapid prototyping tools has further reduced cycle time. This reduction of cycle time yields gains in market share, thus increasing the potential for profits."

Design and manufacturing engineers have always faced tough questions about whether to build a prototype to assure understanding or to forego a prototype to save time and cost (Marks, 1993). Rapid prototyping tools are changing the "right" answers. Whether it is "hard" or "soft tooling, the promise of rapid prototyping is to gain greater knowledge for product performance earlier in the development cycle.

The ability of a company to reduce concept and experimentation time as well as allowing the company to locate potential problem areas with the CAD casting technology, has the potential to reduce production costs in half. It will also be a key element for companies to stay competitive in ensuring profitability and survival (Davis, 1993).

Don Backens, a supervisor and tooling engineer for pattern development at John Deere's gray and ductile iron foundry located in Waterloo, Iowa, stated, "Speed is the most important benefit of this type of technology. The prototype allows the designer to compress the product development cycle, accelerate manufacturing speeds, increase experimentation and make improvement changes easily, all with an increase in visual communication" (personal communication, September 13, 1993).

Pattern Shop Perspective

The majority of pattern and moldmaking shops are yet content with traditional methods of pattern making. What soon is becoming a common reality is an onset of problems with traditional methods. According to Northland Pattern, a pattern shop in Indiana, who has made a change to more modern practice (Root, 1994), related that pattern making industry has seen problems that have impacted the entire U.S. moldmaking industry. These problems include the following:

<u>High levels of handwork</u>
Finishing operations are becoming a major bottleneck for high production of precision patterns and molds. Too much time is being spent to finish critical features.

<u>Disappearing skills</u>
With the average age of patternmakers in the U.S. now at 58 (Root, 1994) and long apprenticeship discouraging replacements, skills and experience are no longer enough to meet the stringent requirements of today's competitive foundries.

<u>Tighter tolerances and greater accuracy</u>
Foundries today are moving toward near-net shape casting. In order to do so they are tightening tolerances to those expected of machining. Where a 1/16" was good enough, 0.005" is now the standard tolerance and some customers demand 0.002" or better.

Pattern Making Options

The means of master pattern development used in the cast metals industry are divided into three unique processes. The first, the traditional hand-worked wood and metal pattern methods are the same techniques that have been used for two hundred years. Although used very seldom today for tooling production, they are still used in small job shops and pattern making centers.

The second means uses CAD/CAM/CNC methods and has become the major tool making method for most pattern shops for the past few years, and for some, the last few decades.

This method has become the desired machining method for producing master patterns because of its high dimensional consistency, as well as offering the patternmaker repeatability of a desired tolerance specifications.

During the last three years a new type of technology, referred to as automated fabrication or rapid prototyping technologies (used interchangably throughout this paper), have developed into viable tool making methods and now account for nearly 5% of all applications (Wohlers, 1993). This method, although relatively new, is expected to achieve as much as 35-40% of the market within the next 3 years. This increase is thought to be caused by the market demand driven by the need for castings at reduced costs.

Prototype Methods

Wood Patterns

Wood patterns certainly were an appropriate technology for tooling when drawings were the media for communication. The use of traditional wood patterns is still used today, primarily by the casting industry, but the methods in which they are produced have been changed drastically from the more traditional means of former pattern making as it was known. Most pattern making is now accomplished through the use of CNC machines that machine the wood tooling patterns into shapes that are desired.

Computer-Numerically-Controlled Manufacture

Computer-aided-design and manufacturing (CAD/CAM), when coupled with the precise accuracy that can be produced using computer control for machining using a lathe, or various milling machines, is by far the number one advantage which exceeds all other types of technologies available today. CNC machining of prototype patterns, commonly referred to as "hogout" patterns (production of intricate parts out of rough stock), offers advantages that set industry standards for extremely accurate dimensional stability and surface characteristics, reaching tolerances to the thousandths for components required by industry. Although I will describe the comparison of this relatively old technology in greater detail later, the main disadvantage of CNC is in the area of software development and the lack of automation in applying tool paths to models. This is the human intervention factor and can produce defects in tooling such as missing features and cutter radii inaccuracies (Davis, 1993).

Automated Fabrication

Automated fabrication technology is a relatively new development (Wohlers, 1993) that has proven to significantly reduce the time and cost that long have burdened the foundry's role in responding to customer's needs in the new product development cycle. The computer designed and built tooling patterns can be formulated using more than a dozen varying types of methods that produce the master pattern for a part, which can ultimately be implemented directly in making molds for casting purposes. Cost and timing (Davis, 1993) based on traditional methods and the potential use in simultaneous engineering practices, make these technologies very attractive for pattern making.

Additionally, automated fabrication is a process that can be used to complement manufacturing techniques, such as concurrent engineering, which are becoming increasingly popular. Here, all phases of the product life cycle, from concept design to obsolescence, are evaluated and optimized simultaneously during the design phase (Montaque, p. 22).

Some fabrication techniques, such as the Selective Laser Sintering, Stereolithography, and Laminated Object Manufacturing, can produce models that can be used as functional, testable prototypes, as well as conceptual geometric models. This offers to the engineer the ability to functionally test the design during actual use before the part is committed to production (Montaque, 1991). These processes can also be used for short-run production of custom parts or parts that can be used for marketing samples, as well as wax patterns for molds that are used in investment casting processes, a method of mass production used for smaller parts. An example of the strategic impact that rapid prototyping has had on the manufacturing industry carries over into other important manufacturers as well.

Biomet Inc., designs, manufactures, and markets products used primarily by orthopedic medical specialists in both non-surgical and surgical therapy. They saw the need to implement the modeler into their concurrent engineering strategy for developing parts without the need to develop expensive hard tooling. Gary Johnson, Vice President of manufacturing at Biomet Technologies (personal communication, September 20, 1992), says this about the impact of the system,

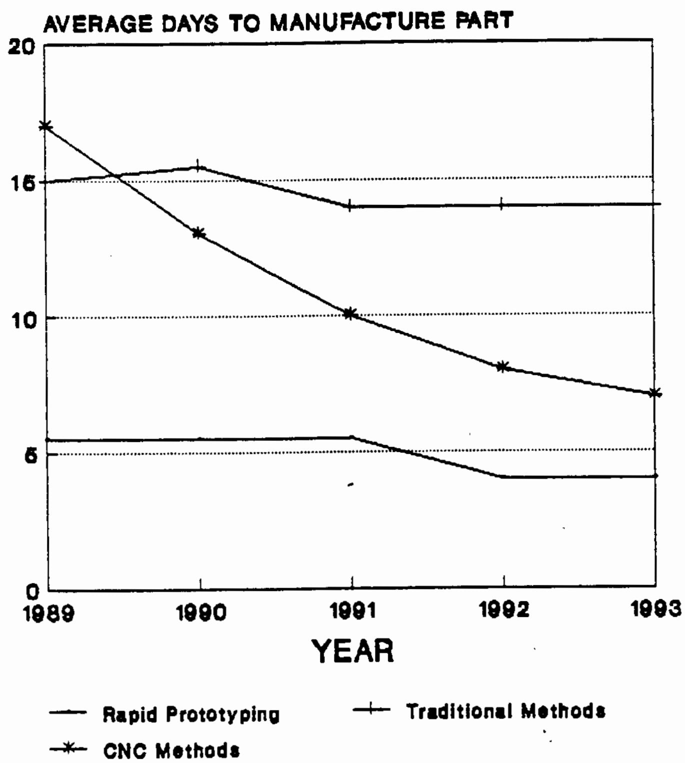
> "Biomet has been working with the modeler for nine months. Our savings in R&D and manufacturing time has been eight fold using the system. The flexibility, speed and accuracy of the technology will help launch us into the next century. This is the kind of technology that our intensive R&D and manufacturing efforts demand."

Case Studies

According to case studies that have been performed, Wohlers (1993) and Davis (1993), analysis of each type of technology can truly be examined. The main characteristics that concern pattern makers who are directly responsible for the production of the master patterns used in the metalcasting industry, are the tolerances, the time needed to develop the desired pattern within the specifications of the design parameters, and the direct and indirect costs involved, as well as surface finish of the pattern.

As seen in the figures provided, comparisons for time and tolerances tested for each technology are observed. In Figure 1, time needed to produce traditional patterns (those

FIGURE 1. Time comparison for producing prototypes using the various technologies.



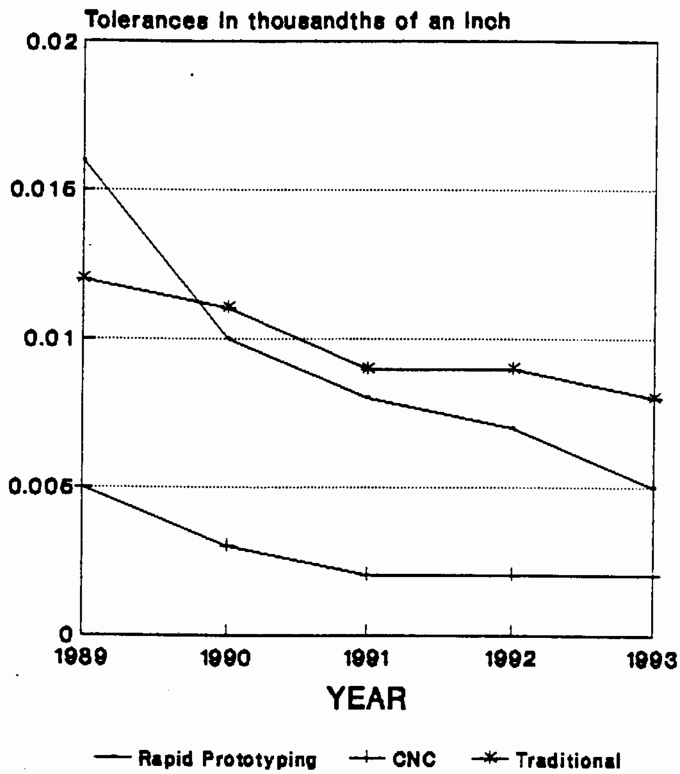
Note. From "Tooling advances in die-cast prototypes". Davis, S., (1993, September 20, 21). Research presented at John Deere rapid prototyping conference. Davenport, IA. Adapted by permission.

produced by hand tools) has not decreased significantly over the past five years. Comparatively, master patterns produced using CNC now average 6.5 days to produce. Programming tools and learning curves have been the reason for these time reductions. Also it can be seen that rapid prototyping methods have almost reached a static point. Small decreases in time have been seen in finishing and can be expected to improve as technology progresses.

As seen in Figure 2, the time savings is very significant for this parameter and has been an important aspect for those concerned with decreasing experimental time needed before a part can be okayed for production.

The second parameter of significant importance, is the tolerances that can be achieved. Tolerances in wood patterns are determined mainly by hand-eye coordination. Sanding machines, saws, planers, and glue have not undergone any significant improvements. This leaves traditional methods lacking in this important aspect. CNC improvements have been in the areas of pattern material that is more dimensionally stable, decreased learning curves, and improved data. Software that has been developed has allowed the manufacturer to bypass data translation further decreasing the tolerance bandwidth (Davis, 1993).

FIGURE 2. Relative tolerance of pattern features for producing prototypes.



Note. From "Tooling advances in die-cast prototypes". Davis, S., (1993, September 20, 21). Research presented at John Deere rapid prototyping conference. Davenport, IA. Adapted by permission.

According to Davis (1993), automated fabrication technologies have undergone significant improvements in all phases of development from chemistry of the resins, which provides increased stability, to weave style, or other construction parameters. This is the pattern class that has seen the most significant change in the last five years and now is narrowing the tolerances seen between CNC and this new technology. Although this may be true, there is still some speculation about the consistency seen with this technology in comparison with CNC (Davis, 1993).

To bring all of these parameters together into one specific part it is necessary to make a point of a case study performed by Metalcast Engineering of Oakland, California, and their work done with development of a Motorola Mobile Radio (Davis, 1993). The project was done using two methods of manufacture, CNC and a method of rapid prototyping, Selective Laser Sintering (a method developed by the University of Texas). The results, as revealed through the study, are seen in Table 1.

TABLE 1.

CNC/RAPID PROTOTYPING BENCHMARK

Pattern Cost & Time comparison			
SLS:	$2500	4 days	
CNC:	$4500	7 days	
Tolerances achieved and feature definition			
SLS:	+- 0.005	almost sharp surface	
CNC:	+- 0.003	sharp surface	

Note. From "Tooling advances in die-cast prototypes". Davis, S., (1993, September 20, 21). Research presented at John Deere rapid prototyping conference. Davenport, IA. Adapted by permission.

As seen in the data given, the tolerance of the parts from the different pattern methods is very close. The conclusions based on the study put out by Metalcast Engineering state that with the tolerances so close it is difficult to determine method selection. Even the finished castings were virtually indistinguishable from a tooling standpoint (Davis, 1993). This is one more indication that the methods of rapid prototyping are making significant improvements toward closing the gap between the two technologies.

Earlier studies performed by Frost Prioleau (1993) of Plynetics Corp of San Leandro, California, performed a comparative study of three forms of rapid prototyping technologies: Computer Numerically Controlled machining, Selective Laser Sintering, as well as Stereolithography, analyzing requirements in several areas, including accuracy, materials, properties, speed, cost, geometry and others in producing plastic prototypes. However, these technologies are not equal, as they each offer unique capabilities to developing optimal design prototypes in the shortest amount of time.

A similar benchmarking study performed by Douglas Van Putte, Eastman Kodak Co. (1992), compared automated fabrication processes found that when comparing four other technologies to the SLA 250, none where more or as accurate in producing a part holding to the X-Y-Z dimensions specified in the study.

CHAPTER III

Research Design and Methodology

Sample

The sample consisted of users of rapid prototyping technologies and potential users in the cast metals industry. This included pattern shops, technical centers, research facilities, service bureaus, and foundries involved with pattern and product development. The sample consisted of at least 20 mid to large size foundries, 30 pattern/ tooling shops that have at least one type of rapid prototyping technology in-house, and 10 service bureaus which offer the technology in-house.

Methodology

This study is designed to compare conventional methods of prototype development to methods of modern fabrication techniques of rapid prototyping and what effect this has on product development and concurrent engineering cycles. The methodology will focus on a variety of means to gather information pertinent to this research. Research was used to gather information on existing benchmark studies that have been done by paralleling studies comparing the two or more methods used to fabricate the initial prototype. Quite often studies have compared conventional methods and one or more rapid prototyping methods. In these studies comparisons have addressed tooling cost, development cycle time and cost, lead time, product quality and design optimization by reduction in errors that lead to re-tooling and re-manufacture costs.

Determining what forms the technology took was the first challenge. Four approaches to this task were used to gain a background knowledge of available technologies. The first centered on researching past literature and publication journals catering to the engineering and manufacturing industry. From these, compiled information on various systems, their manufacturers, their general characteristics of operation, and in what application they were currently being used was noted.

The second approach for gathering information was to gather the information available through the various vendors of the technology. Information available through the vendors included product descriptions, video demonstration footage, and other forms of informative propaganda available through the companies. Utilizing these types of media material allowed the author to gain low level introductory information useful in building a foundation into the available technology available through each vendor. The third segment was of the preliminary investigation involved the attending of introductory seminars available through the Rapid Prototyping Association (RPA) of the Society of Manufacturing Engineering, as well as attending a conference put on by Deere & Company, which brought in a variety of service bureaus to speak on, and demonstrate their technology, as well as offering the opportunity for Deere technical employees to explain benchmark studies that were implemented on specific projects within the company. A listing of the itinerary is available in APPENDIX C.

The fourth preliminary investigation carried on throughout the entire research timeline and involve the actual observance of all six primary technologies available and a few in development. As mentioned earlier the author took the opportunity to travel to remote sites to view systems in operation and discuss with the operators the advantages of using the various automated fabrication modeling machines compared to more conventional means such as CNC, and skilled hand fabrication, which many still had in operation.

During this phase of the project, many questions, concerns and characteristics of the various systems were recorded. Compiling this information for analysis provided a base from which comparisons between the present prototype development technologies available and those beginning to be implemented could be compared whether it be in raw data, or through existing benchmark studies. Information gathered during these on-site visitations included equipment characteristics, cost comparisons, methods of prototype manufacture, use of secondary tooling, time constraint comparisons, costs of changes during development, and CAD usage.

The primary setting for which the research was completed was for the foundry industry, so it was pertinent to gain information knowledge into current fabrication practices and pattern development techniques for both the development engineer's side as well as the prototype application side within a typical foundry. This was necessary to fully understand the operation of a prototype casting from concept to production tooling. To interact in this capacity, the author was able to perform as supervisor of an experimental/prototyping molding business unit at John Deere's gray and ductile iron foundry in Waterloo, Iowa. Through this experience the author was able to begin to fully understanding time constraints, casting techniques, as well as a full avenue of prototype production and tooling re-work with local pattern shops.

In addition to direct prototyping experience at the foundry level, a link was made with corporate personnel at Deere & Company's Technical Center who where directly responsible for providing technical assistance for each of the product engineering centers in the area of technology transfer specifically in rapid prototyping. This gave the author the direct opportunity to address the focus that large industry has into implementing new technology into its own developmental structure.

The next level of research was to observe each of the systems in service to develop a working knowledge of application and niche that each system was designed to achieve. Since the project goal was to establish this relationship to product development cycles it was necessary to visit direct users of the modeling equipment in-house. Although time for travel was limited, the facilities that were chosen where the most prominent research facilities, service bureaus, pattern shops, and manufacturing facilities. Each of these having two (2) or more types of machines in operation. In addition to the modeling machines, many of these facilities were equipped with capabilities for secondary tooling operations, CNC machining, extensive CAD availability, and for some complete casting capabilities involving spin casting, sand casting, plaster casting, investment casting, and urethane molding. During these visits, many questions, concerns, and comparisons could be made pertaining to the various technologies available, as well as the comparison to conventional methods used in a pattern development facility.

To gain an even greater representation of product engineering centers, pattern and machine shops, and service bureaus, the author contacted knowledgeable personnel by phone in positions directly responsible for the design, fabrication, and implementation of part. This included personnel dealing with part design work on a 3-D modelers (such as Pro-Engineer, Unigraphics), pattern development, pattern shop/service bureaus, foundry personnel, as well as consultants directly involved with implementing benchmark studies.

The combination of review literature, information provided by RPA and other technical journals and books, the application of a working knowledge from the foundry side, supplemented with tooling and pattern development knowledge, and facility visits, provided the author with a good understanding of the various automated fabrication modelers and methods for rapid prototype manufacture available. These attributes include: part build envelopes, build tolerances, geometric capabilities, achievable surface finish, as well tooling capabilities.

Based upon the literature reviewed, facilities and conferences visited, the following areas of importance were identified.

- Reduced product development lead time,
    - using rapid prototyping in product development
    - visualization
    - iteration and optimization
    - verification

  - fabrication
  - production
- Reduced tooling cost and re-work using Automated Fabrication
- Alternatives to traditional fabrication methods
- Implementing Integrated Product and Process Development (IPPD)

After identifying these areas, it became possible to characterize project time optimization and reduction in tooling costs for casting production. The results of the analysis along with benchmark studies will be found in Chapter 4: Reported Findings for Research.

CHAPTER 4

Reported Findings for Research

Rapid prototyping/Automated fabrication users have advanced to use a wide range of prototyping technologies such as computer aided manufacturing, and reverse engineering, the backbone being 3-D computer modeling. Utilizing the power of 3-D computer modeling by converting 3-D computer data into a 3-D physical part, this automated manufacturing process eliminates the need for 2-D detailed drawings and fabricates a highly accurate model for a multitude of uses including:

- Pattern and tool development
- Design verification
- Form, function, and fit
- Quoting and marketing models
- Concept model
- design method of manufacture
- Scale test models
- Non-destructive testing
- Visualization for manufacturing

Models replicate the design precisely from the 3-D computer model eliminating any misinterpretation and allowing functional prototypes to be manufactured exactly to design intent. These CAD driven models come in a fraction of the time required to receive conventional pattern making methods. Models that take weeks to make using 2-D drawings can be fabricated in as little as 4 hours to five days using automated fabrication methods.

Automated Fabrication can be adapted to most prototype casting or molded plastic processes including:

- RTV/silicone molding
- sand casting
- plaster casting
- vacuum casting
- investment casting
    - ferrous
    - non-ferrous
    - magnesium
    - urethane plastics
- others

A further benefit of automated fabrication is in design verification. The automated fabrication design verification process allows engineers to catch flaws in designs before tooling is manufactured and allows the opportunity for multiple design iterations before any production tooling is manufactured.

Electronic Data Systems Study

According to a study conducted by Design Insights to examine the best practices in CAD/CAM at several manufacturing companies in the U.S. (Wohlers, 1994), companies were asked to list the most important areas of opportunity for speeding the development of new products. Some of the larger companies responding included AMP, Apple Computer, Eastman Kodak, GE Aircraft Engines, 3M, and Motorola.

The top 3 responses included.

1. Reduce the time to get fully functional molds and dies from suppliers.
2. Reduce the time to model and re-model as a design moves from initial design, through engineering, documentation, process planning, and various supplier operations.
3. Reduce the time needed to get marketing, engineering, manufacturing - and the customer - to agree on new product specifications. RP processes will contribute in all three areas, making it a technology of strategic importance at companies that use it properly.

Casting Processes

Through preliminary research, current practices in pattern and casting development were observed to follow many methods for processing. For many, the casting process is the same, being various sand casting, investment, plaster, centrifugal, permanent mold processes, as well as variations of others. Costs for tooling, part size, cost per part, and the lead time all fall into the considerations for selecting the process in which to produce the desired part. The concern lies in the procurement from concept through the production stages of casting development. Table 2 shows a complete listing of the casting process and characteristics to consider for each.

TABLE 2. Casting processes and characteristics.

Process	TEKCAST SPIN CASTING	Die Casting	Plaster Mold Casting	Sand Castings	Lost-Wax Investment Castings	Permanent Mold Casting	Graphite Mold Casting	Plastic Injection Molding
Types of molds used	Vulcanized "Teksil" rubber	Machined tool steel	Plaster	Sand	Ceramic	Machined iron, steel	Machined graphite	Machined aluminum, brass or tool steel
Type(s) of casting material(s)	Zinc, tin, lead, epoxy, polyester polyurethane	Zinc, aluminum, magnesium	Most nonferrous metals	Most foundry castable metals	Most foundry castable metals	Zinc, aluminum, magnesium	Zinc	Most thermo-plastics
Average cost of mold tooling (US Dollar)	$35 to $250	$10,000 to $250,000 and up	$1,000 to $25,000 (wood or metal pattern)	$500 to $10,000 (wood or metal pattern)	$1,000 to $25,000 (machined aluminum)	5,000 to $125,000 and up	$2,000 or $30,000	$5,000 to $150,000 and up
Economical ordering* quantities	1 and up	25,000* and up	100 and up	100 and up	1,000 and up	10,000* and up	5,000 and up	15,000* and up
Economical part size (length or width)	< 1/2-12in < 1.25-30cm	< 1/2-24in < 1.25-60cm	4-36in 10-90cm	3-36in 7.5-90cm	1-24in 2.5-60cm	4-24in 10-60cm	4-24in 10-60cm	< 1/2-24in < 1.25-60cm
Economical part wall thickness	< 1/8 - 1/2 in < 0.3-1.25cm	< 1/8 - 3/4 in < 0.3-2cm	1/8-1in 0.3-2.5cm	1/4-1in 0.6-2.5cm	1/8-1in 0.3-2.5cm	1/4-1in 0.6-2.5cm	1/4-1in 0.6-2.5cm	< 1/8 - 1/2 in < 0.3-2.5cm
Casting tolerances	Very close	Closest	Close	Lowest	Very close	Loose	Loose	Closest
Ability to make design changes	Easiest	Very difficult	Difficult	Easy	Very Difficult	Difficult	Difficult	Very difficult
Per part cost	Very low	Lowest	Very high	Very low	Highest	Low	High	Lowest
Usual secondary machining required	Very little or none	Lowest or none	Low	Highest	Very little or none	Low	Low	Lowest or none
Usual initial parts lead time required	4 hrs-2days	12-24 weeks	6-12 weeks	4-12 weeks	8-16 weeks	12-24 weeks	8-16 weeks	12-24 weeks

*Depends largely on cost of mold tooling <less than

Note. From "Spin-casting: assists automotive products designers in developing fully functional metal and plastic test parts from SLA models. Schaer, L.. TEKCAST Industries, Inc. (1994, April 28). Proceedings of the '94 Rapid Prototyping and Manufacturing Conference. Dearborn, Michigan: RPA. Adapted by permission.

Presently, there are many variations for foundries to produce ferrous and non-ferrous castings. The area in which the greatest profitability can be seen in process and product development is in stages from concept design to production tooling of the product. There is no standard being used, no precedent set, really no "best" method to produce prototype castings for new products, at least not until now in the age of change, where the average product life is only 18 months and companies are being forced to look for more efficient production techniques. Rapid prototyping can and has changed this. Until recently, the primary method for prototype mold and corebox fabrication, was in using CAD data and 2-D drawings for design engineers to communicate between themselves and with skilled patternmakers to produce prototypes by hand fabrication or CNC subtractive machining to make mock-ups, and preliminary patterns out of wood (cherry, mahogany, etc.), Renwood, plastics and sometimes aluminum stock. From these patterns, prototype pilot runs of castings are scheduled for testing, mock-builds, form, fit, function and modeling. Many times these are early iterations of the prototype where problems have not been detected through visualization modeling. In this instance, the casting is being used as the proving model and test part, or to receive customer verification. In some instances it may even have undergone preliminary milling operations, potentially becoming the most costly level before production tooling. It is at this level that the castings are potentially scrapped, or an additional iteration of the design is integrated and the process starts all over.

Secondary tooling: Applications for die casting

Die casting presents finest example for putting prototyping to good use because of its high cost, attention to surface finish and detail, high volume, and methods to produce the production tooling. Rapid prototyping has demonstrated the ability to "fit this mold".

In the past 3 years, methods that use rapid prototyping techniques to prototype die cast parts have been developed and implemented in a number of areas. These areas include (Mueller, 1994):

1. Low Cost- Die cast parts are typically prototyped for a total cost of 2-5% of the cost of the production die. At this cost it is cost effective for making sure the design is correct before making a much larger investment into production tooling.
2. Fast Turnaround- Prototype castings are usually available in 3-4 weeks, faster than any alternative process for obtaining prototypes. Additionally, patterns are available in a week or less to visually inspect.

3. Larger Parts- The process is increasingly being used to prototype large die castings. Even though prototyping cost is more expensive, the risk is much higher on larger dies. Consequently, the benefit for prototyping is much higher.
4. More Complex Parts- Designs that require side actions or pulls are increasingly being prototyped.
5. Tighter Tolerances- Improvements in accuracy are enabling prototyping of die cast parts that were previously not achievable.
6. Greater Number of Parts- The prototyping of die cast parts allows for pilot tests to indicate market minimizing risk before production tooling is fabricated. It can also be used as low volume backup tooling in the even that tooling is late.

The costs of discovering design errors after production tooling is complete can be exasperating for die casting. The benefit to be seen through using rapid prototyping in creating the initial die cast molds and parts is in the discovering of design errors before the die is in final production. Elements of cost include (Mueller, 1994):

- Tool Re-work- Perhaps the most obvious benefit for rp uses in die casting is the ability to detect design errors. Die shops indicate that approximately 75% of dies require some rework ranging from simple changes to major redesigns. The average cost of rework is 10% of the cost of the die. Therefore the cost of the average die is increased by 7.5%. Given the cost of dies, this is significant.

- Late Delivery of Product- In most cases the rework of a die with delay production and delivery schedules. If a product is late to market, the product will ultimately receive lower market share, than if it would have been delivered on time. McKinsey, a top business consulting firm, claims that if a product is six months late to market, the total profits generated by the product will be reduced by one-third (Mueller, 1994).
- Shorter Tool Life- Every time a tool is re-worked, integrity of the die material is reduced, thus shortening the time in which it needs replacement. Even if the average reduction is only 3% of the life of the tool, considering that 75% of tools must be reworked, this adds 2.25% of the cost of the die to every development project.

Although not readily used for production of die cast prototypes, rapid prototyping, especially Stereolithography with the 5170 Epoxy resin, is capable of achieving detail, surface finish, tolerances needed in producing dies through conventional means of sand casting, investment casting, and plaster mold casting.

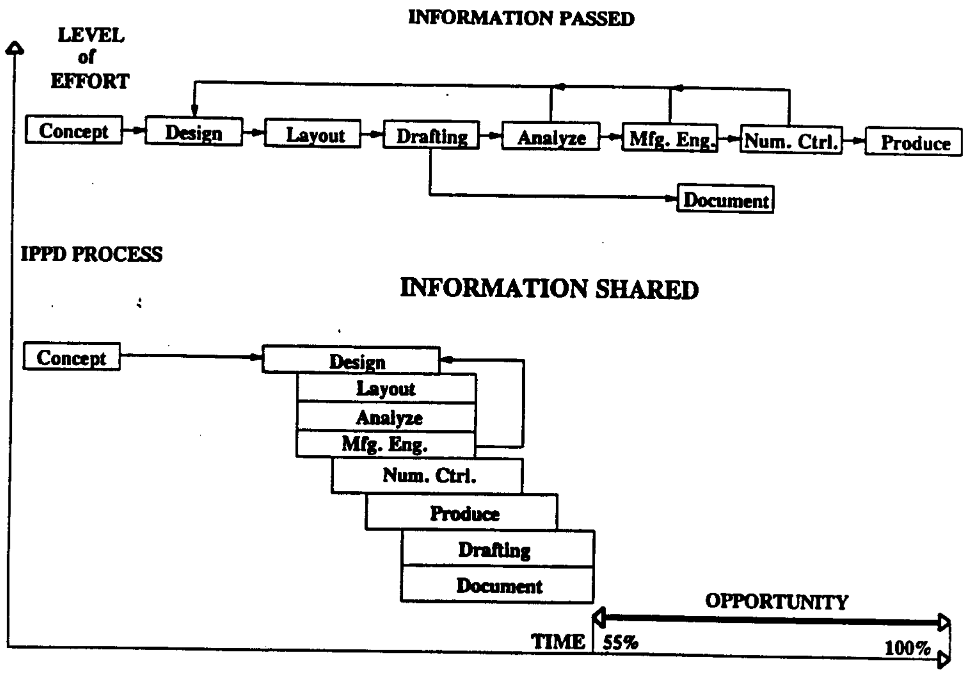
Corporate Strategy-Concurrent Engineering/IPPD

Many companies throughout the United States are rethinking their organizations strategic plan in an effort to improve productivity and quality, and at the same time increase market share by shortening schedules in an effort to get more new products to market in a shorter lead time. A number of "change" techniques have evolved in recent years that are allowing companies to have control over this portion of their corporate strategy. It wasn't until recently that the emphasis was placed on integrating the entire organization in a teamwork environment that significant progress was made. Also, dramatic improvements in CAD software capability facilitated information sharing. "Today's emphasis focuses on integrating people, process improvement and CAD/CAM technology in what has become known as integrated product and process development" (Gee, 1994). However, resistance to change prevents many companies from reaching the goal. Research has provided information from a variety of companies that have implemented change as their strategy, implementing new technologies to facilitate their change, and also those companies that continue to resist change and have fallen behind in leading edge technologies (Gee, 1994).

Integrated product and process development (IPPD) uses an environment of cross-functional teams, made up of a team of people from a cross-functional environment from throughout the company (Gee, 1994). A team consisting of skills from engineering, manufacturing, and design layout are brought together to develop products and their manufacturing processes concurrently. At later stages of development specialists are brought in at appropriate times to perform critical functions (quality control, industrial engineering, etc.) necessary in the product's development. As observed in figure 3, a diagram illustrates the concept surrounding information shared rather than information passed.

Information shared allows for free exchange of ideas for success and past failures, while concurrently developing the part. This type of flow allows for standardization to be implemented because in the team environment, experience and knowledge of existing products influence each new design. All during this process the team begins to take on more and more ownership for the product because they work together and can use each other's strengths to benefit the end result. This also allows the inexperienced to work alongside the wise and skilled tradesmen.

FIGURE 3. IPPD serial process layout.



Note. From "Implementing Integrated Product and Process Development--Changing Company Culture", Gee, R. W. (1994, April 28), Proceedings of the '94 Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan: SME\Rapid Prototyping Association. Adapted by permission.

Rapid Prototyping and IPPD Implementation

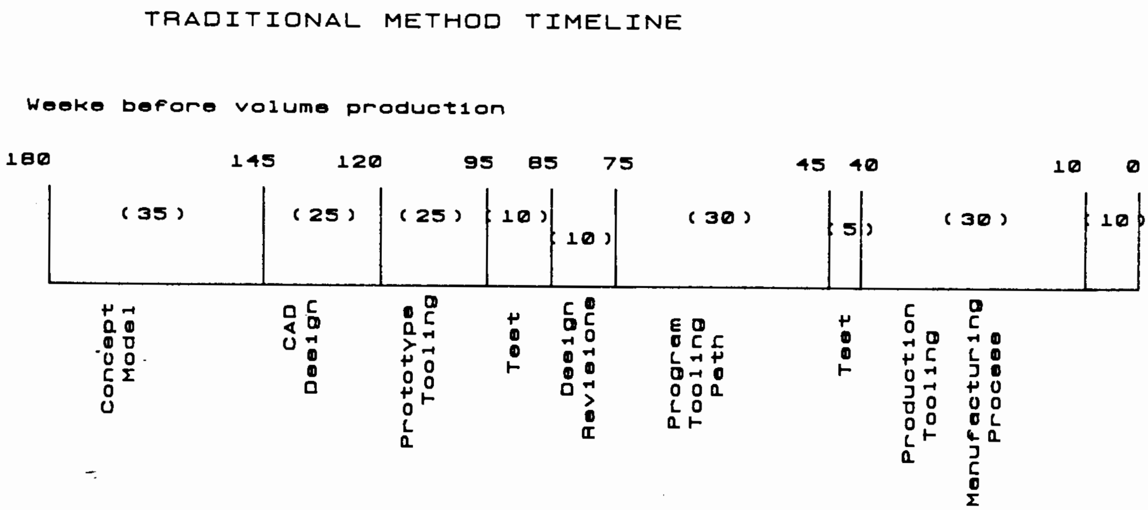
Although rapid prototyping and integrated process and product development are defined as two separate concepts, they each are proponents of each other and together form a ingenious working tool for corporate strategy in the global competitive market.

Computer aided design and manufacturing (CAD/CAM) is a vital, as well as dynamic "information sharing" tool within the IPPD team. It performs not only as the front end to product design, but also the backbone for a responsive product environment. The focus should be on using the CAD/CAM system for integration and process development rather than for use as point solutions with specific CAD or CAM tools. The purpose of a CAD system has evolved, not to produce drawings, but to use it as a design tool coupled with rapid prototyping to "evolve" the design and evaluate it against the customer's requirements. Drawings in this case either becomes non-existent or a by-product of the design after the IPPD team has successfully integrated the product.

As presented by one such company using rapid prototyping to implement rapid tooling technology, a comparison was done using rapid prototyping in the design process to build composite tooling for production. For this analysis, comparisons were between conventional tooling versus the rapid prototyping approach to analyze the development of a product before volume production was procured. The comparison data was drawn from analysis of cost of change as production increased, product development timelines for conventional and RP methods, and an analysis of engineering changes throughout the development cycle and costs associated with those changes at various development stages were recorded.

For this particular study, a timeline illustrating a route of development using traditional methods (Figure 4), versus a paralleling route for rapid prototyping (Figure 5), for particular part was recorded for each stage of a comprehensive development cycle.

FIGURE 4. Chrysler's traditional method approach study.



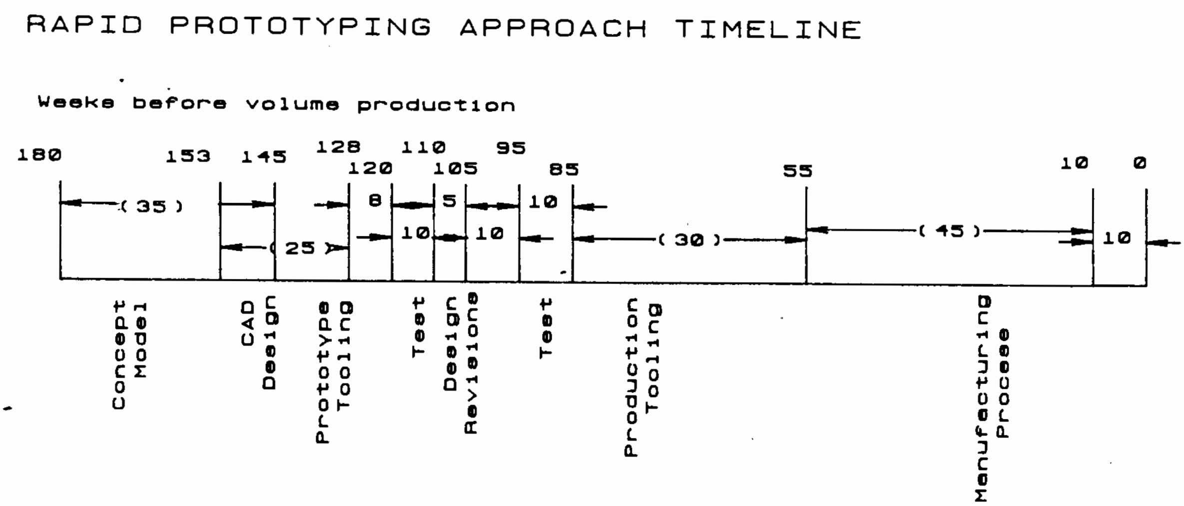
Note. From "Rapid Prototyping at Chrysler", Griffin, R., & Foley, M. (1994, April 27), Proceedings of the '94 Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan: SME\Rapid Prototyping Association. Adapted by permission.

Based on the results using the parallel comparison for these two (2) methods of manufacture, the rapid prototyping method in comparison to the traditional:

1. Allowed for substantial time reductions.
2. Met or exceeded the original prototype parts twenty-five weeks earlier than traditional methods.

3. Tooling created using RP (Thermo-plastic Composite TRP) eliminated the need for previous program tooling.
4. Allowed time for manufacturing process planning and review.
5. Allowed time for multiple integrations during design phase virtually eliminating the likelihood of production tool changes.
6. Traditional took approximately 85 weeks to deliver first production/prototype parts.

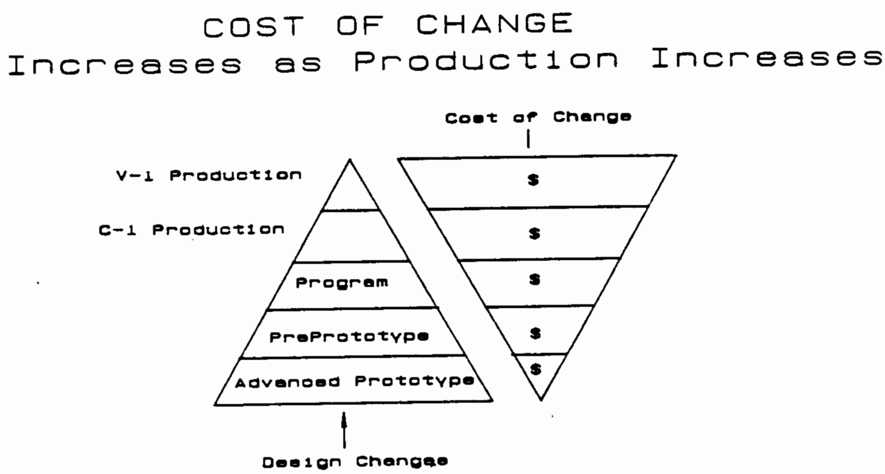
FIGURE 5. Chrysler rapid prototyping method approach study.



Note. From "Rapid Prototyping at Chrysler", Griffin, R., & Foley, M. (1994, April 27), Proceedings of the '94 Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan: SME\Rapid Prototyping Association. Adapted by permission.

Based on a standard chart as seen in figure 6, the cost of change significantly increases as the part progressively makes its transition from CAD modeling through changes in production tooling. Using traditional methods, due to the fact that more errors are identified later and later in the development cycle, results in higher costs for re-work.

FIGURE 6. Traditional cost for engineering change as production increases.



Note. From "Rapid Prototyping at Chrysler", Griffin, R., & Foley, M. (1994, April 27), Proceedings of the '94 Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan: Rapid Prototyping Association. Adapted by permission.

Figure 7 makes comparisons of the relative cost versus when the changes are made. This correlates to the figure 6 (increase/production) for the incremental increases in costs for design and engineering changes which occur during the developmental stages. Although these figures are inflated to show a relative relationship (not based on actual cost), they represent the ratio in prospective dollar amounts for engineering changes as they occur in designs that are premature and perhaps in terms of manufacturability, are high problem production runners.

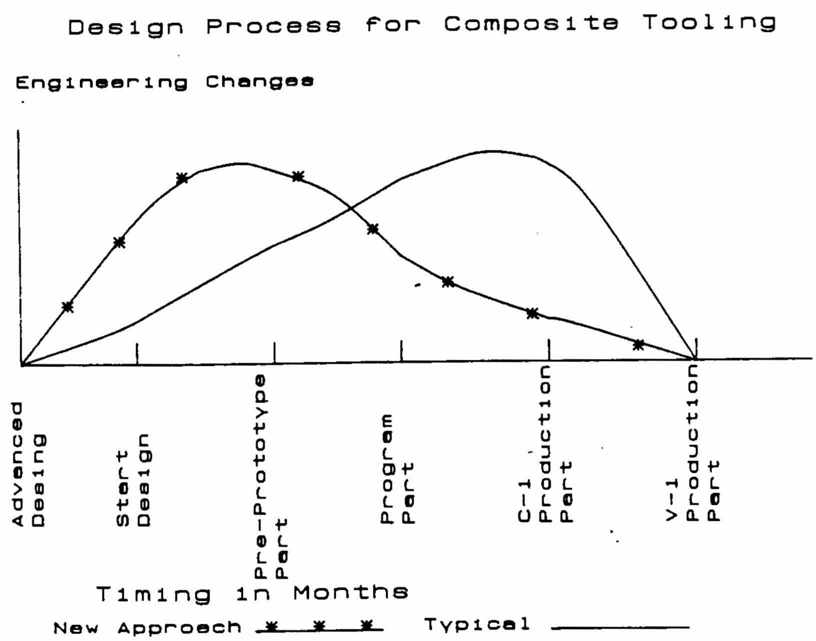
FIGURE 7. Costs of engineering changes at various development stages of development.

When Changes Are Made	Resulting Cost
During Design	$ 1,000
During Test	$ 10,000
During Process Planning	$ 100,000
During Initial Production	$ 1,000,000
During Final Production	$10,000,000

Note. From "Implementing Integrated Product and Process Development--Changing Company Culture", Gee, R. W. (1994, April 28), Proceedings of the '94 Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan: SME\Rapid Prototyping Association. Adapted by permission.

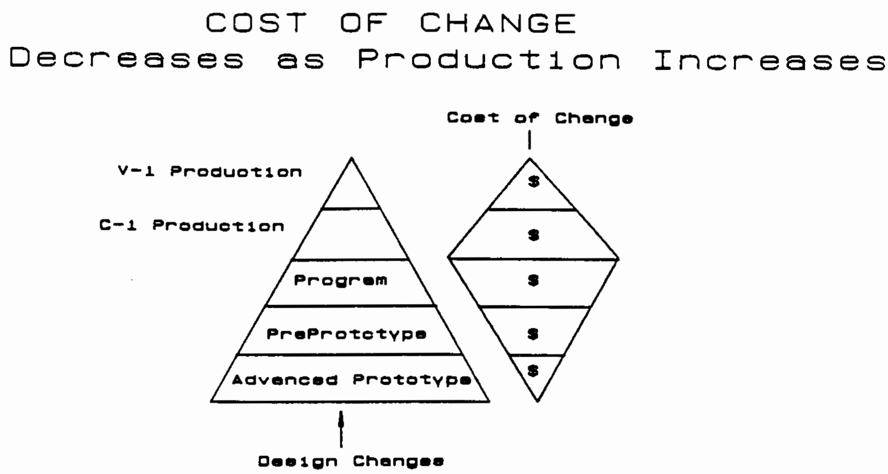
By using IPPD coupled with rapid prototyping processes, the ability to decrease engineering changes, or potentially surface problems, or engineering changes earlier in the design process is brought about. The graph in figure 8 illustrates this. By using rapid prototyping in the development, the height of the engineering curve is brought closer to the beginning of the cycle where changes are less critical and less costly. The typical method shows engineering changes later into the levels near the production stages. This change is seen with passed information and with typical approaches.

FIGURE 8. Comparison of engineering changes comparing rapid prototyping versus traditional methods.



Note. From "Rapid Prototyping at Chrysler", Griffin, R., & Foley, M. (1994, April 27), Proceedings of the '94 Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan: Rapid Prototyping Association. Adapted by permission.

FIGURE 9. Cost comparison for production increase using rapid prototyping.



Note. From "Rapid Prototyping at Chrysler", Griffin, R., & Foley, M. (1994, April 27), Proceedings of the '94 Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan: SME\Rapid Prototyping Association. Adapted by permission.

By making use of IPPD and rapid prototyping as seen in figure 9, cost of change decreases as the production increases. In this model, most of the changes have occurred at or near the test phases of development rather than during production were changes are less critical and less costly for re-work and are less likely to cause production delays.

Breaking time and costs down

Based on the study performed by Gee (1994), the potential savings that may be experienced using integrated process and product development (IPPD) coupled with rapid prototyping and rapid tooling process applications can be significant in many areas of development over traditional development processes. The potential savings from IPPD and process change can be seen in many areas as a significant percent reduction in overall cost. They can be seen as:

- 50% Reduction in engineering changes
- 25% Reduction in engineering development time
- 75% Reduction in design errors
- 50% Reduction in manufacturing errors
- 10% Reduction in production cycle time
- 50% Reduction in scrap costs
- 50% Reduction in rework costs

When analyzing the cost of tooling (Wohlers, 1994) whether using conventional or rp methods, 70-80% of all manufacturing cost is determined and fixed during the design phase. While only 5% of the product development budget is spent during the design, engineering and documentation phase. Yet organizations continue to use CAD to reduce the 5%, instead of using it to make better decisions about the 70-80%. This statement can be used to prove that rapid prototyping can potentially reduce that percentage, thus reducing the cost of re-work to the tooling. Design and fabrication of prototype tooling can give the design engineer the ability to detect earlier problems in designs thus reducing incorrect tooling and minimizing tooling costs later due to production tooling re-work.

Based on a variety of sources compiled by the Peter Marks study (1993), as much as 25% of a design engineers time is spent creating/innovating processes or parts. This includes creating designs to manufacture tasks, researching new ideas, problem solving, and creating new products. As much as 50% is spent in communicating those ideas. Even though much of their time is spent designing and solving problems, the majority of their time is allotted to traveling, attending meetings, writing reports, advocating, persuading, asking & answering questions. The remaining 25% is spent evaluating ideas or concepts and checking work for errors to make sure they do not creep into the process at any stage. This time goes into analysis, checking for performance specifications, simulation and evaluating suppliers.

While these percentages can vary (Marks, 1993), the goal for concurrent engineering is to use time more effectively, thus providing more time to innovate. Today's development team would like to catch every potential error before it can have even the slightest impact in a process or design stage.

Saving time is one thing, but improving the product while shortening the development cycle are merits for careful consideration in a competitive market. In essence, automated manufacturing can actually save time for all three areas of design and development efforts. Based on the study performed by Marks (1993):

• Prototypes are an essential aid to creativity and innovation. Computer based prototyping methods can save as much as half the time of traditional tooling methods of CNC and hand-made patterns.

• Three dimensional visualization and hard copies assure rapid and clear communication of a design. Efficient use by competent individuals of 3D tools can save as much as an hour per day (Marks, 1993).

• Errors that hide in the works and members of reports or in an array of lines and constructs of a blue print become obvious in a solid object form. The real time savings then can be seen in eliminating errors the first time and adding changes during the first integration. Delays due to rework in production schedules can add virtually months to product development. These are the areas that automated fabrication has found only part of it's niche.

Time to market: An example

An example of the benefit of reducing the time a product takes to market can be illustrated through a breakdown as prepared by the Rapid Prototyping Report (June 1993). In an environment of ever increasing competition, reducing a products's time to market can yield significant advantages in market share. Cutting product development and tooling shares is important because it accelerates the cash flow derived from a new product. Being late can be extremely expensive because of loss of market shares and potential sales, being early can be lucrative.

For example (RPR, June 1993), assume that a new product has development costs of $50 million and is expected to

TABLE 3. Shortening product development time from 36 to 30 months can generate significant additional revenue over the life of a product.

Time period (years)	36 - month Development		30 - month Development	
	Cash flow ($)	Discounted cash flow ($)	Cash flow ($)	Discounted cash flow ($)
0	($16,666,667)	($16,666,667)	($20,000,000)	($20,000,000)
1	($16,666,667)	($14,492,754)	($20,000,000)	($17,391,304)
2	($16,666,667)	($12,602,394)	($2,500,000)	($1,890,359)
3	$15,000,000	$9,862,743	$15,000,000	$9,862,743
4	$15,000,000	$8,576,299	$15,000,000	$8,576,299
5	$15,000,000	$7,457,651	$15,000,000	$7,457,651
6	$15,000,000	$6,484,914	$15,000,000	$6,484,914
7	$15,000,000	$5,639,056	$15,000,000	$5,639,056
8	$15,000,000	$4,903,527	$15,000,000	$4,903,527
Total		($837,625)		$3,642,526
Discount rate = 15%				

Note. "System justification: shortening time to market", Rapid Prototyping Report, June 1993, p. 2-3. Copyright CAD/CAM Publishing, Inc.

generate $15 million of gross profit margin per year.

Through the use of rapid prototyping, the development cycle for this project can be reduced from 36 months to 30 months. This means the company can begin to recover its investment 6 months earlier. Using the method of discounted cash flows, we can compare the actual cost and revenues over a six-year product life.

As seen in table 3, even a modest shortening of the development cycle yields a significant improvement in cash flow over the life of the product. When the discounted cash flow of this shortened development cycle summed, the new product exceeds the company's cash flow target by $3.6 million. Bringing new products to market earlier generally increases cash flow and market share and increased sales.

CHAPTER 5

Summary and Conclusions

Design

By using automated fabrication/rapid prototyping, designers and engineers will no longer have to worry about how parts will be manufactured. They will instead focus on optimizing assembly cost, reliability, performance, and so on. With distinction between prototypes and production parts obliterated, designers will be able very rapidly to test new products and obtain feedback from co-workers and customers. They will quickly correct errors and optimize designs with complete confidence that once the products are in production, there will be no major changes.

Manufacturing

Automated fabrication will save manufacturers enormous amounts of money in a multitude of areas. They will eliminate the huge cost of designing, manufacturing, verifying, storing, and maintaining tooling. By eliminating these costs, manufacturers will begin to realize the profits on newly developed products sooner in the product's market life.

The labor costs of running a manufacturing facility will fall dramatically for several reasons. First, part-specific setup and programming will be eliminated. Second, labor now associated with machining, casting, and other operations will be greatly reduced. Finally, labor requirements once needed for inspection, planning, purchasing, inventory, and assembly will decrease substantially.

<u>The road to the future</u>

Overall, a customer-focused management style and an aggressive product development philosophy will be critical factors for success in the marketplace for both today as well as tomorrow. Rapid prototyping's purpose is to facilitate this by shortening product development cycles, reducing cost, and enhance the overall design quality put into a part.

Although more work needs to be done in transferring knowledge of pattern building to the design level to make this process feasible, it is a viable alternative that is steadily making its way into the competitive production market. It must also be competitive in terms of cost and timing in relation to conventional tooling development. Currently, there are limits on the size of tooling that could be produced directly on an available rapid prototype system and there are still emerging needs to develop materials that are durable enough to withstand production of multiple parts.

Based on the review of literature and data collected from manufacturer's benchmark studies, significant improvements have been made in decreasing the time it takes to get good functional parts into production, in reducing the time and money needed for multiple integrations or rework costs to production tooling, as well abilities of companies to reach the full market potential for their product.

Product development time can be shortened by weeks or months by incorporating automated fabrication methods into the prototype tooling process that is being procured by concurrent engineering practices. Functional metal and plastic parts can be manufactured in a fraction of the time of traditional tool making methods while improving accuracy and replicating exact design intent from the 3D CAD computer model into the finished part. This advancement in design technology has provided for a picture window of opportunity that can make conceptual reality in achieving desired objectives in product manufacture.

Product development is continuously changing and will never be the same as before. The opportunities are infinite but we are not competing on a global playing field. We need better planning to define what products and value our customers really want, and increase the level of innovation in the design and development process and then by properly selecting and more effectively using all the technology tools and manufacturing processes available for optimum results. A well executed plan creates a more efficient timeline to market and increases the number of products introduced. Rapid prototyping is an important key element for this plan.

Remember: Rapid Prototyping Today

Evolutionary

Rapid Prototyping Tomorrow

Revolutionary

Unknown

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Commercially Available Fabricators

Vendor	Machine	Method	Materials	Envelope (dm³)	Weight (kg)	Price (1,000 US$)
Subtractive (The machines listed in this category are only a very small sampling of what is available.)						
Giddings & Lewis	Planer-Type M. C.			38,000 .. 454,000	up to 800,000	2,000 .. 8,000
Boston Digital	BostoMatic 5-axis	Milling	All solids (machinability desirable)	48 .. 140	4,500 .. 6,400	185 .. 325
Kira Machinery	DrillMill			18 .. 125	2,200 .. 6,000	66 .. 134
Light Machines	proLight			10	150 .. 160	12 .. 17
Okuma	LR Series	Turning		5 .. 74,000	4,500 .. 13,700	140 .. 560
Emco Maier	Unimat PC			6	13	1.6
Sodick	A Series	Wire EDM	Electrical conductors	19 .. 105	3,200 .. 5,500	140 .. 250
Additive						
3D Systems	SLA			9 .. 156	272 .. 932	110 .. 450
CMET	SOUP			64 .. 255	850 .. 1,200	kDM 900
Sony	JSC	Laser curing	Photopolymers	23 .. 400		
EOS	Stereos			18 .. 144	800 .. 1,300	kDM 500 .. 1,000
Teijin Seiki	Soliform			27 .. 125	700 .. 750	k¥ 35,000 .. 45,000
Cubital	Solider 5600	Masked-lamp curing		88	4,500	550
DTM	Sinterstation 2000	Laser sintering	Thermoplastic powders	28	2,000	289
Stratasys	3D Modeler	Robot-guided extrusion	Thermoplastics	27	340	172
Soligen	DSP System	Droplet deposition	Powder + adhesive	64	900	250
Hybrid						
Helisys	LOM	Stacking + laser cutting	Adhesive sheets	31 .. 198	410 .. 1,500	95 .. 180
Salvagnini	S4+P4	Shearing + bending	Metal sheets	625	41,000	1,900 .. 2,000
Iowa Precision	Fabriduct			843	23,000	450

APPENDIX B

Other Developments in Rapid Prototyping

Researchers at universities, government labs and corporations around the world have developed, or are presently developing, rapid prototyping system technology. The developments range from patent-pending concepts to systems that are near completion. Many of the organizations are moving ahead aggressively, while others have put their work on hold until they secure additional funding. The partial list of efforts (below) are listed at random. Unless otherwise indicated, the developments are US-based.

Active Developments. The following organizations are presently developing RP system technology.

Organization	*Technology*
BPM Technology Inc.	Ballistic Particle Manufacturing (Jetting)
Light Sculpting	Photosolidification
MIT	Jetting (ink jet)
Texas Instruments	Jetting
Laser 3D (France)	Stereolithography
Kira Machinery Co., Ltd. (Japan)	Laminated Object Manufacturing
University of Nottingham (England)	3D Welding
Carnegie-Mellon University	Thermal Spray Metal Deposition
Incre, Inc.	Incremental Fabrication (Jetting)
University of Southern California	Precision Droplet Stream Manuf.
CNRS (France)	Stereolithgraphy
Laser Fare Ltd.	Proprietary
Rensselaer Polytechnic Institute	Concrete Layer & Chemical Layer Deposition
University of Texas at Austin	Sintering and Chemical Vapor Deposition
E-Systems	3D Plotting
Fraunhofer-Institute (Germany)	Sintering, Jetting, Others
University of Tokyo (Japan)	Stereolithography
Osaka Sangyo University (Japan)	Stereolithography
Sanyo Kiko (Japan)	Laminated Object Manufacturing

Inactive Developments. The following organizations have, at one time or another, researched the development of an RP system or developed an experimental system.

U.S. Navy David Taylor Research Center	Electrosetting
Babcock & Wilcox	Shape Melting
Visual Impact Corp.	Jetting
Automated Dynamics Corp.	Ballistic Particle Manufacturing (Jetting)
Battelle Memorial Institute	Photochemical Machining
Osaka Institute of Industrial Tech. (Japan)	Stereolithography
Formigraphic Engine Company	Photochemical Machining
Quadrax	Stereolithography
Landfoam Topographics	Laminated Object Manufacturing
Chem-Form	Masked Photosolidification
Nagoya Municipal Ind Research Inst. (Japan)	Stereolithography
Dynell Electronics Corp.	Solid Photography
3M	Solid Object Generation
Fujitsu (Japan)	Stereolithography
Du Pont	Stereolithography
Nissei Sangyo Company (Japan)	Stereolithography

APPENDIX C

RESEARCH ITINERARY SCHEDULE
KELLEY KERNS

Project Title: Independent Research
Submitted to: University of Northern Iowa
Ashland Chemical, Inc.
Time Period: December 1, 1993 through May 15, 1994

December 1993
None Scheduled

January 1994
4 Eldora Plastics, Eldora, IA -Service Bureau
Laminated Object Manufacturing
14 John Deere, Moline, IL -Technical Center
Technical Transfer for rapid prototyping
28 John Deere, Moline, IL -Technical Center
Technical Transfer for rapid prototyping

February 1994
7-8 Fundamentals of Rapid Prototyping and Applications in Manufacturing -SME "Road Series", Milwaukee, WI
11-15 Sandia National Laboratories, Albuquerque, NM
Federal research facility, casting research
Selective Laser Sintering
Stereolithography
Direct Shell Production Casting
24-27 Ashland Chemical, Inc. Development Center
Research facility
Direct Shell Production Casting

March 1994
11 John Deere, Moline, IL -Technical Center
Technical Transfer for rapid prototyping
13 Grede Foundry, Midwest, Wichita, KS -Foundry
16 Midwest Pattern Company, Waterloo, IA -Pattern Shop
17 K&P Pattern Company, Waterloo, IA -Pattern Shop

April 1994
1 John Deere, Moline, IL -Technical Center
Technical Transfer for rapid prototyping
1 General Pattern Company, Moline, IL -Pattern Shop
Laminated Object Manufacturing
11 Ford Powertrane/Engine Engineering, Dearborn, MI
Casting Design and Development Center
13 Grede Foundry, Liberty, Milwaukee, WI -Foundry
25 Ford's Alpha Mfg. Development Center -Dearborn, MI
Design, Development and Jobbing Foundry
Stereolithography
Laminated Object Manufacturing
Fused Deposition Modeling
Selective Laser Sintering
Secondary tooling
25 Mack Industries, Troy, MI -Service Bureau/Pattern Shop
Secondary tooling, composite fabrication, casting
Laminated Object Manufacturing
Stereolithography
26-27 Rapid Prototyping & Mfg. Conference, Dearborn, MI
Stereolithography
Laminated Object Manufacturing
Sanders Prototyping- 3-D printing