3D Printing vs. CNC Machining

Comparing Two Rapid Prototyping Alternatives

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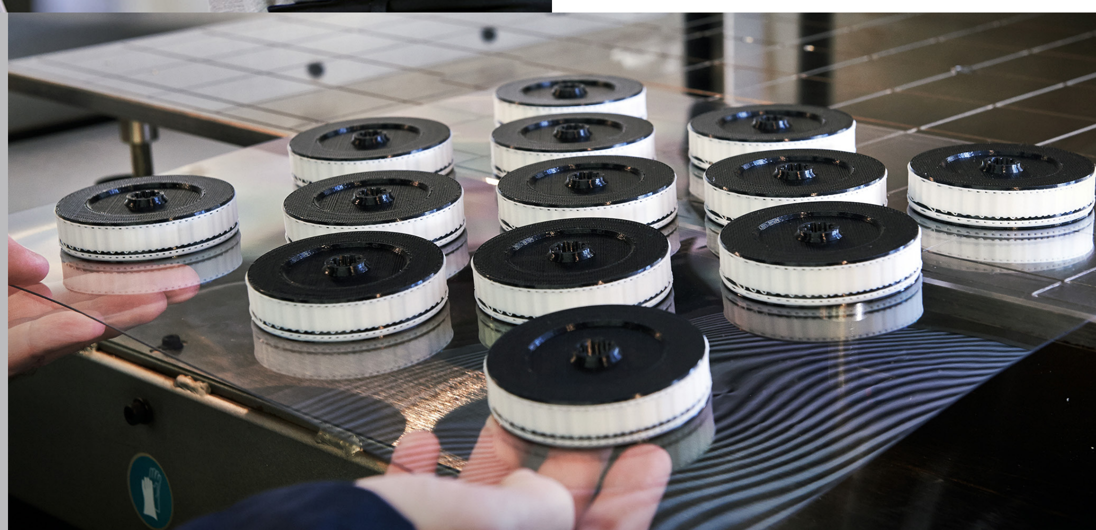

White Paper

3D Printing vs.
CNC Machining

In the product development phase there are many process options for creating models, prototypes, patterns or molds. Selecting the best approach requires an appreciation for the project requirements, an understanding of the process considerations, and an evaluation of the resulting time, cost and quality. Without this information, it is difficult to identify the optimal approach.

3D Printing vs. CNC Machining

When designs are still fluid and product specifications are in flux, two common choices are 3D printing and CNC (computer numerical control) milling. Both can meet the needs for early concept models through functional prototypes without the delays imposed by mold, tool, or die making. Both processes can make parts in a variety of materials. And both technologies can produce the low part quantities needed for product development at a reasonable cost.

However, the similarities end there. In many ways, 3D printing is the opposite of CNC milling. Most notably, the factors that influence time and cost are quite different. Additionally, the size, shape and configuration of suitable or ideal parts for 3D printing are a reversal from the ideal for CNC machining. To choose between the two, a thorough understand of both processes is necessary.

With the assumption that the methods of CNC machining are generally understood, this white paper will elaborate on 3D printing to allow process selection based on an understanding of its capabilities and associated considerations.

WHAT IS COVERED

The focus of this discussion is on rapid prototyping to support the product development cycle. Although both 3D printing and CNC machining can be used for production purposes, the goals and demands are different from those when product designs are taking shape. Generally, the discussion will address quick-turn, low-volume part making.

The discussion of 3D printing will broadly encompass all technologies. However, when specific examples are required, Stratasys FDM® (fused deposition modeling) will be the source of detailed information.

There are many CNC processes, such as routing, turning and drilling. This discussion will focus solely on CNC milling, and from this point forward, will be referred to as "CNC." By definition, this precludes manual machining. Additionally, the discussion will cover only 3-axis CNC because 4- and 5-axis CNCs are commonly dedicated to repetitive, production applications.

TERMINOLOGY

Rapid Prototyping: In the 1990s, rapid prototyping was the term used for technologies that additively construct parts direct from 3D CAD data. Today the term applies to an application: making prototypes quickly to support product development evaluations and decision making.

Additive Manufacturing: Technically speaking, 3D printing is a subset of additive manufacturing that includes either the technologies that were derived from early MIT patents (which called the method 3D printing) or those that represent the low-cost, desktop modelers.

However, 3D printing and additive manufacturing have become synonymous, with each term encompassing all applications, all technologies and all price points.

3D Printing vs. CNC Machining

The 3D Printing Process

3D printing is a collection of additive processes that construct prototypes on a layer-by-layer basis. This eliminates the need for tooling and allows the fabrication of extremely complex geometry with no impact on time or cost. Fundamentally, this is the primary advantage of 3D printing, and it translates to rapid delivery of small batches of parts and the flexibility to quickly accommodate design changes.

The additive nature of 3D printing also supports parallel part processing: multiple parts are manufactured in a single job in less time than that needed to make each individually. This capability allows production of multiple parts from a single project, multiple revisions of a single part, or multiple parts from different projects. The only limiting factor is the XY area of the 3D printer's working envelope.

Another advantage is that there is never a need for multiple setups to make a part. After initiating a job, it runs until the parts are complete. This supports around-the-clock production without the need for operator oversight or intervention.

Workflows

The workflows of 3D printing and CNC, at the highest level, are the same. Following part design (in CAD) there is a programming step where the instructions for the machine's operations are defined. Next, the machine is prepared for the job and the part is then manufactured. Upon completion, secondary processes are performed. The execution of these workflows, however, are quite different both in terms of time, labor and effort, which directly affects lead time and cost.

Design (CAD)

Both 3D printing and CNC use a 3-dimensional design definition that is completed in CAD. The requirements for the CAD data are common between them so the time and labor cost are comparable.

Note that this assumes that detailed engineering drawings are not required to provide a CAM programmer information needed to complete the project. The other assumption is that the CAD data is machinable as-is. If engineering is needed to document the part or to make it machinable, additional time will be necessary for CNC.

Complexity – What is it?

"Complexity is free with 3D printing" is a common statement. But what does that really mean? Simply stated, complexity relates to the design elements that increase time and cost with CNC milling. For example:

- High feature count: Numerous pockets, holes, ribs, and bosses
- Difficult features: Undercuts and deep, narrow channels
- Multiple feature axes: Holes and bosses with centerlines off of the primary (XYZ) axes
- Multi-part assemblies: Consolidated assembly components built in a single job
- Hollow parts: Lightweighting by making an internal honeycomb structure

This is not an exhaustive list of example of complexity, but it is a start.

3D Printing vs. CNC Machining

Program

For 3D printing, preparing files is commonly a 5- to 30-minute process that is highly automated. Upon importing an STL file (which is the output from CAD), a technician selects an orientation, specifies a material and selects from pre-defined build options. Beyond selecting an optimal orientation, there is little thought needed to prepare files. Note that for demanding jobs, there can be more operator interaction required, but this is uncommon for prototyping applications and does not increase processing time significantly.

This process is easily trained and requires no special skills. Some companies even opt to have engineers and designers perform this function. This is not true for CNC, which requires machining experience and a programming skill set.

For CNC, the CAD data is imported into a CAM program where all aspects of the machining process are defined, most of them manually. Among the decisions to be made are how to fixture the part; how many machining passes are needed; and what cutters, speed and feed rates to use. Frequently, these decisions are made on a feature-by-feature basis. The time for this process commonly ranges from one-half to eight hours.

Set up

Preparing a 3D printer is a quick process. While each technology has its own procedures, many require only material replenishment and preheating. In just 5 to 15 minutes, the printer is ready to manufacture parts. There is no need for any other set up before or during the printing process. For CNC, the machine operator will load the cutters needed for the job and fixture the work piece. When the CNC machine has a tool changer, the cutters are loaded only once. Lacking a tool changer, the machine operator will load the appropriate cutter for each machining operation. Like 3D printing, the set up operation is relatively quick, but when repeated for multiple set ups, it can slow the process down.

Manufacture

As described previously, the 3D printing process is fully automated, requiring no operator interaction until the job is complete. With a 3-axis CNC, this is seldom the case since the workpiece must be repositioned to cut upon faces that are not up-facing (in the original orientation), and therefore, not accessible to the cutters. For each repositioning, an operator needs to reorient and re-fixture the workpiece.

The factors that influence the time to manufacture a part are distinctly different for 3D printing and CNC. Manufacturing times for 3D printing are dictated primarily by the volume of material in a part and the part's height. Feature count and feature type have little impact on time. The opposite is true for CNC. Size and volume have marginal impact, but the number of features and their design characteristics dictate time. Because the time factors are so dissimilar, it is not prudent to state that one process is faster than the other nor to offer general rules of thumb.

Finish/Assemble

Upon completion of the manufacturing process, 3D printed parts will require post-processing. Most, but not all, will need removal of a sacrificial support structure that attaches the part to the build plate of the printer and holds unrestrained features in place. Unlike the manufacturing process, the time for support removal is geometry-dependent. This step may be a manual operation that takes between five minutes and one hour to complete or an automated, batch operation that takes between one and four hours.

CNC parts on the other hand, have no mandatory secondary operations.

3D Printing vs. CNC Machining

	Labor	Manufacturing	Material	Total
3D printing time	0.3 hr	2.0 hr	–	2.3 hr
3D printing cost	$11.10	$2.00	$17.50	$30.60
CNC machining time	1.0 hr	0.3 hr	–	1.3 hr
CNC machining cost	$37.00	$0.30	$8.75	$46.05

Table 1: Pocket tray time and cost.

Time And Cost Illustrations

The following examples use a burdened labor rate of $37.00/hour. For an hourly cost of machine ime, the examples use $1.00 for both 3D Printing and CNC*. For material cost calculated based on the extent volume, 3D printing uses $1.00/in^3 while CNC uses $0.50/in^3**.

Pocket Tray

Although 3D printing excels at making complex parts, it can be competitive for even simple parts like the pocket tray shown in Figure 1. As shown in Table 1, 3D printing is 55% less expensive than CNC. However, it takes 77% longer to produce, assuming that both processes can start immediately and that there are no delays imposed by availability of labor, materials and machine.

As will be shown later, CNC gains the time advantage because of the simplicity of the pocket tray's design.

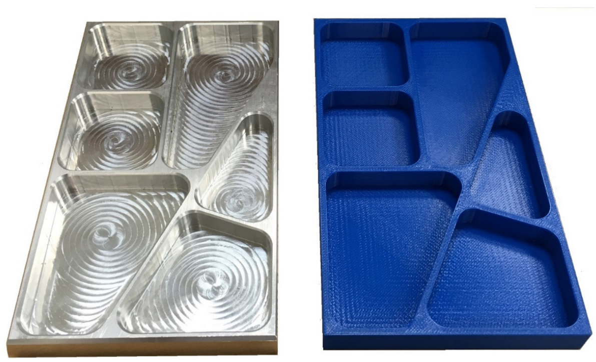

Figure 1: CNC (aluminum) on the left, 3D printed (plastic), right.

*** Effective Hourly Machine Cost**
For similarly sized and positioned machines, 3D printing is assumed to have a purchase price that is twice that of a CNC. However, when utilization rates are taken into account, the hourly cost is similar.

Assuming the machines' prices are amortized over 10 years, an annual cost of $5,000 is allotted for 3D printing and $2,500 allotted for CNC.

Since 3D printing is fully automated, there are 5,000 production hours available when accounting for downtime and idle time. This yields $1.00 per operating hour when fully utilized.

Requiring some operator intervention, CNC is assumed to have 2,500 production hours if run 12 hours a day and accounting for some downtime. This yields an hourly cost of $1.00 per operating hour.

For both processes, all other operating expenses, including consumables, are excluded.

****Effective Material Cost**
3D printing materials are more expensive than CNC materials. The cost of 3D printing materials are generally around $5.00/in^3 while commodity materials for CNC can be as low as $0.50/in^3.

For CNC, the effective material cost is calculated, at a minimum, by multiplying the cubic volume of the extents of the part by $0.50. The effective material cost will be higher when the raw material block is larger than the desired part.

For 3D printing, the actual material cost is determined by the volume of the part. Assuming that part volume is typically 20% of extent volume, the effective material cost is $1.00.

3D Printing vs. CNC Machining

	Labor	Manufacturing	Material	Total
3D printing time	0.3 hr	3.5 hr	–	3.8 hr
3D printing cost	$11.10	$7.00	$32.50	$50.60
CNC machining time	1.5 hr	1.0 hr	–	2.5 hr
CNC machining cost	$55.50	$1.00	$16.25	$72.75

Table 2: Adaptor time and cost.

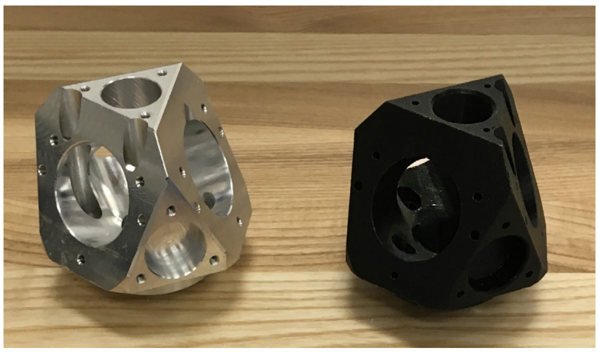

Figure 2: CNC (aluminum) on the left, 3D printed (plastic), right.

Industrial Robot Adaptor

Although not as simple as the pocket tray, the adaptor for an industrial robot is not overly challenging for CNC. The result is that CNC is faster than 3D printing, but more expensive, as shown in Table 2.

The adaptor once again shows that 3D printing can be the lower cost option with a 30% savings. This highlights the financial impact of the labor that CNC requires. With a total time that is 52% more than CNC, it also demonstrates the influence of a part's design on the speed advantage that is possible with 3D printing. Even though a 3-axis CNC requires an operator to perform six setups, the milling is straightforward, consisting only of some face milling, bore milling and drilling.

Time Drivers

Excluding set up and finishing for both 3D printing and CNC, the question of which process has higher throughput can only be answered after selecting a part design.

The time factors for 3D printing are simple and straightforward. A part's volume and height dictate most of the manufacturing time. The only design-related consideration that adds time results from support structures. When features need to be supported, a small amount of build time is added, usually in the 5% to 15% range. Unlike CNC, adding features that remove material, such as pockets and holes, will decrease the time needed to make a part.

CNC time is determined by the volume of material subtracted and the rate at which it is removed. The amount is dictated by the design and the size of the raw material stock. The rate is dictated by many factors, such as:

- **Specified tolerances:** Tighter tolerances require more machining time.
- **Size and depth of holes and pockets:** Deep and narrow require smaller cutters and slower cutting speeds, which adds time.
- **Wall thickness:** Smaller cutting depths and slower speeds are needed to prevent walls from deflecting.
- **Material:** The material dictates cutter depth, speeds and feeds. For example, plastic is more challenging to machine than soft metal, and feed and speed rates are decreased to prevent melting and sticking.

3D Printing vs. CNC Machining

Workflow must also be considered when evaluating the total elapsed time to deliver a prototype. Here 3D printing has the advantage because it has fewer steps to coordinate, fewer labor demands, and fewer resource requirements. The only gating factors are having labor resources to process files and available machine capacity. In addition to these gating factors, CNC requires a machinist on hand for all set ups, an inventory of raw material and a tool crib with the right fixtures and cutters. These aren't big issues, but lacking any of these resources will delay a project.

Operations

The in-house machine shop has been displaced by outsourcing in many companies. There are numerous reasons for this shift, but many cite the expense of staffing and the challenge in finding skilled CAM programmers and CNC machinists. 3D printing is a bit different. While some companies will not add a full-blown 3D printing lab due to the overhead expense, many have installed 3D printers within their design and engineering teams. Effectively, 3D printing becomes a selfserve function. In doing so, there is no addition to labor costs, but there is an opportunity cost when an engineer spends a few minutes to launch a 3D printing job. Those that do justify a 3D printing lab build the justification partially on the labor efficiency; a single individual can support all functions of a lab with five or more 3D printers and still have time for other duties.

Having the process in-house makes it much more responsive and more cost effective, if utilization is reasonable. For example, one prototype shop noted that the average 3D-printed prototype takes two to three days to deliver and costs $200 to $300. The same part, when CNC machined, would cost $400 to $500 and have a seven-day lead time. If the 3D printed prototype were done in-house, the difference would be much more dramatic with costs around $100 and the potential for same-day delivery.

In-house 3D printing also fosters a design and engineering culture of fast and frequent design iterations. When innovative ideas become a physical reality quickly and cost effectively, more concepts can be considered resulting in better= products. The product development team can get more aggressive with its designs, knowing that tomorrow's prototype will either validate the idea or illustrate that it will not work.

Time And Cost Considerations – Continued

Previously, it was shown that the pocket tray and robot adaptor could be made less expensively with 3D printing while taking longer to produce (ignoring workflow delays). However, neither example fully capitalizes on the advantages of 3D printing.

Building on the concepts that influence time and cost, the following discussion illustrates the impact of leveraging 3D printing's strengths.

	Time	Cost
Pocket tray: 3D printing	2.3 hr	$30.60
Pocket tray: CNC milling	1.3 hr	$46.05
Robot Adaptor: 3D printing	3.8 hr	$50.60
Robot Adaptor: CNC milling	2.5 hr	$72.75

Table 3: Time and cost summary from Tables 1 and 2.

3D Printing vs. CNC Machining

Workflow

Assume that an order is released a half hour before the end of the business day. With 3D printing, the job can be processed and started before the shift ends. The parts are now available at the start of the next day. Considering the labor demands of CNC, machining may start the next morning.

Bottom line: 3D printed parts are available 1.3 to 2.5 hours earlier.

Assume that the queue is already filled with orders and schedules cannot be juggled. For CNC, the projects have to wait until there is machine capacity. With 3D printing, the parts can be combined with other projects, so long as there is room in the machine.

Bottom line: 3D printed parts are available day(s) earlier.

Assume that the requirement is for three pocket trays, which will fit in one run of the 3D printer. For both CNC and 3D printing, the set-up time remains constant. But for 3D printing the manufacturing time is four hours for three parts (not 3 X 2.3 hours). For CNC, assume that there are three machining operations that start without any delay.

Bottom line (time): 3D printed parts available in 4.3 hours and CNC parts available in 3.3 hours.

Bottom line (cost): $75.00 cost for 3D printing and $140.00 for CNC.

Building on the three pocket trays, now assume that each is a different version, reflecting alternative design concepts. For 3D printing, the total time is 4.5 hours since there is only a small addition of time to process three different files. For CNC, the total time would be 4.9 hours.

Bottom line (time): 3D printing is 0.4 hours faster (and the design team becomes more efficient).

Bottom line (cost): $128.00 cost for 3D printing and $218.40 for CNC.

If three robot adaptors with three different designs were ordered, its bottom line would be a 3D printing advantage of $100.00, and it would take just a half hour more to make, assuming that each machining operation starts without delay.

Design

Assume that the pocket tray has cutouts on all four walls and several pockets on the bottom face. For 3D printing, there will be a slight decrease in manufacturing time. For CNC, there will be an increase in set-up time and a small increase in machining time.

Bottom line (time): The time for 3D printing and CNC become equal.

Bottom line (cost): $20.00 cost for 3D printing and $80.00 for CNC.

Adding pockets and cutouts does not increase the difficulty to CNC the pocket tray. Just imagine the time and cost difference if this prototype's design had thin ribs; deep, narrow channels; and undercuts. Also consider the significant time and= cost advantage of 3D printing if all of the above scenarios came together at once: there were three different revisions of this challenging design, the order was placed at 5:00 PM, the schedule was full, and each action was preceded by an interruption in the workflow (Table 4). 3D printing has the flexibility and efficiency to deliver when the conditions are less than perfect.

	Time	Cost
Pocket tray: 3D printing	1 day	$120
Pocket tray: CNC milling	7 days	$300
Robot Adaptor: 3D printing	1 day	$150
Robot Adaptor: CNC milling	7 days	$400

Table 4: Time and cost estimates adjusted for typical product development conditions.

3D Printing vs. CNC Machining

When To 3D Print

The following is a summary of the characteristics of a good 3D-printing project.

Design considerations:

- **Part size to order quantity:** Smaller parts are economical in larger quantities
- **Part size to design complexity:** Small or medium parts with moderate to high complexity are ideal
- **Part surface area to bounding box volume:** More surface area per cubic inch indicates high feature count

Drivers:

- Fast, efficient delivery
- Multiple design iterations warranted
- Design subject to change

Quality Characteristics

To this point, the discussion has been about time, money and effort. However, fast, inexpensive and easy are meaningless if the qualities of the prototypes do not meet a project's requirements. Generally, CNC has the perceived advantage in terms of materials, tolerance and finish.

Materials

Although 3D printing processes include a broad range of material classes, each technology will address a single class and offer a small number of materials within the class. For example, FDM technology works exclusively with thermoplastics and offers about a dozen different materials. CNC, on the other hand, can machine a wide variety of materials, spanning plastics, metals and composites. Within each of these classes, there are numerous options. The limiting factors are only if the material is machineable (e.g., it isn't possible to machine soft silicone) and if raw material is available in the form needed.

Material properties

After CNC machining, the resulting prototype will have mechanical properties nearly identical to the raw material. With 3D printing, the properties are similar to those of the raw material. Also consider that 3D printed parts are often anisotropic due to the layered nature of the process.

Tolerance

Run-of-the mill CNC work can produce prototypes with tolerances of +/-0.005”. For high-precision work, tolerances of 0.0002” are possible. In general, 3D printing produces parts with a tolerance that starts at 0.005” and has an additional allowance of 0.001” to 0.0015” per inch.

Surface finish

3-axis cutter movement with a CNC delivers smooth surfaces, if programmed with a finishing pass. 3D printing is a 2.5D process, so there will be some evidence of surface roughness on side walls, and possibly, visible tool paths on the upfacing and down-facing surfaces.

Assess Requirements And Goals

The trap that many people fall into is assuming that what they have always had is what they always need. Without stopping to consider what is critical for success and what is unnecessary, they default to specifying performance characteristics and output qualities of the established process. If this happens, the only solution will be the one that is currently being used.

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For example, if specifying 0.001" tolerances, 55 RMS surface finish and CYCOLAC material (a trademarked ABS offered by SABIC), the only option would be to use CNC.

To open the door to alternative solutions, start with an honest assessment of the requirements that support the goals and intent of the project. The best solution may still be CNC, but by thinking through the specifications, the option to leverage 3D printing arises.

Conclusion

With an understanding of the difference between 3D printing and CNC, and a thoughtful examination of goals and requirements, companies, both small and large, have access to an alternative for the product development process. Also add to that an open-mindedness to taking actions that were previously unthinkable or ignored, and the product development team can discover more about its designs faster and earlier in the cycle.

There isn't a single "best" solution. 3D printing is an alternative to CNC that opens the door to more options and new capabilities. Step inside a well-equipped shop and you will see CNC mills sitting side-by-side with 3D printers. For them, and for those that have the insight to what makes these processes different, the combination creates a workflow where the best solution is always available.

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