Direct Digital Manufacturing: Impact and Opportunity

Part 2 — Freedom of Design

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PREFACE

Direct digital manufacturing is a process that employs additive fabrication technology (aka rapid prototyping) to produce end-use items. Directly from CAD data, components are manufactured without molding, casting or machining. The impact of direct digital manufacturing is far-reaching, and the opportunities and advantages are extensive. This is why direct digital manufacturing is heralded as the next industrial revolution.

Since the earliest days of rapid prototyping, experts have envisioned the application of the technology in the manufacturing process, and the focus of this vision has been on the initial cost and time savings that are realized when tooling is eliminated. However, the relative impact pales in comparison to the wide ranging advantages that exist when direct digital manufacturing is implemented.

Direct Digital Manufacturing

"Rapid Manufacturing" has become a generic term that is applied to any process that produces manufactured goods quickly. To avoid confusion, the Society of Manufacturing Engineers has adopted a new term, direct digital manufacturing. The association's definition of direct digital manufacturing is "The process of going directly from an electronic, digital representation of a part to the final product via additive manufacturing. "

Industry has failed to recognize many of the opportunities that direct digital manufacturing offers. Some will yield unprecedented efficiencies; some will generate annual savings that far exceed the cost of a tool; and others will facilitate new methodologies that address age-old constraints. Direct digital manufacturing will benefit nearly every discipline within a manufacturing organization, and it will change fundamental business processes. When adopted en masse, it truly will be an industrial revolution.

In this series of white papers, the often unrecognized benefits of direct digital manufacturing will be disclosed to reveal the huge potential that the process offers. Part 1 discussed the positive impact of a newfound freedom to redesign or alter products while in production. In Part 2, the discussion highlights direct digital manufacturing's elimination of design constraints imposed by conventional processes. The freedom of design that it offers is so significant that many associate it with a paradigm shift.

The freedom of design eliminates design rules and creates a paradigm shift.

STATUS QUO

Every product manufactured is constrained by the capabilities of the process used to make it. Designers and engineers are not free to create perfect products, sub-assemblies and components. Instead, they must adhere to the design rules of the manufacturing process. Any breach of these rules will drive up production costs, diminish quality, degrade performance or impact visual appeal. Balancing design and manufacturability suppresses innovation and quashes great ideas.

Product design is a collaborative effort that requires design concessions. Negotiations between design goals and manufacturing requirements consume much time and result in products that do not match the original vision and design intent. And while this collaboration is intended to improve quality and reduce costs, the process constraints can actually cause the opposite effect by increasing the part count and number of operations.

Seeking to align design and manufacturing, companies implement design for manufacturability (DFM) and design for assembly (DFA). Collectively DFMA (design for manufacturability and assembly) expresses the limitations and constraints of the manufacturing process. Combining the design vision with DFMA, the goal is to create parts that can be manufactured at a reasonable cost with acceptable quality. This practice requires that a manufacturing process be selected before design begins and that the constraints are addressed throughout the product's design. It also dictates that designers have a keen understanding of all manufacturing processes used to make the company's products.

> *Adhering to the constraints and limiting design freedoms are necessary for conventional manufacturing processes.*

For example, DFM for injection molded parts dictates that product design address tooling and process constraints, including:

- Draft angles
- Parting line location
- Extraction (elimination of undercuts)
- Constant wall thickness
- Aspect ratio
- Ejection and gating location
- Radiused, filleted corners

There is also consideration of molding constraints:

- Knit lines
- Freeze off
- Sinks

While DFM defines the constraints, DFA promotes designs that are easily and affordably assembled. The key goals of DFA are minimizing part count, fasteners and handling time while making assembly easy and error proof. With DFA, significant improvements in cost, labor time and quality are achieved.

However, like product design, DFA is constrained by the DFM guidelines for the manufacturing process. For instance, part consolidation may be unattainable because the resulting design cannot be manufactured.

In light of the limitations of conventional manufacturing processes, DFMA is a critical methodology for improving product quality and reducing production costs. If designers and engineers were allowed to create parts solely for form, fit and function, inappropriate and unreasonable designs would negatively impact manufacturing processes and corporate profits. Adhering to the constraints and limiting design freedoms are necessary for conventional manufacturing processes.

FREEDOM OF DESIGN

Direct digital manufacturing eliminates all of the design constraints imposed by conventional manufacturing methods. It offers designers and engineers an unprecedented freedom to design a product and its components exclusively for the desired form, fit and function. Breaking the link between complexity and cost, innovative and sophisticated designs are released from DFM constraints. In effect, whatever the mind can conceive can now be manufactured practically and affordably.

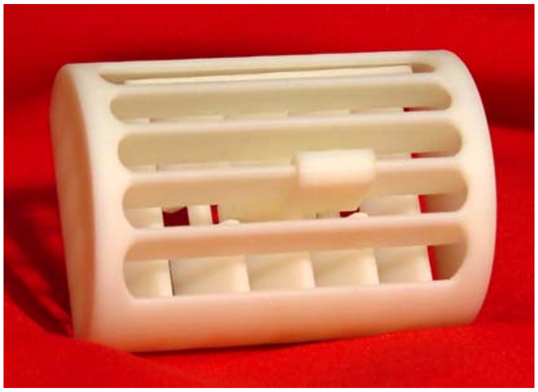
> *With few exceptions, direct digital manufacturing can replicate whatever is designed in 3D CAD.*

Leveraging the additive, layer-by-layer construction method and eliminating tooling, machining, molding, casting and fabrication, direct digital manufacturing offers unprecedented freedom of design. Undercuts, variable wall thickness and deep channels can be part of the design with no affect on manufacturing cost or manufacturability. With conventional methods, each feature on a part adds time and cost, but with direct digital manufacturing, parts can be feature-laden without an increase in either. For example, a part with a thousand 0.05 inch holes can be produced as cheaply and quickly as the same part without holes.

Parts can also assume previously unthinkable forms. They can flow, twist and contort into every nook and cranny in the design envelope or borrow from the organic shapes found in nature. Allowing limitless complexity, direct digital manufactured parts can be designed with extraordinary strength-to-weight ratios. This could be achieved by designing an internal lattice that is covered by solid outer surfaces. With few exceptions, direct digital manufacturing can replicate whatever is designed in 3D CAD.

The freedom of design also diminishes the time from design to manufacturing. Since there is no tooling or machining, there is no investment of time in modifying a part for manufacturability or designing the necessary tooling, fixtures and tool paths.

Eliminating DFM constraints also take DFA to new levels. No longer limited by the process, direct digital manufacturing allows complete assemblies, both static and dynamic, to be constructed as a single part. This degree of part consolidation eliminates assembly time, expense and errors while drastically reducing manufacturing costs and inventory part counts. For instance, an automobile air vent is assembled from many components, including the main housing, louvers and flow control mechanism. With direct digital manufacturing, the entire assembly can be produced as one piece, which eliminates all cost, time and quality problems that result from an assembly operation.



The air vent, constructed as a one-piece assembly, illustrates rapid manufacturing's ability to consolidate parts.

Direct digital manufacturing will excel when parts are designed to capitalize on the capabilities of the technologies. The gains of the process will be marginal if existing parts are merely transitioned to direct digital manufacturing. The first, and easiest, step in this conversion is to unlearn all that has been taught about designing for conventional processes.

The second step, which will yield tremendous benefits, will require new education. Just as designers have been schooled on DFM, academia and industry will need to develop a similar concept for direct digital manufacturing. Perhaps it will be called DFDDM (design for direct digital manufacturing). Instead of instruction on limitations, early education on DFDDM will focus on the new, previously impossible capabilities of the technology. With this paradigm shift, remarkable benefits will be discovered.

To understand all of the benefits and impact on an organization, and to see the true justification, the full scope of the effects of direct digital manufacturing must be considered.

Of course, direct digital manufacturing is not without limitations and considerations. DFDDM studies will also address aspects that are unique to direct digital manufacturing, and those that are unique to specific technologies. Support structures, stairstepping, surface finish and minimum wall thickness must be considered in a component's design. An understanding of achievable accuracies and resultant mechanical, thermal and electrical properties—two aspects that are believed to be the biggest constraints of direct digital manufacturing—will also be required. However, DFDDM will address design alternatives that overcome these limitations. For example, a multi-piece assembly with tight tolerances for its components can be consolidated into a single piece that has only loose tolerances at its attachment points.

Two other barriers to direct digital manufacturing that require a new way of thinking are unit cost and production time. Using traditional thinking for process justification may dissuade the use of direct digital manufacturing where production time may be measured in hours, not minutes, and cost measured in dollars, not pennies. To understand all of the benefits and impact on an organization, and to see the true justification, the full scope of the effects of direct digital manufacturing must be considered.

RETURN ON INVESTMENT

ROI CALCULATION

Assumptions

Number of parts per product:	25
% direct digital manufacturing:	50%
Part consolidation:	25%
Number of products:	10
Product life:	5 years
Labor rate (burdened) engineering:	$50/hr
Engrg/mfg labor per part: (for manufacturability)	40 hrs
Annual sales per product:	$1,000,000
Gross profit:	50%
Assembly cost (% sales):	5%
Inventory carrying cost (% sales):	5%

Profit Gains

Engr/Mfg labor	
25 parts @ 50%:	12.5
X 40 hours:	500
x $50/hr:	$50,000
x 10 products:	$250,000
Inventory	
25% consolidation @5%:	1.25%
x $1,000,000/product:	$12,500
x 10 products:	$125,000
Assembly:	
25% consolidation @5%:	1.25%
x $1,000,000/product:	$12,500
x 10 products:	$125,000
Lifetime savings:	
Sub-total:	$500,000
X 5 years:	**$2,500,000**
Sales:	
Weekly gross profit:	
$1,000,000/50 weeks:	$20,000
X 50% gross profit:	$10,000
X 10 products:	$100,000
Gross profit:	
2 weeks @ $100,000:	**$200,000**
Total Profit Improvement:	**$2,700,000**

As with the freedom to redesign (Part 1), the value of the freedom of design is immeasurable. It goes well beyond the standard accounting metrics that justify an activity or demonstrate a positive ROI (return on investment). This is because it delivers benefits that are difficult to measure, and it facilitates new business practices that benefit the company, its products and many design and manufacturing processes.

However, even if evaluating only the measurable, tangible financial gains, the impact on the bottom line can be staggering. As shown in the example, there is a direct affect on profitability that results from:

- Cost savings from the elimination of redesign for manufacturability, design of tooling and programming.
- Expense reduction from decreased inventory levels and assembly operations due to part consolidation.
- Decrease in time-to-market from the elimination of DFM and manufacturing programming.

Although a simplistic representation of the cost and profit impact of direct digital manufacturing, the example shows that a $10 million company could enjoy increased profits of $700,000 in the first year. However, with the exception of time-to-market acceleration, the profit improvement is not a one-time event. It extends over the entire life of the product, which increases the profit improvement to $2,700,000. It is important to note that this simplistic example fails to recognize savings in facility expense, unit cost reduction from part consolidation, elimination of secondary operations, and other expenses attributed to manufacturing. Unique to each organization, projections of the total impact on the bottom line must include all savings that are derived from a direct digital manufacturing implementation.

While these numbers are impressive, they do not reflect the most important gains that result from the freedom of design— better and more innovative products. The financial analysis also fails to recognize the benefits of higher throughput and increased operational efficiency.

Throughput and Efficiency

On the manufacturing floor, the production process is a choreographed sequence of individual processes. Each step adds time and introduces complications. Since direct digital manufacturing can eliminate assembly through part consolidation and minimize secondary operations by incorporating all features in the part, the freedom of design can increase throughput and efficiency. This translates to faster production rates and lower costs.

As illustrated in Eliyahu Goldratt's "The Goal," the production rate of a single operation will be the gating factor for a plant's throughput. The bottleneck operation controls the throughput rate of all upstream and downstream processes. If, for example, a part is injection molded at a rate of 90 units per minute and an ultrasonic welding operation has a rate of 10 units per hour, the effective throughput rate is only 10 units an hour. Unless excess work-in-progress inventory is desired, this means that the injection molding process will be idle for seven hours of an eight-hour shift.

In those cases where the freedom of design eliminates all downstream operations, the direct digital manufacturing machine can be run 24 hours a day because it is the only gating factor.

As Goldratt notes, the bottleneck operation will vary from day-to-day and hour-to-hour. Downtime in any operation, due to equipment problems or part shortages, will have a ripple effect on the effective throughput rate. With each operation, there is also the increased possibility of creating scrap, which drives up costs. Managing this dynamic workflow is challenging and balancing the work load at each process is difficult.

What potential presents itself if the best attributes of various manufacturing processes can be combined?

When the design eliminates secondary operations and consolidates parts, the manufacturing flow is streamlined, which makes it easier to manage and much more efficient. With direct digital manufacturing, throughput and efficiencies can increase and production costs can fall.

Product Enhancement

It is impossible to place a dollar amount on the value derived from the ability to design products, assemblies and parts solely for the purpose of form, fit and function. To do so would be akin to estimating the value of creativity or innovation. However, it is implicitly understood that better products translate to greater financial gain for a company.

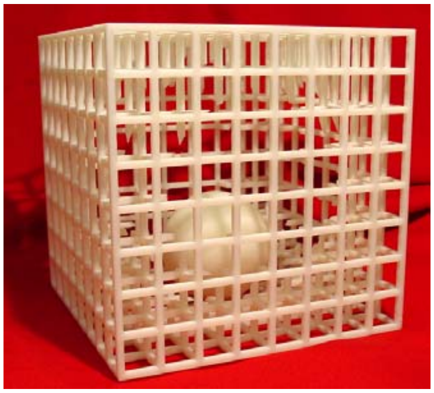
The freedom of design allows a product and its components to assume the form that is best for the function. The product can be as complex and feature-laden as it must be to serve its purpose. Severing the direct relationship of cost to complexity and severing the ties to DFM rules, direct digital manufacturing promotes good design for better products.

How many great ideas have been shelved because they were impossible or impractical to produce? If these ideas had become a reality, what would the impact be? These are no longer valid questions if the direct digital manufacturing process has been implemented. The new question that will arise is "what can we do now?"

What potential presents itself if the best attributes of various manufacturing processes can be combined? For example, imagine combining blow molding's ability to make hollow parts with injection molding's ability to make strengthening ribs. Imagine combining the capabilities of investment casting with those of die casting to achieve parts with freeform passages, fine features and thin walls. These thoughts become the new "what ifs" that direct digital manufacturing introduces. As the "what ifs" are asked and answered, product enhancement will naturally occur.

The next generation of products can even capitalize and improve on structures found in nature. Due to arches at each end, the egg has great longitudinal strength. With the freedom of design, the outer structure of the egg can be combined with an internal lattice to give a product impressive longitudinal and latitudinal strength. Likewise, the inherent strength of a honeycomb can be contained within solid, bounding surfaces.

In the earliest days of rapid prototyping, the caged ball—a sphere captured within a top and bottom plate that are connected by four vertical legs— was used to demonstrate the unmatched ability to produce complex designs. In the world of direct digital manufacturing, the caged ball is an equally powerful example. If constrained to a conventional process like injection molding, production of the caged ball would require three molds—one each for the ball, top plate and bottom plate with vertical legs—and an assembly operation. These requirements could make the caged ball impractical to manufacture. With direct digital manufacturing, it becomes practical because it can be produced in one operation, without tooling or assembly.



The caged ball illustrates that what was once impractical or impossible can be economically produced with rapid manufacturing.

With the freedom of design, some products will have better performance and some will have enhanced design aesthetics and ergonomics. Either way, this will translate to increased sales. For the truly innovative, the freedom of design will unleash new products and new ideas that would have been deemed impossible or impractical if bound by the limitations of conventional manufacturing processes.

CONCLUSION

With freedom of design, direct digital manufacturing opens the door to previously impossible design concepts, strategies and innovations. Those that embrace this freedom will realize improved sales, lower costs and greater efficiencies, which translate to profit improvements. Combined with the advantages of the freedom to redesign (Part 1), the benefits are staggering and impossible to ignore.

As shown, direct digital manufacturing can be justified solely on the freedom of design. However, there are many other advantages that the process offers. Throughout this series of whitepapers, these advantages will be discussed. Part 3 in the series will reveal the benefits gained when direct digital manufacturing is applied to bridge tooling. It will discuss the opportunities created when the process is used to delivery production goods before production molds are completed.

Direct digital manufacturing will be the next industrial revolution. With it, as with any revolution, there will be a total upheaval, a radical change and an overthrow of existing practices. Direct digital manufacturing will infiltrate all processes and every discipline within a company. It will change how manufacturing is done.

About the Author

Todd Grimm is president of T. A. Grimm & Associates, Inc., an independent consulting firm that focuses on rapid prototyping and reverse engineering. Todd has worked in the field of rapid prototyping since 1990. He is the author of "Users Guide to Rapid Prototyping" and holds a Masters Certificate in Rapid Prototyping. Todd serves on the Society of Manufacturing Engineers' Rapid Technologies and Additive Manufacturing steering committee, and he chairs the 3D Data Capture/Reverse Engineering technical group.