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RAPID PROTOTYPING – CONCEPTS, TECHNIQUES , APPLICATIONS AND FUTURE TRENDS

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Abstract. *During last years a new family of machines highly innovative have enabled, with technologies and different materials, to produce a prototype of a model in an accurate and fast way starting from the solid model generated in the CAD system. Such machines, known as Rapid Prototyping machines, allow to obtain finished parts with complexity and details that would be difficult by conventional machining process or would require complex operations in numerically controlled machines. Also, in some cases these techniques allow to obtain a tooling that can be directly used in the production process. This technology allows the companies to develop new products faster (smaller time-to-market) and with lower costs, and mainly, with an increment in the quality by means of a better evaluation of the project. It also decreases the uncertainties and risks.*

This work presents a literature review of the main aspects of the Rapid Prototyping technology such as concepts, techniques available, applications worldwide and in Brazil, as well as future trends. The main objective is to make the mechanical designers aware of the technology and of its potential to reduce costs and time-to-market.

Keywords: Rapid prototyping, Product development, CAD applications.

1. INTRODUCTION

In a conventional way, most companies spend years designing, prototyping, testing and tooling for a product that may have a life of only a couple of years. The development of Rapid Prototyping (RP) technology since the 1980s has enabled in a fast way the fabrication of a prototype from the CAD solid model. This technology can produce prototypes or models that are extremely complex in structure and it is impacting the way products are designed and manufactured. Some authors even claim that Rapid prototyping is the most important inventions since CAD solid modeling. The two technologies are complimentary, and when they are put together, a strong competitive edge can be achieved. The link between the CAD model and the RP machine is the STL file. An STL file is nothing more than a list of x, y and z coordinate triplets that describe a connected set of triangular facets. Also, it includes the direction of the normal vector for each triangle, which should point outward. CAD systems with an STL translator perform a surface tessellation and then output the facet information to either a binary or ASCII STL file. Binary STL files are much smaller and usually preferred, but ASCII STL files permits to view the contents of the file and even edit it if necessary.

RP machine sales and services began to expand significantly in 1994 and continues to grow. There are several reasons for that. First and perhaps the most important, it is the fact that the companies are becoming aware of the potential of the technology. Second, it is the fact that RP nowadays is more widely applicable allowing for the production of parts in materials as epoxy resins, ABS plastic, and glass-filled nylon. The list of possibilities continues to grow. Third, companies are finding that they can justify the cost of RP on the basis of improving the quality of a design early in the design cycle. This allows to make improvements in the design when changes are inexpensive, before production tooling. The correction of possible errors in the production tooling can avoid delay in the introduction of the product in the market, what is unacceptable nowadays, especially with products that have a life of one or two years.

This work presents a literature review of the main aspects of the Rapid Prototyping technology such as concepts, techniques available, applications worldwide and in Brazil, as well as future trends. The main objective is to make the mechanical designers aware of the technology and of its potential to reduce costs and time to market.

2. REASONS TO USE RAPID PROTOTYPING

Nowadays the high competition between manufacturers has created the need to reduce product development time and consequently a demand for fast approaches to prototyping. This, coupled with the growth of computers in designs offices, has motivated inventors to create new ways of producing physical objects from computer model data. From this scenario it was originated the Rapid Prototyping techniques, which will be described later. The fact is that, at this moment, such techniques has helped many manufacturing companies to shorten product development time, discover design flaws and improve product quality. It is rather difficult to calculate the total economic impact from RP, but some believe it is already in the billions of dollars.

Some organizations are trying RP for the first time. Others are buying their third, fourth, even tenth systems. Indeed RP processes are changing the way manufacturing companies around the world design, model, prototype and tool for new products. One of the main reasons for that is the possibility to make changes to improve the quality of a design early in the design cycle. Revision cycles occur whenever there is a need to modify a design. The cost of an engineering change increases by roughly an order of magnitude as the design progresses from one significant development phase to the next, as shown in Table 1.

Another aspect is that people responsible for materials, tooling, assembly, and painting can use the physical models to consider how easy or difficult it will be to move the product through their respective processes. Early involvement from these groups enhances communication and shortens the time it takes to manufacture products.

Table 1- Changing costs along the design cycle

Phase	Increase em cost
Conceptual Design	x 10
Detail Design	x 100
Prototype/Test	x 1,000
Tooling	x 10,000
Production	x 100,000
Field Service	x 1,000,000

3. DEVELOPMENT OF RP TECHNOLOGY

Rapid Prototyping systems for mechanical parts design emerged in 1987 with StereoLithography (SL) from 3D Systems in the USA. After, Japan commercialized their versions of stereolitography, 1988, NTT Data/CEMET with the system called Solid Object Ultraviolet Plotter (SOUP) and in 1989 Sony/D-MEC with the product Solid Creation System (SCS). Then, in 1990, Electro Optical Systems (EOS) of Germany sold its first Stereos stereolithography system.

Next came Fused Deposition Modeling (FDM) from Stratasys, Solid Ground Curing (SGC) from Cubital, and Laminated Object Manufacturing (LOM) from Helisys, all in 1991. Selective Laser Sintering (SLS) from DTMA and the Soliform stereolithography system from Teijin Seki became available in 1992.

In 1993, Soligen commercialized Direct Shell Production Casting (DSPC), and Denken introduced a solid-state stereolithography system that would fit on a bench top. The process that Soligen uses, was invented and patented for the Massachusetts Institute of Technology.

In the year of 1994, many new RP systems were introduced. ModelMaker from Sanders Prototype became available, as did two new systems from Japan and two from Europe.

One of the new systems from Japan, another stereolithography system, was from Meiko. Meanwhile, Japan's Kira Corp. commercialized the first non-stereolithography system called Solid Center.

Also in 1994, Fockele & Schwarze of Germany introduced a stereolithography machine, but on a limited basis. German company EOS commercialized a machine called EOSINT based on laser sintering technology in the same year. Japan's Ushio sold its first UniRapid stereolithography machine in 1995.

Personal Modeler 2100 from BPM Technology was sold commercially in 1996 (BPM stands for Ballistic Particle Manufacturing). The same year, Aaroflex commercialized DuPont's SOMOS stereolithography technology for sale in the USA.

Also in 1996, Stratasys introduced its Genisys product, an extrusion process similar to FDM, but based on an RP system development at IBM's Watson Research Center. After eight years of selling stereolithography products, 3D Systems sold its first Actua 2100 system in 1996, a technology based on ink-jet printing. In the same year, Z Corp. launched its Z402 3D printer for concept modeling.

Other technologies and companies have appeared and disappeared over the years. Quadrax introduced its Mark 1000 stereolithography system in 1990. Legal conflicts led to the absorption of the technology by 3D System in 1992. Companies such as Light Sculpting (US), Sparx AB (Sweden), and Laser 3D (France) have developed and introduced versions of RP, but they have not had a commercial impact on the RP industry. Except for Cubital's Solider System, none of the machines from Europe or Asia are available for sale in the US at the present time.

4. PROCESSES DESCRIPTION

Following, a more detailed description is given on the most used RP techniques.

Stereolithography (SLA)

This is the leading technology, with over 500 SLA machines installed worldwide, developed by 3-D Systems Inc, USA. Stereolithography creates 3-D models out of acrylate photopolymer or epoxy resin, by tracing a low-powered ultraviolet laser across a vat filled with resin. The material is cured by the laser to create a solid thin slice. The solid layer is then lowered just below the surface and the next slice formed on top of it, until the object is completed.

A recent development by Zeneca is a translucent resin which changes to red when acted upon by a higher laser energy. This can be used to display local regions of interest.

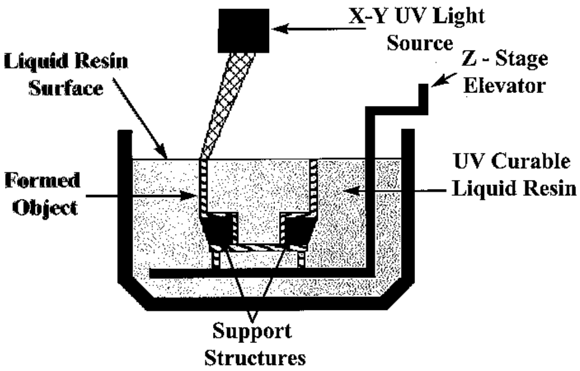

Figure 1 – The sthereolithography process

Selective Laser Sintering (SLS)

This technology was commercialized by DTM Corp., USA. SLS creates 3-D models out of a heat-fusible powder, such as polycarbonate or glass-filled composite nylon, by tracing a modulated laser beam across a bin covered with the powder. Heating the particles causes them to fuse or sinter together to create a solid thin slice. The solid layer is the covered by more powder and the next slice formed on top of it, until the object is completed.

The same process can be performed with a combination of low-carbon steel and thermoplastic binder powder, resulting in a 'green state' part. The binder is then burned off in a furnace and the steel particles are allowed to sinter together. The resulting steel skeleton is subsequently infiltrated with copper, resulting in a metal-composite part. A similar technology is also used by EOS GmbH, of Germany, which can fabricate metal parts out of bronze alloy powder that can be sintered into a solid mass.

Fused Deposition Modelling (FDM)

This technology was developed by Stratasys Inc, USA. FDM creates 3-D models out of heated thermoplastic material, extruded through a nozzle positioned over a computer-controlled x-y table. The table is moved to accept the material until a single thin slice is formed. The next slice is built on top of it until the object is completed. FDM utilizes a variety of build materials, such as polycarbonate, polypropylene and various polyesters which are more robust than the SLA models. A similar approach is used by Sanders Prototype Inc, of Wilton, NH, to produce 3-D models by extruding thermoplastic material through ink-jet printer nozzles. FDM models can also be made in wax.

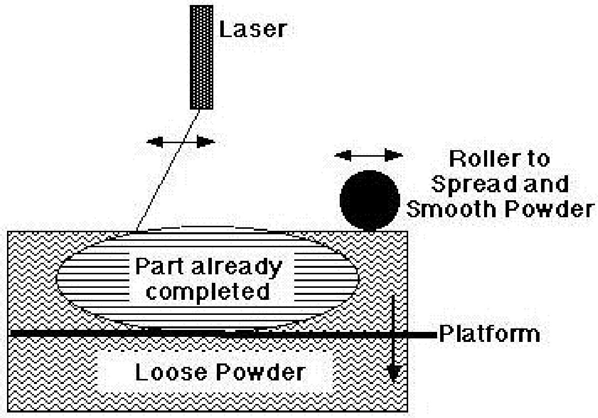

Figure 2 – The SLS process

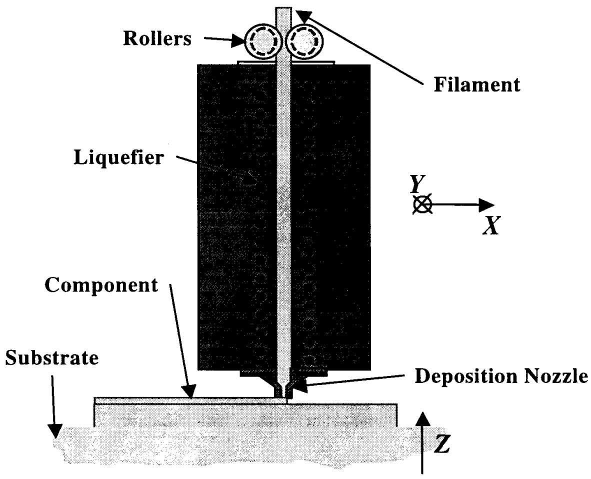

Figure 3 – The FDM process

Laminated Object Manufacturing (LOM)

This method was developed by Helisys Inc, USA. LOM creates 3-D models by laminating adhesive-coated sheets of paper; the adhesive is heat-activated by a focused laser beam, which cuts around the edges of each layer on an x-y table. Further sheets are bonded on top until the model is built. Although these models are robust, it is difficult to remove unwanted regions of paper from areas of complex geometry.

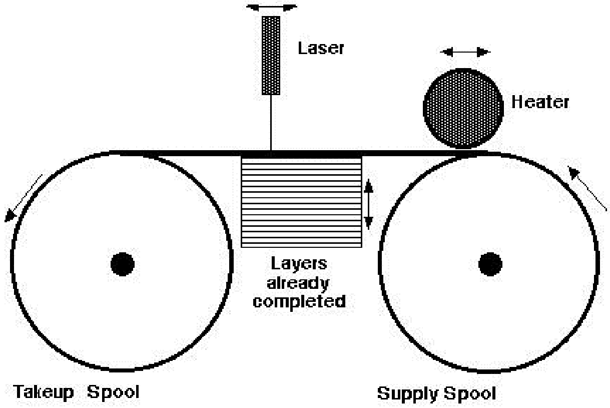

Figure 4 – The LOM process

5. ADVANTAGES AND LIMITATIONS

The comparative qualitative advantages from the most used systems are summarized in Table II.

Table II – Advantages and limitations of the most used systems

System	Advantages	Limitations
Stereolithography (SLA)	Well proven system Best surface finish of currently available techniques Most parts can now be "right first time"	Expensive raw materials. Expensive annual maintenance charges Support structures needed but these are automatically supplied from purpose written software Care needed with environmentally hazardous solvents used to clean up models
Selective Laser Sintering (SLS)	Wide range of model materials Polycarbonate models after surface treating with wax can be used as sacrificial patterns Lower cost of raw materials than stereolithography or solider systems	Wax models need 12 hour cooling cycle on the machine Wax models very fragile Recycled unsintered powders need careful sieving to be re-used Support structures can be necessary, especially for complex, overhanging features of wax models Learning curve necessary with most new parts Expensive maintenance charges
Fused Deposition Modeling (FDM)	Lower initial cost of system Low cost materials Can be operated in office environment Highly reliable machines Short build time for thin wall parts	Poor surface finish but can be improved by hand working Support systems necessary for complex overhanging features
Laminated Object Manufacture (LOM)	Relatively lower capital cost system Low cost of raw materials Finished models resemble wood – popular with model makers	Inherent fire risk Most models require subsequent hand working to improve surface finish Inherent difficulties with undercuts and re-entrant features Waste material can be difficult to remove

A quantitative comparison of the systems in terms of accuracy, surface finish, build rate, capacity and costs is given bellow:

Stereolithography:

Supplier: 3-D Systems (USA)
Initial cost: $250,000 to $450,000
Maintenance (cost per year): High, approximately 15% of purchase price
Materials: Acrylate and epoxy photosensitive resins
Raw material costs: High cost to fill vat. Model costs low
Layer thickness (µm): 62.5 to 250 (typical 125)
Accuracy (µm): ± 100 typical with epoxy, ± 150 typical with acrylate, ± 50 (best)

Selective Laser Sintering:

Supplier: DTM (USA), EOS (Ge)
Initial cost: $300,000
Maintenance (cost per year): High, approximately 20% of purchase price
Materials: Powdered wax, nylon polycarbonate, metals
Raw material costs: Relatively high
Layer thickness (µm): 125
Accuracy (µm): ± 125 to ±250

Fused Deposition Modeling

Supplier: Stratasys Inc. (USA)
Initial cost: $78,000 to $400,000
Maintenance (cost per year): Low, around 5% of purchase price
Materials: ABS, Wax, polyolefins and polyamides
Raw material costs: Low
Layer thickness (µm): 125
Accuracy (µm): ± 200

Laminated Object Manufacture

Supplier: Helysis (USA)
Initial cost: $95,000 to $180,000
Maintenance (cost per year): Relatively high, approximately 10% of purchase price
Materials: Kraft paper
Raw material costs: Low
Layer thickness (µm): 140
Accuracy (µm): ± 250

6. APPLICATIONS

In the early days of RP, the automotive and aerospace industries dominated the RP market, accounting for about half of the total market. This is no longer the case as RP has spread into other industries. The following chart (Figure 5) shows the industry sectors that are now using RP technology in USA. From the chart, it is clear that consumer products has firmly established itself as the number one market for RP systems. The other category includes industries such as professional sporting goods, non-consumer and non-military marine products, and other industries that do not fit into the named categories.

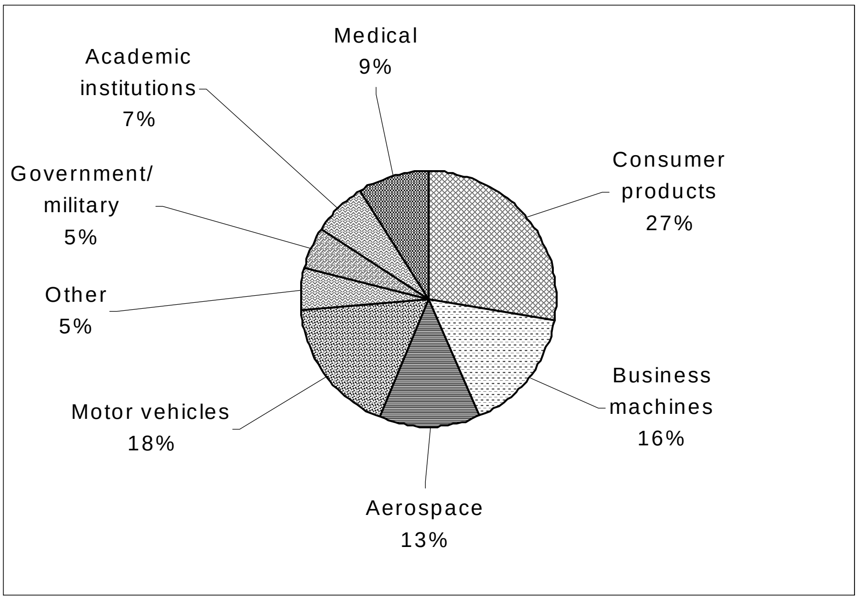

Figure 5 – Applications of RP in different areas (USA)
(Wohlers Associates, 1997)

The following pie chart, Figure 6, shows how customers are using RP models in USA. About 28% of all RP models are being used for fit and function applications, while nearly 36% serve as visual aids for engineering, tooling, requesting quotes, and presenting proposals. Meanwhile, about 25% are being used as patterns for prototype tooling and metal casting.

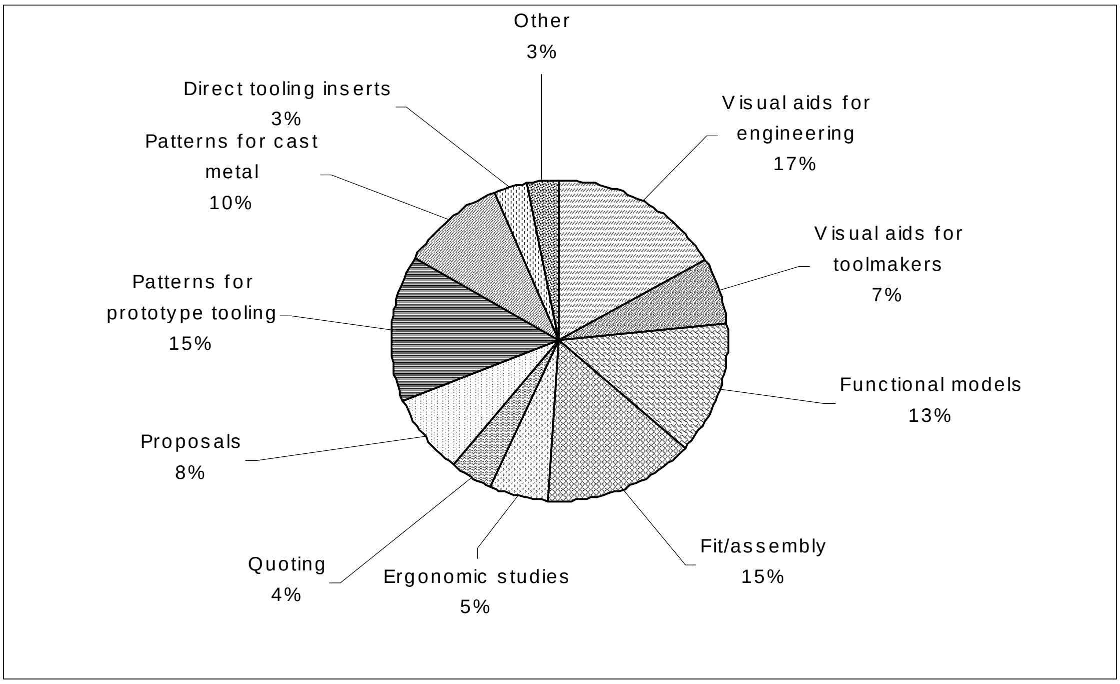

Figure 6 – Use of RP models in USA
(Wohlers Associates, 1997)

There is little information about the use of RP in Brazil. One of the few data about that is given by Sisgraph - SP, which commercializes and sell services in FDM technology (Figure 7).

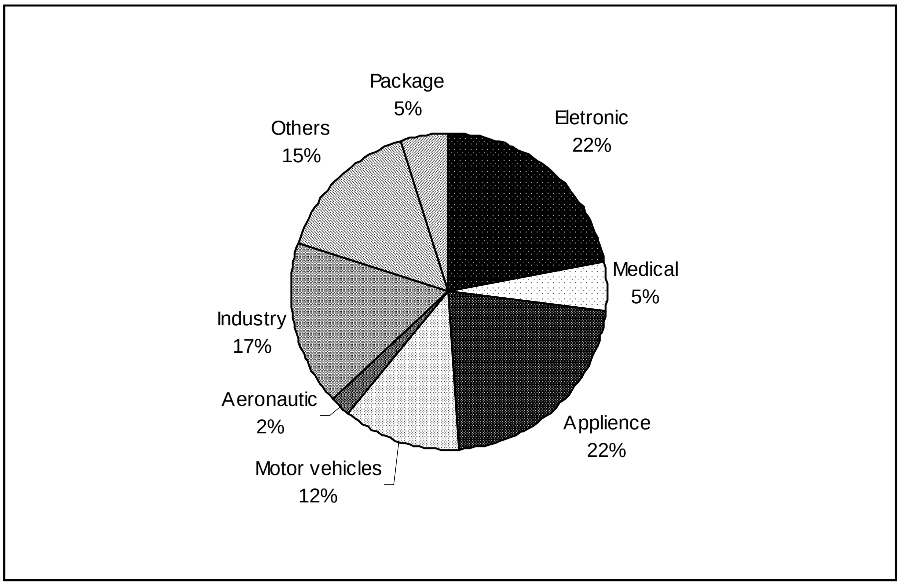

Figure 7 – Applications of RP in different areas in Brazil

The following chart, Figure 8, show the systems installed in countries around the world from RP's inceptions through 1997. The information represents 3,016 of the 3,289 systems that have been sold and installed worldwide. It is noted that Brazil does not even appear on the chart.

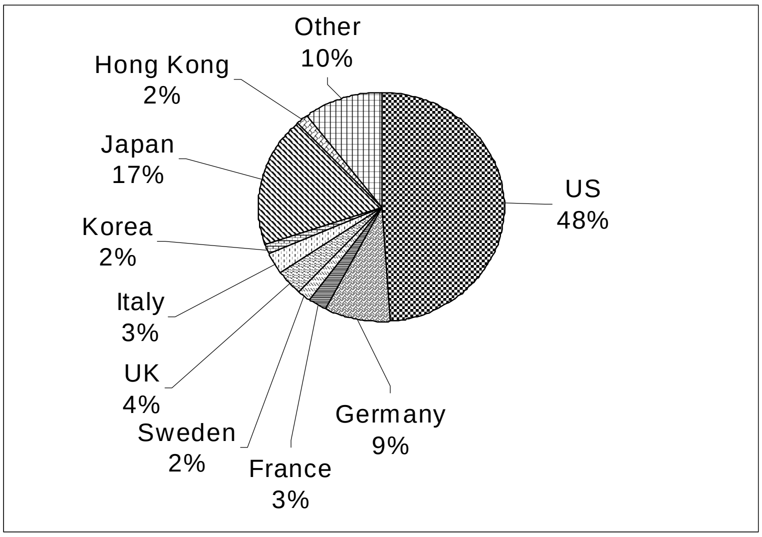

Figure 8 – System sold and installed worldwide
(Wohlers Associates, 1997)

7. FUTURE TRENDS

RP is being taken up by an ever-widening range of industries. The automotive and aerospace sectors used to account for about half of installations but the consumer products sector has now overtaken the automotive as the leading sector, with 23 per cent of all installations.

Looking to the future, low cost RP processes will accelerate the growth of the RP market in the next few years. Traditionally, RP machines have sold for at least $100,000, if not $200,000 or even $300,000. In the year of 1997 were introduced machines costing as little as $35,000-65,000. They do not replace the more expensive machines because the models they build are not very refined, though perfectly satisfactory for the visual verification of a design. Often referred to as 3D printers or concept modelers, these low-cost RP machines are as safe and easy to use as any office photocopier or printer. They are likely to be widely installed in engineering offices, and when the price drops below $20,000, this 3 D printers certainly will be installed in every design office.

The concept of 3D printers will enable the designers to quickly produce physical models, early and often, when engineering changes are least expensive. This approach to modeling minimizes the need for high-priced prototypes and reduces costly mistakes at the tooling phase of product development

8. CONCLUSION

The possibility to obtain finished parts with complexity and details in an accurate and fast way starting from the solid model generated in the CAD system, makes the Rapid Prototyping techniques one of most powerful tool for the product development cycle.The use of such techniques started to expand significantly in 1994 and continues to grow. Some reasons for that is the wide range of materials available today, the quality improvement of the design, and also the fact that most companies are becoming aware of the potential of the technology. Also the correction of possible errors in the production tooling can avoid delay in the introduction of the product in the market.

This review intended to show to mechanical designers the high potential of such techniques to reduce costs and time-to-market. The most used techniques were described, as well as some characteristics of each system, which could be used as a first reference guide to choose the most adequate for a specific application. The applications of such systems worldwide were also presented, and unfortunately it is clear that Brazil is still starting to use it. Making the designers aware of the advantages these techniques can offer is probably the first step to use them, and it is certainly the most important contribution of this review.

For the future, it is expected that low cost RP processes will accelerate the growth of the Rapid Prototyping market. The concept of 3D printers will enable the designers, in an office environment, to produce physical models when engineering changes are least expensive.

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