Selecting Either Layered Manufacturing or CNC Machining to Build Your Prototype.

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Two fundamentally different methods are currently available for Rapid Prototyping: Layered Manufacturing Technology (additive) and CNC milling (subtractive). In order to create a prototype using RP, a designer will have to choose one of both methods. This paper gives guidelines for choosing the most appropriate method.

First the available technologies are described for both methods, and the differences are explained between 'traditional' CNC machining, and CNC machining for RP. After that both methods are compared, and the strengths and weaknesses are presented. These (dis)advantages then lead to finding preferred application areas for both CNC and LMT: most important conclusions are that for styling block models CNC milling is best, where for fully functional prototypes LMT based RP is best suited. These conclusions are illustrated using real-life example projects.

1. Introduction.

The activity called 'Rapid Prototyping' originated only about 12 years ago, with the appearance of the stereolithography system. This (then brandnew) process made a very large impact on the design community. It was based on 3D CAD (which at that time slowly became generally accepted), and it was announced as a "magical miracle process", involving unknown powers such as UV laser light and photosensitive polymers. Obviously in fact the activity of rapidly creating a prototype was not new: still a skilled craftsman can create a 3D foam model by hand (based on a 2D drawing) more rapidly than any current Rapid Prototyping (RP) system. May this craftman's activity be called RP or not ?

Many authors do use a very limited definition of RP, and only include technologies that build a prototype by stacking numerous thin layers (like the original stereolithography system). We will not use such a limitation, as in our opinion it is an arbitrary limitation and does not make much sense. The important aspect of RP as a black box is the automatic translation from 3D CAD model to physical model, and the technology actually used is not important at all. We will define Rapid Prototyping as [Lennings, 1997]: *"A Process that Automatically creates a Physical Prototype from a 3D CAD-Model, in a Short period of Time."*

This definition makes a much broader theory of RP possible than only focusing on RP systems that are currently available (though it excludes the skilled craftsman just mentioned). A theory that is in fact valid for all fabrication processes: RP is just an automated fabrication process. In this theory we can see that fundamentally three fabrication processes do exist: additive, subtractive and formative [Burns, 1993], see figure 1. Additive or incremental processes build by attaching or fusing separate pieces of material, like in masonry (bricklaying). Subtractive or decremental processes build by dividing a single piece of material into separate parts, like in woodcarving. Formative or deforming processes change the shape of a single piece of material, like in metal forging and in various moulding processes. Combinations are possible as well, like spinning pottery on a potter's wheel (most examples come from [Burns, 1993]).

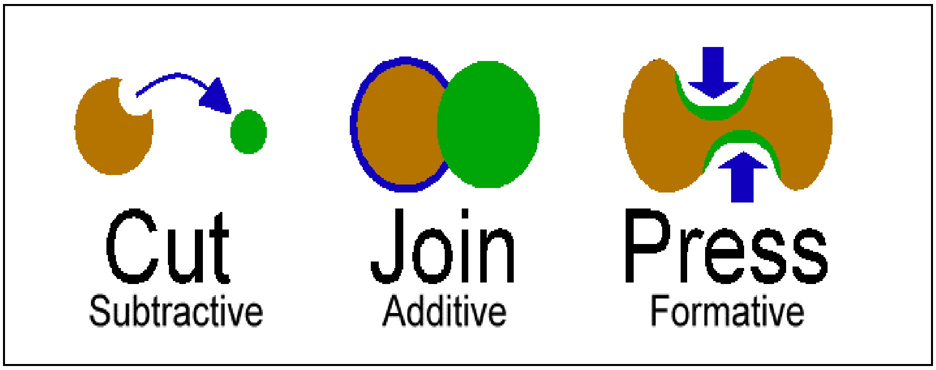


Figure 1. The three fundamental processes of fabrication (courtesy of Marshall Burns, Ennex Corp, USA).

Applied to current Rapid Prototyping systems we can clearly distinguish between additive and subtractive systems. The systems that stack thin layers are additive: starting with an empty space and adding material until the geometry of the model is completely filled. We will refer to these systems as Layered Manufacturing Technology (LMT) based, examples are Stereolithography, Selective Laser Sintering, etc. CNC milling systems are subtractive, starting with a solid block and cutting off chips until only the geometry of the model is left. Formative RP systems are not (yet) commercially available. Also in RP, combined systems are present, like the LOM system that cuts and stacks layers of paper.

The development of LMT methods like Stereolithography has created the growing demand for Rapid Prototyping. Still the advertised automatic translation from 3D CAD model to prototype using a laser operation results in the perception of a magical miracle machine. This perception has obscured the fact that most LMT machines are not so easy to use, requiring a skilled operator and manual postprocessing. On the other hand CNC machining has suffered from the notion that it was supposed to be too complicated to be called Rapid Prototyping, that it could not meet the 'Automatic' requirement. This may have been true in the past [Wall, 1992], however, new developments in both software and machines have now emerged which have made CNC a very competitive process for Rapid Prototyping.

The result is that there are now two RP methods available, LMT and CNC. Each of them having specific strengths and weaknesses, each of them having a distinct application area within the total RP field. After presenting the currently available technologies for both methods in sections 2 and 3, the (dis)advantages of both methods will be reviewed in section 4. This leads to recognizing which method to use for which application area (preferred application areas) in section 5, and finally some conclusions in section 6.

2. Layered Manufacturing Technologies for RP.

There is no need to give an in-depth presentation of the currently available Layered Manufacturing Technologies and LMT based RP systems in this paper. Many other authors have done so already, for instance [Pham, 1998], and [Wohlers, 1999]. Still a short overview can be given, including some observations concerning current developments.

As already mentioned, the first LMT process that became commercially available was stereolithography from 3D Systems, using a liquid polymer material which solidifies when hit by an UV laser. Still 3D Systems is one of the largest system suppliers. Soon other processes were developed, some of them variations on the stereolithography process, some of them applying a new technology. New processes that have appeared in the past years are:

- Selective Laser Sintering from DTM Corp, applying a laser to locally 'sinter' layers of powder
- Fused Deposition Modelling from Stratasys, extruding very thin plastic filament to form layers
- Layered Object Manufacturing from Helisys, using 'prefabricated' paper layers, cut to size by a laser
- Multi Jet Modelling from 3D Systems, depositing small drops of material using inkjet heads
- Three Dimensional Printing from MIT (commercialized amongst others by ZCorp), also using inkjet heads to deposit glue to locally bind layers of powder.

These newer technologies do offer advantages such as a wider choice of materials (including some engineering plastics and even metals), more ease-of-use, and lower prices. During the past years also the build speeds have significantly grown. These developments will continue, certainly leading to mass production of RP systems in the near future, available at much lower prices than today. In my opinion especially the inkjet based systems are promising as the technology used basically is very simple and suited for a lowcost implementation.

3. CNC milling as an RP process.

The application of CNC milling as an RP technology still is new, and has been made possible by a number of new developments. As these are not yet so well known, we will briefly describe some developments in CNC machining that have made it a competitive technology for RP.

The basics of machining are very straightforward: cutting off small chips. Traditionally the cutting tool was moved by manual control (rotating a wheel), after World War II new developments made Numerical Control (punched tape) possible, and now for many years CNC (Computerized Numerical Control) has become mature a technology. CNC milling has been used for prototype building in the past: involving large, heavy and expensive machines, powerful, though very complicated, CAM software, and skilled CAM operators. Surely not an automatic process, so not to be called Rapid Prototyping.

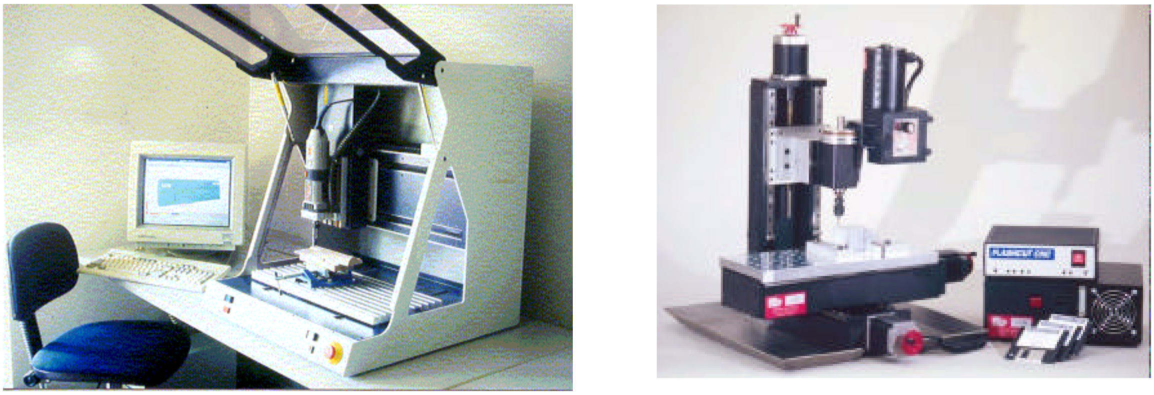
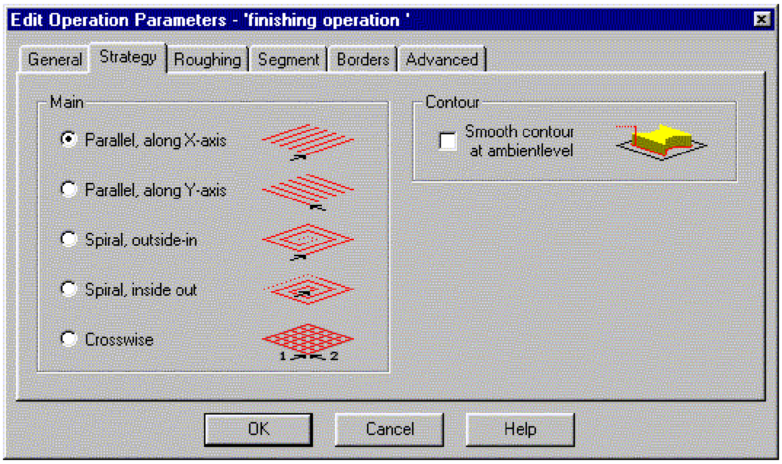


Figure 2. Examples of low-cost 3D CNC milling machines, perfectly suited for RP applications. (sources Delft Spline Systems - left, and Minitech - right).

Since that time things have changed: both on the hardware side and on the software side. New hardware developments resulted in small, light and very inexpensive CNC milling machines. Nowadays prices for a 3D CNC milling machine even start below USD 1,000 ! Such a machine (obviously with very limited capabilities) is within the reach of any product designer. Many manufacturers now offer a large variety of light CNC machines, including a fit for almost any application (figure 2). The heavier industrial machines can of course also be used for RP purposes, offering advantages such as larger size, speed, stability, power, etc. You can find machine prices ranging between USD 1,000 and 1,000,000 - for any specific application a fit can be found.

A second important development in machining hardware is High Speed (HS) milling. Here the advantage is not in price but in speed. Using a very high spindle speed being ca 40,000 to 80,000 rounds per minute (rpm), the cutter can move much faster than on traditional machines (which run at ca 1,000 to 10,000 rpm). Advantages are that the cutting forces remain small, cooling is not needed as the chips take away the heat and vibrations can be minimized. For HS milling both machine and controller need to be specifically designed, making it possible to maintain a high feedrate while processing large numbers of movement commands (a 'look-ahead' capability is needed) [Gunnink, 1998].

On the software side new developments have resulted in a new type of CAM software, specifically aimed at the application of Rapid Prototyping. This in contrast to 'traditional' CAM-software which is aimed at mould-makers, needing a high-end solution for perfect results. This traditional type of CAM-software needs a trained CAM-specialist, who can correctly interpret and set the many parameters. He must also be able to check the resulting toolpaths, as errors are possible that must be prevented by changing the parameter settings. The new software is aimed at product designers, who do not know much about machining and do not want to be bothered with such know-how either. CAM software for RP should work like a 'black-box', making the prototype creation process as automatic as possible. This does solve the problem signalled in [Wall, 1992]: at that moment the time needed to generate the CNC toolpaths was too long for real RP. Obviously in this new software the number of parameters is limited (figure 3): the software is not meant to compete with the numerous outstanding high-end CAM packages currently available.



● Parallel, along X-axis
○ Parallel, along Y-axis
○ Spiral, outside-in
○ Spiral, inside out
○ Crosswise

☐ Smooth contour at ambientlevel

Figure 3. Dialog box from DeskProto, a CAM software package for RP:
limited number of parameters, easy to understand (source Delft Spline Systems).

Other important characteristics of CAM software for RP are:

- The capability to import STL files: the standard filetype for RP, offering a much more stable geometry transfer than IGES.
- The high speed of calculating the toolpaths: RP has to be Rapid.
- The low price: especially important for Concept Modellers. Do note that large price differences can be seen for CAM software as well: prices range between ca USD 1,000 and 50,000)

Obviously the easy-to-use and lowcost CAM software for RP has a number of limitations when compared to the 'high-end' CAM software for moldmakers. Differences in CAM software capabilities can be found in the following areas:

- Tooling strategies. In the case of parallel toolpaths the distance between the toolpaths limits the achieved accuracy. If combined with, for instance, waterline machining the exact geometry can be machined (within the tolerances to be set for cusp height and chordal deviation). High-end CAM software may also offer options like detection and removal of rest material at sharp inner corners, optimizes start- and end-procedures for operations, and the use of machining features.
- Support of 2.5 D machining, which creates a model by combining a number of 2D contours, each at a constant Z-level. Options like drilling holes on certain positions belong to this category as well. This way of machining is very standard for mechanical applications.
- Number of axes supported. The basic CNC machine uses 3 controlled axes: X, Y and Z. More elaborate machines may be equipped with a fourth axis (type 'barbecue' or rotation table), or with 5 axes where the tool can be rotated to approach the geometry from different directions.
- Capability to optimize the toolpaths for HS milling, by removing all angles (all subsequent movements connected at a continuous tangent).

Combining these new developments of a light CNC milling machine and an easy-to use CAM software package results in a Rapid Prototyping system that offers a number of special characteristics, and as we will show, supplements the LMT based RP systems.

4. LMT versus CNC: advantages and disadvantages.

Each of the two available RP methods, LMT and CNC, has its specific strengths and weaknesses. In this section the advantages for both methods will be listed, which will lead to indicating preferred application areas within the total RP field. Only the advantages are listed, as in this comparison the advantages of the one method will be the disadvantages of the other.

4.1 Advantages of LMT.

The list is not very long, however the advantages listed are very important indeed, giving LMT technology a distinct place in the field.

- Design freedom.

Using LMT the design freedom is almost unlimited. Even hollow prototypes and functioning assemblies can be produced in one run. CNC milling is at a disadvantage too for sharp inner corners. As tools are by definition round, many sharp inner corners cannot be machined. See the illustrative example in figure 4.

- Complex geometry is just as easy.

The price of an LMT prototype is independent of its complexity. For CNC machining a dependence is present: in the case of many details a small tool has to be used with a small toolpath distance, resulting in a long production time.

- Ease of use.

In theory LMT systems have the advantage at this point, as there is no need to first make a block of material in the correct dimensions and then fix it on to the machines working table. In practice most LMT machines are not yet so easy to use. A large number of process parameters have to be correctly set: it may take up to a few months before a new machine is actually operating. For most LMT processes some (laborious) manual postprocessing is needed as well. The new generation of Concept Modellers using '3D printing' technology achieves much better, promising real black-box 3D printers for the near future.

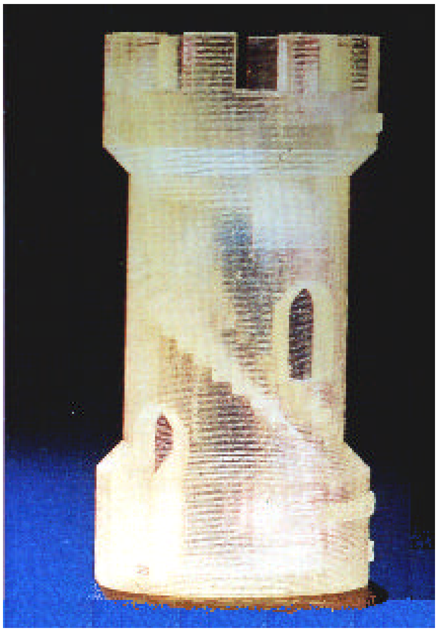


Figure 4 (left). Example of a geometry that cannot be created by CNC milling: note the staircase inside the hollow Chess tower (manufactured by Stereolithography).

Figure 5 (right). Example of a model that cannot be created by LMT systems: this perfume bottle was CNC milled in transparent perspex (solid) and then finished and textured (courtesy of design bureau SDA, Hoofddorp, the Netherlands).

4.2 Advantages of CNC.

This list is longer than the list of LMT advantages. Some of these advantages however only apply to specific application areas.

- Price of the system.

Prices of high-end LMT machines like a StereoLithography Apparatus will start at USD 100,000 (the total investment being higher because of the training needed). Concept Modellers are cheaper, however still at least USD 50,000. In contrast, a complete CNC system (software and machine) is available (far) under USD 10,000.

- In-house system possible.

As any design bureau or department can afford a light CNC milling machine, in-house RP is now possible. This will not only save time, it will also improve design quality, as the designers will use a local machine more easily than an external service.

- Trouble-free operation.

As the process of removing material is not complicated, the chances of failure are low. This is in contrast to the LMT processes, where small variations in, for instance, operating temperature and humidity may lead to unusable results, for instance because of warping, delamination and shrinkage.

- Capable of handling incorrect STL files.

LMT systems need correct STL files, containing correct normal vectors for each triangle and describing a solid geometry without cracks, gaps, orphan surfaces etc. CNC systems do not care much about such small inconsistencies, and can even handle single surfaces without thickness (as used in the Concept phase of the design process).

- Choice of materials.

Any material can be CNC milled. Obviously the light milling machines used for desktop prototyping have limited capabilities (no metals), however the choice of materials is much larger than with LMT systems. Using a material with specific properties is possible, like transparency (perspex, see figure 5), temperature resistance, strength/stiffness, easy to finish, low cost (foam), etc.

- Large prototypes.

A desktop CNC milling machine will have maximum model dimensions comparable to those of an LMT machine. However larger CNC machines are easily (externally) available and larger LMT machines (say 1 by 2 meters) are not.

- Free choice of accuracy.

LMT systems operate using an almost constant layer thickness. When using CNC milling the distance between the toolpaths can be freely chosen, from for instance 0.01 mm (which will result in a very long machining time) to 10 mm or larger. This free choice in accuracy means a choice in building speed as well, opening the possibility to create 'quick and dirty' Concept Models.

- Easy transfer to production tooling.

For large series the production tooling will be created using CNC milling.

5. LMT versus CNC: preferred application areas.

The advantages mentioned above already indicate a few application areas where one of both methods is preferred: LMT in case of a complex geometry (many small details), CNC in case of specific materials, large prototypes and incomplete STL files. In order to present a more detailed indication we will use an example design project: a handheld electrical hobby tool like a drilling machine.

The designers of this machine need prototypes for two different purposes: first to evaluate its appearance and styling, and second to evaluate its functioning. These two purposes cannot easily be combined using one prototype, so in most cases two different types of prototype are created: styling block models ('looks like models') and functioning prototypes ('works like models'). Both types are needed during the complete design process: two types of Concept Models as well as two types of Pre Production Prototypes.

A ***styling block model*** may well be solid, as only the outside that can be seen is important. For this type of model CNC machining is preferred, because:

- A material can be used that is easy to finish (up to high gloss). In fact the result can be that good that it is almost impossible to visually distinguish the finished presentation model (solid!) from the actual product (figure 7).

- The resulting model is firm and can easily be touched by lots of people (as in a consumers panel) without being damaged.
- The outside geometry is easy to machine, showing freeform surfaces that can be reached by the tool (no undercuts, as the production technology will be injection moulding). Such a model can be machined in two separate halves, which are very easy to fix on to the milling machine (see figure 6).
- For consumer goods the outside geometry is most important, and so very early in the design process concept styling models are needed, which can be machined very easily in foam.

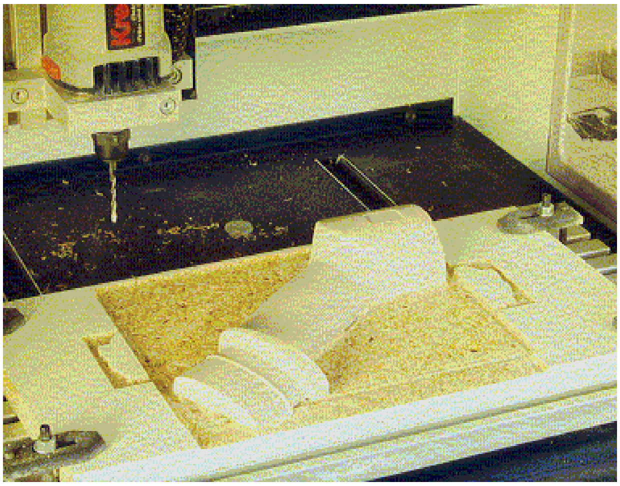


Figure 6 (left). A styling block model of a handheld tool (in fact one half) being milled in tooling board (courtesy of design bureau IDE, Belmont, Switzerland).
Figure 7 (right). A CNC milled presentation model of a heat gun, after finishing, which is almost impossible to distinguish from the final product (courtesy of Brandes & Meurs Industrial Design, and Skil Europe, both from the Netherlands.).

A ***functioning prototype*** has to meet completely different requirements. This prototype has to function, so it must be possible to assemble all inside parts like motor, switches, electrical wires etc. A thin walled shell model of the housing is needed, including all inner construction details like stiffening ribs and attachment points for other parts. For this type of model LMT systems are preferred, because of the complicated inside geometry: see figure 8. Such a LMT model is great for assembling the total product and using it (in the example to actually drill holes), in order to evaluate both the assembly of the product and it's functioning. The prototype however does not look perfect - it does not need to.

Obviously this general rule has its exceptions. In some cases it is still needed to create a prototype of the thin-walled housing by CNC milling, for instance if during the functional tests the prototype will become warm (LMT prototypes do not like that). Machining this type of geometry is indeed possible, also on a low-cost CNC based RP system. However, to do so a trained operator is needed and it will cost a lot of time. This type of model building may thus, in fact, not be called Rapid Prototyping.

Other preferred application areas do result from a specific advantage of one of the two technologies. For instance medical prototyping, where models of bone structures are built based on CT scan geometry information. This type of geometry is so complicated, for instance a human skull, that CNC milling is absolutely inappropriate (too many small details and inaccessible regions). Examples of application areas better suited for CNC are large sized prototypes, rough Concept Models ('quick, dirty and cheap', based on incomplete CAD data), ergonomics models (to be gripped, or sat on) and Rapid Tooling (in aluminum).

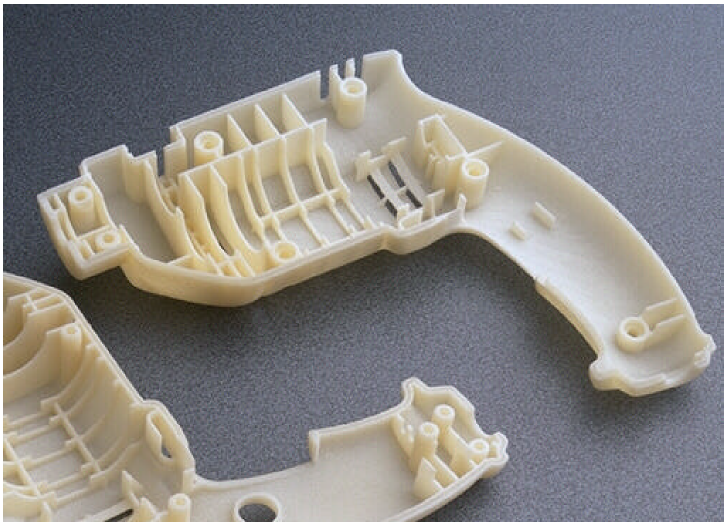


Figure 8. A thin walled housing of a drilling machine, created on an SLS machine to assemble a functioning prototype (courtesy of Mareco bv, Venlo, the Netherlands).

6. Conclusions.

We have shown that CNC milling is a competing technology for Rapid Prototyping. A broad range of CNC based solutions is available, from low-cost to high-end, varying both in price and in capabilities. When comparing CNC to LMT, the major LMT advantage is the 'unlimited' design freedom, the main CNC advantages are a low investment, free choice of material and large sizes possible. As a result we have shown that generally speaking for styling block models and concept models CNC based RP is best, where for fully functional prototypes LMT based RP is the best option. This applies both in Concept Modelling as in Pre Production Prototyping.

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