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# 3D opportunity for production

## Additive manufacturing makes its (business) case

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**> ILLUSTRATION BY IGOR MORSKI**

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*"A pint's a pound the world around. A gallon weighs 8 pounds."*[1]

But what does it cost to fly it? Put three gallons on an airplane flying international routes, and the airline might tell you $440,000 per year.[2]

Leading manufacturers in aerospace and other industries face a daunting challenge. To remain competitive, they must constantly look for ways to deliver superior value to their customers. Cutting costs and competing on price have their place, but who wouldn't prefer delivering superior value with better products and competing on revenue? Truly innovative companies find a way to break the trade-off between better and cheaper and deliver both.[3]

Advocates for additive manufacturing (AM), also known as "3D printing," view the technology as a strong potential contributor to companies' quest for excellence.[4] In the right context, they see the potential to meet or exceed the direct-cost standards established by more traditional manufacturing methods while simultaneously offering the opportunity to achieve superior supply-chain and product performance.

*Additive manufacturing, commonly referred to as 3D printing, is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."*

Many senior executives, operations managers, and financial professionals find themselves trying to understand the business case for AM. This should begin with careful consideration of the direct costs that drive AM and traditional production economics and continue with an examination of some of the less direct factors that can add dramatic value for companies and their customers under the right circumstances.

Such exploration seems justified. Advancements in AM increasingly enable companies to move beyond the technology's historical stronghold of rapid prototyping and into end-product manufacturing. For example, the relative share of AM use for end-product manufacturing is estimated to have grown from 19 percent in 2011 to 28.3 percent in 2012.[5] That represents not just a significant share of the AM market but also growth that exceeds the general (already quickly growing) rate for AM technology.

Deloitte's* analysis suggests that AM can offer truly innovative capabilities for companies, allowing them to simultaneously lower costs as well as differentiate themselves in their markets. Our results also suggest that most currently available perspectives on the economics of AM reflect a clear "path I" bias, according to Deloitte's AM strategic framework.[6] Along path I, companies deploy AM without significantly changing their underlying business models. Of the studies we examined, all but one consider AM as a direct replacement for an identical product manufac-

*As used in this document, "Deloitte" means Deloitte LLP and its subsidiaries. Please see www.deloitte.com/us/about for a detailed description of the legal structure of Deloitte LLP and its subsidiaries.

tured using more traditional methods—in most cases, plastic injection molding. However, this bias belies AM's well-documented ability to shift a company's business model, either by allowing it to leverage improvements in minimum efficient scale to restructure a supply chain (for example, by producing closer to demand) or by activating the superior scope economies offered by AM approaches to create innovative product designs. Figure 1 provides a brief overview of our AM framework.

**Figure 1. Framework for understanding AM paths and value**


Graphic: Deloitte University Press | DUPress.com

Research suggests that AM can add value in two fundamental ways:

- AM has strong potential to match traditional manufacturing methods on a direct-cost basis for production applications. However, the drivers of direct cost substantially differ between the two approaches.
- AM technologies can help companies differentiate themselves by creating unique market offerings and positions, thanks to its ability to transform supply chains, products, and business models.

## FRAMEWORK FOR UNDERSTANDING AM PATHS AND VALUE

AM's roots go back nearly three decades. Its importance is derived from its ability to break existing performance trade-offs in two fundamental ways. First, AM reduces the capital required to achieve economies of scale. Second, it increases flexibility and reduces the capital required to achieve scope.

**Capital versus scale:** Considerations of minimum efficient scale can shape supply chains. AM has the potential to reduce the capital required to reach minimum efficient scale for production, thus lowering the manufacturing barriers to entry for a given location.

**Capital versus scope:** Economies of scope influence how and what products can be made. The flexibility of AM facilitates an increase in the variety of products a unit of capital can produce, reducing the costs associated with production changeovers and customization and, thus, the overall amount of required capital.

Changing the capital versus scale relationship has the potential to impact how supply chains are configured, and changing the capital versus scope relationship has the potential to impact product designs. These impacts present companies with choices on how to deploy AM across their businesses.

Companies pursuing AM capabilities choose between divergent paths:

**Path I:** Companies do not seek radical alterations in either supply chains or products, but they may explore AM technologies to improve value delivery for current products within existing supply chains.

**Path II:** Companies take advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the products they offer.

**Path III:** Companies take advantage of the scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer.

**Path IV:** Companies alter both supply chains and products in pursuit of new business models.

### ADDITIVE MANUFACTURING AND DIRECT COSTS

As early as 2003, researchers established that AM could compete with traditional manufacturing methods at levels of production up to approximately 14,000 parts,[7] but recent analyses demonstrate the economic benefits of AM production for small electrical components in runs of up to 121,000 pieces.[8] Yet a variety of complex factors make it difficult to build specific costing models for AM deployment.[9] Equipment manufacturers closely guard competitive cost information, and despite the relative youth of the industry, there is still a large variety of system providers and models to choose from.[10] Furthermore, selecting the right process demands a focus on the trade-offs between system size, cost, speed, quality, and other considerations.[11] However, careful consideration of existing research and current use cases provides insights into the direct-cost drivers of AM business cases. Prior to examining those drivers, it is important to note several common attributes of these studies:

- With limited exceptions, most analytical work in this field has focused on direct comparisons with injection molding, overwhelmingly for plastics. This is appropriate given that, as of 2012, plastics and polymers accounted for approximately 81 percent of the total AM materials market, while metals accounted for less than 6 percent.[12]

*For example, the relative share of AM use for end-product manufacturing is estimated to have grown from 19 percent in 2011 to 28.3 percent in 2012. That represents not just a significant share of the AM market but also growth that exceeds the general (already quickly growing) rate for AM technology.*

- Studies tend to focus on three common AM technologies: stereolithography (a light polymerization process), fused deposition modeling (an extrusion deposition process), and selective laser sintering (a granular material binding process); the latter technology is receiving attention as the most potentially cost-effective AM technology for plastics.[13]
- Existing AM research focuses almost exclusively on the production of relatively small objects.[14] We note, however, that some industry watchers report "remarkable promise" in the application of AM technologies for large structural parts, particularly in aerospace and defense applications.[15]
- Analyses also tend to take for granted the superior ability of AM to compete economically for the production of relatively complex parts, and they tend to focus on objects that are higher than average in this regard.[16]

In light of these common assumptions, a comparison of the direct costs associated with AM and traditional manufacturing methods consistently points to four elements as key differentiators: tooling, machine costs, materials, and, to a lesser extent, labor.

**Tooling:** In some cases, the cost of tooling far outweighs the unit cost of each additional part.[17] For example, in a comparison of AM and injection molding (IM) for the manufacture of electrical components, Italian researchers found that 93.5

percent of the IM cost structure was associated with the creation of the mold.[18] Beyond its production, tooling must be maintained, stored, and often tracked over long periods of time.[19] A key attribute of AM is its ability to improve or eliminate costs associated with tooling.[20] Any full business case comparing manufacturing methods must account for this difference.

**Machine costs:** In contrast, machine costs tend to dominate cost structures for AM applications, representing 60–70 percent of total direct costs.[21] New production-capable AM systems can require hundreds of thousands or millions of dollars in investment. Build volume, machine utilization, and depreciation can dramatically influence business-case comparisons with traditional manufacturing methods.

*AM technology offers the potential to match more traditional manufacturing methods on a direct-cost basis for low and intermediate levels of production (that is, up to and above 100,000 units).*

Build volume is critical. Frequently, AM technology demonstrations focus on the creation of a single object. This is effective for showing off the capabilities of the technology but terrible for efficient production. Almost every study we evaluated makes the point that, rather than focusing on single units, achieving volume sufficient to "pack" the production envelope is critical. Some suggest that the relevant measure of cost is not the number of units but rather the user's ability to fill the available production envelope.[22] To this end, companies need to leverage the inherent flexibility of AM through the mixing of different components in order to fill out build volumes, implementing envelope-packing algorithms where needed. Failing that, managers should consider leasing excess build capacity to external bidders.[23]

Assumptions about machine utilization are also critical, and managers should carefully explore the appropriateness of their assumptions with system providers. Research points to supplier-provided assumptions of 80 percent utilization, but they typically assume a more conservative 60 percent utilization in their own analyses.[24] That said, there are applications in production over the past 10 years that are reported to achieve upward of 90 percent utilization, comparable to those of IM equipment, when applied to standard builds produced at higher volume.[25]

Regardless, managers can expect machine costs to contribute a dominant fraction of the total unit cost for AM. Beyond assumptions related to build volume and utilization, managers need to think carefully about issues related to expected machine life and maintenance. Furthermore, those charged with exploring the trade-offs between AM and more traditional manufacturing approaches will want to consult with their colleagues in finance to study the implications of depreciation and tax incentives on the overall business case. The trade-offs imposed by comparing newly acquired AM systems with fully depreciated traditional manufacturing technology could be significant in the short to medium term, regardless of the long-term benefits.

*Speed is important for delivery as well as production. Given shorter product life cycles and increasing global competition, speed to market and prompt delivery may be crucial determinants of customer value.*

**Materials:** Analyses place material cost at around 30 percent of the unit cost for AM systems compared with an almost inconsequential amount (0.2–2.7 percent) for traditional methods such as IM.[26] Differences in this regard are due largely to the extreme cost differentials that exist in the market between AM and more traditional material feedstock. According to industry analyses, thermoplastics and photopolymers for AM applications can cost $175–250 per kg, while those used for IM cost just $2–3 per kg.[27] Similarly, the steel powders used in AM applications are 100 times costlier than commercial grade.[28] For example, Italian researchers performed an analysis using a flame-retardant polyamide sold at market (by the system provider) for €54 per kilogram in 2010. The same analysis reports that the comparable material suitable for injection molding cost €3.5 per kilogram (a difference of 1,443 percent).

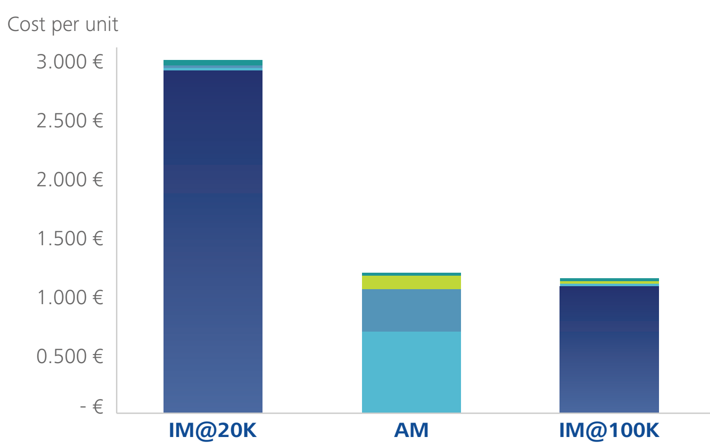
Material recyclability drives cost as well. Assumptions of zero waste in AM applications seem inappropriate. Consensus on the amount of unprocessed material that can be recycled is hard to find. Some cite zero reuse for highly sensitive aerospace applications, while others suggest near-total reuse is possible.[29] Material recycle rates vary by process, system, and application and should be carefully evaluated as part of the business case.[30]

Of course, production scrap is not solely an issue for AM technologies. By their very definition, traditional "subtractive" technologies have scrap as a byproduct. Studies of aerospace manufacturing consider the "buy-to-fly" ratio of manufactured components, citing ratios between 6:1 and 33:1.[31] That is, the amount of discarded material ranged between 83 and 97 percent. We conclude, therefore, that any comparative analysis of AM versus traditional manufacturing includes a careful analysis of both the recyclability of unprocessed AM material as well as a consideration of scrap rates associated with the comparable traditional manufacturing method.

**Labor:** We find no clear evidence that labor rates differ significantly according to the production environment.[32] However, principles may be applied with the goal of part simplification, which can result in substantial labor savings.[33] For one application, part simplification (in this case, a reduction from three pieces to one for a simple product) led to a 67 percent reduction in assembly time.[34]

On a direct-cost basis, most analyses focus on major direct-cost drivers of tooling, machine cost, material cost, and labor (operator and assembly). Results based on these factors alone demonstrate that AM technology offers the potential to match more traditional manufacturing methods on a direct-cost basis for low and intermediate levels of production (that is, up to and above 100,000 units). Figure 2 presents data from an Italian study of the production of a nonflammable, plastic, small electrical component.

**Figure 2. Direct-cost breakdown for a small, nonflammable, plastic electrical component using IM and AM[35]**




| | IM@20K | AM | IM@100K |
|---|---|---|---|
| Assembly | € 0.035 (1.2%) | € 0.012 (1.0%) | € 0.035 (3.0%) |
| Operator | € 0.009 (0.3%) | € 0.117 (9.9%) | € 0.004 (0.3%) |
| Material | € 0.011 (0.4%) | € 0.360 (30.4%) | € 0.011 (1.0%) |
| Machine | € 0.042 (1.4%) | € 0.694 (58.7%) | € 0.024 (2.1%) |
| Tooling | € 2.900 (98.8%) | € - (0.0%) | € 1.075 (93.6%) |
| Total | € 2.997 | € 1.183 | € 1.149 |

Assembly  Operator  Material  Machine  Tooling

Graphic: Deloitte University Press | DUPress.com

## USING AM TO DRIVE DIFFERENTIATION

Analytical studies of AM's direct costs are important, but they are also restricted in their view. From the perspective of Deloitte's AM framework, they are typically focused on the value that can be derived solely on "path I." With limited exception, they tend to ignore the kinds of supply chain and product innovations that can lead to greater value delivery. Furthermore, senior executives know that direct costs seldom tell the whole story. Customers (business or consumer) purchase products to "do a job."[36] They are increasingly likely to assess the full life-cycle cost of that product when making a choice. Finally, Deloitte's research on exceptional companies demonstrates that companies trying to achieve sustained superior performance should focus on being better before they focus on being cheaper.[37] With that in mind, AM offers potential higher-value-added opportunities to companies that choose to leave path I to pursue performance, innovation, and growth along paths II, III, and IV of the AM framework.

### *Time is of the essence*

Product life cycles are decreasing, and design cycles are accelerating.[38] Performance trade-offs related to speed over different segments of the business cycle are, therefore, worth considering as part of the overall AM business case.

*Those charged with exploring the trade-offs between AM and more traditional manufacturing approaches will want to consult with their colleagues in finance to study the implications of depreciation and tax incentives on the overall business case.*

Economic studies of AM rarely focus on the production speed of the technology relative to more traditional methods. However, the issue is routinely cited by managers as important to their consideration of AM as a production technology.[39] AM can be perceived as slow, particularly in the case of single-object builds. Evidence suggests that these perceptions may be valid. For example, one investigation analyzed the production of 85 assorted components out of stainless steel using a direct metal laser sintering (DMLS) process. After optimizing build volume using a packing algorithm, researchers were able to produce the basket of objects in approximately 108 hours—or 76 minutes per part.[40] Managers need to consider their own contexts when determining whether such processing times are acceptable. In making that judgment, managers should remember that the resulting parts are produced to "near net shape," in a single process, and that all steps related to casting, machining, and other equivalent processing (including delays between steps) for more traditional approaches should be considered. Managers should also think about the precise role that production speed must play in the production sequence, and how to balance production speed with delivery speed and other potential benefits.

Speed is important for delivery as well as production. Given shorter product life cycles and increasing global competition, speed to market and prompt delivery may

be crucial determinants of customer value. Where traditional production methods may require centralized, even offshore, production (where transit times can stretch into weeks or months), the ability to take advantage of superior scale economics may position AM-enabled manufacturers to respond more quickly to customer demand. For example, the elimination of tooling can substantially reduce time to market by eliminating delay while the tooling itself is created.[41] Time to market may also be accelerated through faster design iteration. Where individual customization



PHOTO: HIROSHI WATANABE/GETTY IMAGES

## THE ECONOMICS OF 3D PRINTING AT HOME

An interesting study by researchers at Michigan Technological University examined the return on investment (ROI) of 3D printing at home.[49] The study focused on a commonly used AM device (RepRap) that creates plastic parts using an extrusion-based process.[50]
To conduct the study, the researchers selected 20 objects, including shower curtain rings, a garlic press, a spoon rest, and a stand for a tablet computer, which are available on a popular website that provides open source designs for AM,[51] and they checked online shopping services to obtain price information for comparable items.[52]

The researchers calculated the total cost of production (materials, energy, machine cost) for each of their additively manufactured items and compared those costs to the comparable item's purchase price. They assumed only the production of those 20 items during each year of AM device operation.

The total energy and materials cost of these 20 items came to $18.11, compared with retail prices of $312.03–1,943.83.[53] The researchers used these values to compute payback periods for the AM device between four months (when using the higher retail prices) and two years (when using the lower retail prices). ROIs were estimated using both a three-year and a five-year lifetime for the AM device.[54] Using the lower retail prices as a comparison, ROI ranged between 20–40 percent. ROI for the higher retail price comparison exceeded 200 percent for both three- and five-year lifetimes.

The researchers conclude that additive manufacturing of simple plastic components already represents an attractive financial trade-off for US households. With as little as a single day's printing of simple household items, the designs, which are among the more than 100,000 available for free download, more than justify the cost of the device. As these devices continue to improve in quality, availability, and cost, home use of AM may very well become a mass-market application of the technology.

is required, savings of up to 85 percent in logistical steps and energy consumption have been documented.[42] Market responsiveness may also be improved through accelerated product modification and changeover, due to reductions in tooling use.[43] In addition to improved responsiveness and cost savings, market risk may be reduced where an improved ability to make minor product adjustments results in greater market acceptance.

### *Creating value by designing for AM*

Venturing beyond path I in our AM framework also means taking advantage of the inherent scope and flexibility of the AM technology set. A simple "apples-to-apples" comparison on part design may be inappropriate. Studies that allow for the possibility of component redesign offer evidence of significant value delivery. For example, in aerospace applications, industry executives claim the ability to leverage AM can reduce component weight by 30–55 percent and eliminate up to 90 percent of material used.[44] In a specific example, one airline manufacturer redesigned a generic bracket to make use of AM capabilities. The resulting component was estimated to save 22 pounds per aircraft.[45] As reference, in 2008, Northwest Airlines estimated that a 25-pound reduction in the weight of an airplane on international routes was worth approximately $440,000 per year in cost savings.[46] Importantly, AM components in these applications are qualified as performing as well as their traditionally manufactured counterparts.[47]

*In summary, AM lets designers focus on supporting the intended function of an object rather than on its manufacturability.*

In summary, AM lets designers focus on supporting the intended function of an object rather than on its manufacturability.[48] Managers should carefully consider the implications of product redesign, with or without attempting supply chain reconfiguration, in order to truly understand where AM represents a viable production technology and where it does not.

## A FEW KEY DYNAMICS

AM offers companies an opportunity to innovate within their production environment. Managers should consider seven dynamics as they evaluate the business case for AM:

1. Begin with a focus on relatively small, complex, plastic components. It is in this realm of production that the most substantial evidence exists that cost-efficient production using AM can supplant more traditional manufacturing methods.
2. Remain open to applications for larger and metallic components. This is particularly true for applications that, using traditional manufacturing methods, use high-cost materials, involve high buy-to-fly ratios, or involve high levels of machining.

3. Tooling is fundamental and may shift the calculus toward AM due to its expense, flexibility, and impact on time to market. Even if traditional tooling is justified for large production runs, it may be feasible to deploy AM technology for either product introduction or product support, allowing tooling to be recycled or discarded rather than tracked and stored.
4. Watch materials costs. Consider business cases where material costs can be dramatically reduced. In particular, evaluate circumstances where vendor-supplied materials may be required and where they may not.
5. Develop a clear picture of the financial implications of new technology investment. Machine costs dominate the direct-cost model for AM. Seek advice on depreciation and tax incentives.
6. Adopt a broad perspective on time. Before deciding AM is "slow," consider the full production cycle involved in traditional methods, including latency between production steps. Also consider time to market and delivery lead times as a crucial part of the value proposition.
7. Aggressively pursue product innovation based on AM flexibility. Talented designers may find ways to redesign components to reduce material used while maintaining or improving product performance. Redesign can help offset typically higher AM raw material costs and add substantial life-cycle value for customers.

AM is not a panacea. There is no reason to view it as a universal replacement for traditional manufacturing methods. However, there is an important role for these technologies in the constellation of manufacturing methods that managers can deploy in pursuit of performance improvement, innovation, and growth. DR

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Endnotes


1. According to the Math Forum hosted by Drexel University, the exact weight of a gallon of water is 8.33 pounds (http://mathforum.org/library/drmath/view/56355.html, accessed April 13, 2014).
2. David Churchill, "The weighting game," *Business Travel World*, 2008, pp. 21–22.
3. A full investigation of the impact of "better" and "cheaper" on the company's ability to achieve sustained, superior profitability can be found in Michael Raynor and Mumtaz Ahmed, *The Three Rules: How Exceptional Companies Think* (New York: Portfolio/Penguin, 2013). Also see The Exceptional Company collection <http://dupress.com/collection/the-exceptional-company/> from Deloitte University Press.
4. See sidebar for formal definition according to ASTM International, "Standard terminology for additive manufacturing technologies" (designation: F2792−12a), 2013, p. 2. For an overview of additive manufacturing processes and technology, see Mark J. Cotteleer, Jonathan Holdowsky, and Monica Mahto, *The 3D opportunity primer: The basics of additive manufacturing,* Deloitte University Press, March 2014, <http://dupress.com/articles/the-3d-opportunity-primer-the-basics-of-additive-manufacturing/>
5. According to multiple industry reports, the general rate of growth in the sales of AM equipment and services is historically 25.4 percent. Forecasts for industry growth over the next decade are between 18 and 34 percent; see Wohlers Associates, "Additive manufacturing and 3D printing state of the industry," Morgan Stanley Global Research *Blue Paper on Cap Goods,* September 5 2013; J.P. Morgan, *Stratasys, Ltd., Combination with Objet creates 3D printer leader*, North American Equity Research, January 18, 2013.
6. For a full explanation of Deloitte's additive manufacturing framework, see Mark Cotteleer and Jim Joyce, "3D opportunity: Additive manufacturing paths to performance, innovation, and growth," *Deloitte Review* issue 14, January 2014, <http://dupress.com/articles/dr14-3d-opportunity/>
7. N. Hopkinson and P. Dickens, "Analysis of rapid manufacturing: Using layer manufacturing processes for production," proceedings of the Institution of Mechanical Engineers, part C, *Journal of Mechanical Engineering Science* 217, pp. 31–39.
8. Eleonora Atzeni, Luca Iuliano, Paolo Minetola, and Alessandro Salmi, "Redesign and cost estimation of rapid manufactured plastic parts," *Rapid Prototyping Journal* 16, no. 5 (2010): pp. 308–17.
9. Jeff Allen, "An investigation into the comparative costs of additive manufacturing vs. machine from solid for aero engine parts," Cost Effective Manufacturing via Net-Shape Processing, meeting proceedings RTO-MP-AVT-139, paper 17, Neuilly-sur-Seine, France, pp. 17-1–17-10.
10. H. S. Byun and K. H. Lee, "A decision support system for the selection of a rapid prototyping process using the modified TOPSIS method," *International Journal of Advanced Manufacturing Technology* no. 26 (2005): pp. 1338–47.
11. Ibid.
12. Credit Suisse Equity Research Report on additive manufacturing, September 17, 2013.
13. For more detail on the relative strengths and weaknesses of each of these technologies, see Cotteleer, Holdowsky, and Mahto, "The 3D opportunity primer."
14. See, for example, Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts"; Cassandra Telenko and Carolyn Conner Seepersad, "A comparative evaluation of energy consumption of selective laser sintering and injection molding of nylon parts," *Rapid Prototyping Journal* 18, no. 6 (2012): pp. 472-481; Hopkinson and Dickens, "Analysis of rapid manufacturing."
15. V. Saxena (panel chair), "The industrialization of additive manufacturing (AM): Challenges and opportunities for aerospace," panel discussion at the 2nd Annual Aerospace Manufacturing Conference, Mobile, AL, April 1, 2014.
16. See, for example, Telenko and Seepersad, "A comparative evaluation of energy consumption;" Hopkinson and Dickens, "Analysis of rapid manufacturing."
17. Hopkinson and Dickens, "Analysis of rapid manufacturing."
18. Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts."
19. C. Lindemann, U. Jahnke, M. Moi, and R. Koch, "Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing," proceedings of the 23rd Annual International Solid Freeform Fabrication Symposium, University of Texas, August 6–8, 2012.
20. For a deeper discussion on the impacts of AM on tooling for manufacturing, see Mark J. Cotteleer, Mark Neier, and Jeff Crane, *3D opportunity in tooling: Additive manufacturing shapes the future*, Deloitte University Press, April 7, 2014, <http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-tooling>
21. See, for example, Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts"; Hopkinson and Dickens, "Analysis of rapid manufacturing;" Lindemann et al., "Analyzing product lifecycle costs" for a better understanding of cost drivers in additive manufacturing.
22. Recall that, by its very definition, AM works "layer by layer." Within a layer, material (plastic, metal, or other) may be treated with a variety of chemical or energy-based processes in order to create a solid object. The point being made here is that the percentage of the layer that is being processed tends not to influence the overall speed, and therefore cost, of creating the object. See M. Baumers, C. Tuck, R. Wildman, I. Ashcroft, E. Rosamond, and R. Hague, "Combined build-time energy consumption and cost estimation for direct metal laser sintering," proceedings of the 23rd Annual International Solid Freeform Fabrication Symposium, University of Texas, August 6–8, 2012.
23. Ibid. We note that there is some complexity involved in the process of packing the production envelope. Some AM processes require that the object being formed has contact with the "build plate" upon which it rests, in order to promote proper heat dissipation. The complexities of envelope packing should clearly be among the factors discussed with system providers as part of the selection process.
24. Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts"; M. Ruffo, C. Tuck, and R. Hague, "Cost estimation for rapid manufacturing: Laser sintering production for low to medium volumes," proceedings of the I MECH E Part B, *Journal of Engineering Manufacture* 220, no. 9: pp. 1417–1427.

25. Hopkinson and Dickens, "Analysis of rapid manufacturing."
26. Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts"; Hopkinson and Dickens, "Analysis of rapid manufacturing."
27. Wohlers Associates, "Additive manufacturing and 3D printing state of the industry," 2013, Morgan Stanley Research, September 2013; J.P. Morgan, January 2012.
28. Ibid.
29. See, respectively, Allen, "An investigation into the comparative costs of additive manufacturing"; Telenko and Seepersad, "A comparative evaluation of energy consumption."
30. Hopkinson and Dickens, "Analysis of rapid manufacturing."
31. "Buy to fly" refers to a ratio defined by the size of an original billet to that of the finished part that is flown on an aircraft (that is, how much material do you start with versus how much material is in the finished part). See Allen, "An investigation into the comparative costs of additive manufacturing;" R. Dehoff, C. Duty, W. Peter, Y. Yamamoto, W. Chen, C. Blue, and C. Tallman, "Case study: Additive manufacturing of aerospace brackets," *Advanced Materials and Processes*, March 2013, pp. 19–22.
32. Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts"; Lindemann et al., "Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing."
33. Lindemann et al., "Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing."
34. Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts." As a secondary factor, however, investments in training and development may be required in order to take advantage of the broader design opportunities that AM offers. Such considerations may be important in the evaluation of a transition to AM production environments.
35. Ibid.
36. Clayton Christensen and Michael Raynor, *The Innovator's Solution: Creating and Sustaining Successful Growth* (Boston: Harvard Business School Press, 2003).
37. Of course, being both "better" and "cheaper" at the same time is always to be valued but is seldom achievable in the real world. For a deeper understanding of the keys to sustained superior profitability, see Raynor and Ahmed, *The Three Rules*; and The Exceptional Company collection on Deloitte University Press <http://dupress.com/collection/the-exceptional-company>
38. R. McGrath and S. Cliffe, "When your business model is in trouble," *Harvard Business Review* 89, no. 1/2 (2011): pp. 96–98; Hopkinson and Dickens, "Analysis of rapid manufacturing."
39. S. H. Khajavi, J. Partanen, and J. Holmström, "Additive manufacturing in the spare parts supply chain," *Computers in Industry* 65, no. 1 (2014): pp. 50–63; Byun and Lee, "A decision support system for the selection of a rapid prototyping process."
40. Products ranged in size from 9 x 9 x 30 millimeters to 127 x 76 x 52 millimeters, ranged in volume from 960 to 96,645 cubic millimeters, and were selected to be "representative of the products commercially manufactured using DMLS and to reflect variation in product size, geometry, and application." See Baumers et al., "Combined build-time energy consumption and cost estimation for direct metal laser sintering."
41. Cotteleer, Neier, and Crane, *3D opportunity in tooling*; Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts."
42. Lindemann et al., "Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing."
43. Hopkinson and Dickens, "Analysis of rapid manufacturing"; Lindemann et al., "Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing."
44. Churchill, "The weighting game."
45. EOS, "EOS and Airbus group innovations team on aerospace sustainability study for industrial 3D printing," *Business Wire* (English), April, accessed April 13, 2014.
46. Churchill, "The weighting game."
47. See, for example, Dehoff et al., "Case study: Additive manufacturing of aerospace brackets"; Atzeni et al., "Redesign and cost estimation of rapid manufactured plastic parts."
48. Lindemann et al., "Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing."
49. B. T. Wittbrodt et al., "Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers," *Mechatronics* 23, no. 6 (2013): pp. 713–726.
50. The specific machine used for the study was a Prusa Mendel RepRap machine, with an estimated cost (for 2013) of approximately $575.
51. To see the selection from which the researchers chose, go to <http://www.thingiverse.com/>
52. The author takes pains to note that shipping costs, particularly for low-value items, often represent a substantial portion of total costs. Nonetheless, shipping costs have been excluded in the interest of conservatism in the results.
53. In an effort to be conservative, the researchers also incorporate a 20 percent "print failure rate" to account for circumstances where an object needs to be recreated due to quality issues.
54. The machine life is important because it determines the period over which the cost of the AM device itself must be amortized. In this case, the authors note that the expected machine life is much longer than three years, particularly in light of the fact that the RepRap is capable of printing out approximately 57 percent of its own replacement parts.