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ORIGINAL ARTICLE

Costs, benefits, and adoption of additive manufacturing: a supply chain perspective

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Abstract There are three primary aspects to the economics of additive manufacturing: measuring the value of goods produced, measuring the costs and benefits of using the technology, and estimating the adoption and diffusion of the technology. This paper provides an updated estimate of the value of goods produced. It then reviews the literature on additive manufacturing costs and identifies those instances in the literature where this technology is cost-effective. The paper then goes on to propose an approach for examining and understanding the societal costs and benefits of this technology both from a monetary viewpoint and a resource consumption viewpoint. The final section discusses the trends in the adoption of additive manufacturing. Globally, there is an estimated $667 million in value added produced using additive manufacturing, which equates to 0.01 % of total global manufacturing value added. US value added is estimated as $241 million. Current research on additive manufacturing costs reveals that it is cost-effective for manufacturing small batches with continued centralized production; however, with increased automation distributed production may become cost-effective. Due to the complexities of measuring additive manufacturing costs and data limitations, current studies are limited in their scope. Many of the current studies examine the production of single parts and those that examine assemblies tend not to examine supply chain effects such as inventory and transportation costs along with decreased risk to supply disruption. The additive manufacturing system and the material costs constitute a significant portion of an additive manufactured product; however, these costs are declining over time. The current trends in costs and benefits have resulted in this technology representing 0.02 % of the relevant manufacturing industries in the USA; however, as the costs of additive manufacturing systems decrease, this technology may become widely adopted and change the supplier, manufacturer, and consumer interactions. An examination in the adoption of additive manufacturing reveals that for this technology to exceed $4.4 billion in 2020, $16.0 billion in 2025, and $196.8 billion in 2035, it would need to deviate from its current trends of adoption.

Keywords Additive manufacturing · Manufacturing · Supply chain

1 Introduction

In 2013, the world produced approximately $11.8 trillion in manufacturing value added, according to United Nations Statistics Division (UNSD) data [28]. Many products and parts made by the industry are produced by taking pieces of raw material and cutting away sections to create the desired part or by injecting material into a mold; however, a relatively new process called additive manufacturing is beginning to take hold. Additive manufacturing is the process of joining materials to make objects from three-dimensional (3D) models layer by layer as opposed to subtractive methods that remove material. The terms additive manufacturing and 3D printing tend to be used interchangeably to describe the same approach to fabricating parts. This technology is used to produce models, prototypes, patterns, components, and parts using a variety of materials including plastic, metal, ceramics, glass, and composites. Products with moving parts can be printed such that the pieces are already assembled.

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Technological advances have even resulted in a 3D-Bio-printer, which can print skin and other types of tissue [14, 15].

Additive manufacturing is used by multiple industry subsectors, including automotive, aerospace, machinery, electronics, and medical products [37]. This technology dates back to the 1980s with the development of stereolithography, which is a process that solidifies layers of liquid polymer using a laser. The first additive manufacturing system available was the SLA-1 by 3D Systems. Technologies that enabled the advancement of additive manufacturing were the desktop computer and the availability of industrial lasers. Additionally, 3D scanning technologies have enabled the replication of real objects without using expensive molds or recreating parts in a CAD system.

The associated costs and slow print speed of additive manufacturing systems often hinder this technology from being used for mass production; however, as these issues improve, this technology may change the way that consumers interact with producers. Additive manufacturing allows the manufacture of customized and increasingly complex parts. This customization of products will require increased data collection from the end user to determine their preferences, resulting in a new relationship between manufacturer and consumer. This technology has an additional impact on this relationship, as 3D printers create the opportunity for the consumer to produce their own products. An inexpensive 3D printer allows the end user to produce polymer-based products in their own home or office, and there are a number of systems that are within the budget of the average consumer.

There are three primary aspects to the economics of additive manufacturing: measuring the value of goods produced, measuring the costs and benefits of using the technology, and estimating the adoption and diffusion of the technology. This paper provides an updated estimate of the value of goods produced. It then reviews the literature on additive manufacturing costs and identifies those instances in the literature where this technology is cost-effective. The paper then goes on to propose an approach for examining and understanding the societal advantage of this technology both from a monetary viewpoint and a resource consumption viewpoint. The final section discusses the trends in the adoption of additive manufacturing. Although this paper tends to focus on additive manufacturing in the USA, it draws upon research that was conducted in a number of other locations, and many of the findings are applicable to the U.S. and abroad. It is also important to note that this article references current capabilities and potential future capabilities of additive manufacturing. For example, there is some discussion regarding this technology's ability to produce assembled products in one build; however, the current state of technology provides some limit on this ability. This technology is rapidly changing; therefore, it is important to consider future possibilities.

2 Value of additive manufacturing goods produced

Wohlers estimates the 2014 revenue from additive manufacturing worldwide to be \$4.103 billion; however, the estimate that is most consistent with the measure of shipments used in the economic census is the estimate for service providers. Wohlers estimates that there was \$1.307 billion from the sale of parts produced by additive manufacturing systems in 2014 with the USA accounting for \$498 million [37]. Estimating value added requires subtracting off the materials, machinery, and other intermediate goods that were purchased for production. Value added is the increase in the value of output at a given stage of production; that is, the value of output minus the cost of inputs from other firms [13]. Macroeconomics. 8th ed. London, UK: McGraw-Hill. The primary elements that remain after subtracting inputs are taxes, compensation to employees, and gross operating surplus; thus, the sum of these also equal to value added. Wohlers estimates that material sales amounted to \$640 million in 2014; thus, an estimate of global value added for additive manufacturing can be estimated by taking the \$1.307 billion less the \$640 million for materials, totaling \$667 million. This equates to 0.01 % of total global manufacturing value added.[1] US value added for additive manufacturing is estimated as \$241 million, as seen in Table 1. Products are categorized as being in the following sectors: motor vehicles; aerospace; industrial/business machines; medical/dental; government/military; architectural; and consumer products/electronics, academic institutions, and other. The consensus among well-respected industry experts is that the penetration of the additive manufacturing market is 8 % [36]; however, as seen in Table 1, goods produced using additive manufacturing methods represent between 0.01 and 0.11 % of their relevant industry subsectors. Thus, additive manufacturing has sufficient room to grow.

3 Additive manufacturing costs

3.1 Literature review

There are two major motivational categories for examining additive manufacturing costs. The first is to compare additive manufacturing processes to other traditional processes such as injection molding and machining. The purpose of these types of examinations is to determine under what circumstances

[1] This value is calculated with the assumption that the U.S. share of additive manufacturing systems sold equates to the share of products produced using additive manufacturing systems. The share of additive manufacturing systems is available in Wohlers, Terry. "Wohlers Report [36]: Additive Manufacturing and 3D Printing State of the Industry." Wohlers Associates, Inc. 2012: 134.

Table 1 US additive manufacturing shipments and value added, [37]

Category	Relevant NAICS codes	Shipments of US-made AM products ($millions, 2014)*	Total US shipments ($millions, 2014)	AM share of industry shipments	Total value added ($millions, 2014)[a]	AM value added ($millions, 2014)	AM share of value added
Motor vehicles	NAICS 3361, 3362, 3363	80.17	550,798	0.01 %	153,662	22	0.01 %
Aerospace	NAICS 336411, 336412, 336413	73.70	200,645	0.04 %	101,877	37	0.04 %
Industrial/business machines	NAICS 333	87.14	400,466	0.02 %	194,861	42	0.02 %
Medical/dental	NAICS 3391	65.23	96,864	0.07 %	65,306	44	0.07 %
Government/military	NAICS 336414, 336415, 336419, 336992	32.87	30,422	0.11 %	5151	6	0.11 %
Architectural	NAICS 3323	15.93	78,730	0.02 %	38,770	8	0.02 %
Consumer products/electronics, academic, and other	All other within NAICS 332 through 339	142.92	929,447	0.02 %	530,488	82	0.02 %
TOTAL	NAICS 332 through 339	498.0	2,287,373	0.02 %	1,090,117	241	0.02 %

[a] These values are calculated assuming that the percent of total additive manufacturing made products for each industry is the same for the US as it is globally. It is also assumed that the US share of AM systems sold is equal to the share of revenue for AM products. Note: Numbers may not add up to total due to rounding

additive manufacturing is cost-effective. The second category involves identifying resource use at various steps in the additive manufacturing process. The purpose of this type of analysis is to identify when and where resources are being consumed and whether there can be a reduction in resource use. Table 2 provides a literature list for cost studies on additive manufacturing categorized by additive manufacturing processes and materials from Wohlers [36].

Due to conflicting results, there are two cost models that receive significant attention in additive manufacturing: (1) Hopkinson and Dickens and (2) Ruffo et al. [7, 19, 32]. The cost of additive manufactured parts are calculated by Hopkinson and Dickens based on calculating the average cost per part and three additional assumptions: (1) the system produces a single type of part for 1 year, (2) it utilizes maximum volumes, and (3) the machine operates for 90 % of the time. The analysis includes labor, material, and machine costs. Other factors such as power consumption and space rental were considered but contributed less than 1 % of the costs; therefore, they were not included in the results. The average part cost is calculated by dividing the total cost by the total number of parts manufactured in a year. Costs can be broken into machine costs, labor costs, and material costs. Calculations are made for two parts, a lever and a cover, using three different additive manufacturing technologies: stereolithography, fused deposition modelling, and laser sintering. A cost breakout for the lever is provided in Fig. 1, which shows that in this analysis, laser sintering was the cheapest additive manufacturing process for this product. Machine cost was the major contributing cost factor for stereolithography and fused deposition modeling, while the material cost was the major contributor for laser sintering. It is important to note that although it is a significant proportion of the total cost, machine costs decreased by 42 % between 2001 and 2013, as seen in Fig. 2. In addition to Hopkinson and Dickens, a number of other studies examine the costs of additive manufacturing. Many of these studies also identify machine and material costs as major cost factors. Other cost factors include build orientation, envelope utilization, build time, energy consumption, product design, and labor.

Hopkinson and Dickens estimate an annual machine cost per part where the machine completely depreciates after 8 years; that is, it is the sum of depreciation cost per year (calculated as machine and ancillary equipment divided by 8) and machine maintenance cost per year divided by production volume. The result is a cost per part that is constant over time, as seen in Fig. 3. Also seen in the figure is a comparison to Ruffo, Tuck, and Hague's model, discussed below.

The cost of additive manufactured parts is calculated by Ruffo et al. using an activity-based cost model, where each cost is associated with a particular activity. They produce the same lever that Hopkinson and Dickens produced using selective laser sintering. In their model, the total cost of a build (C), is the sum

Table 2 Literature on the costs of additive manufacturing

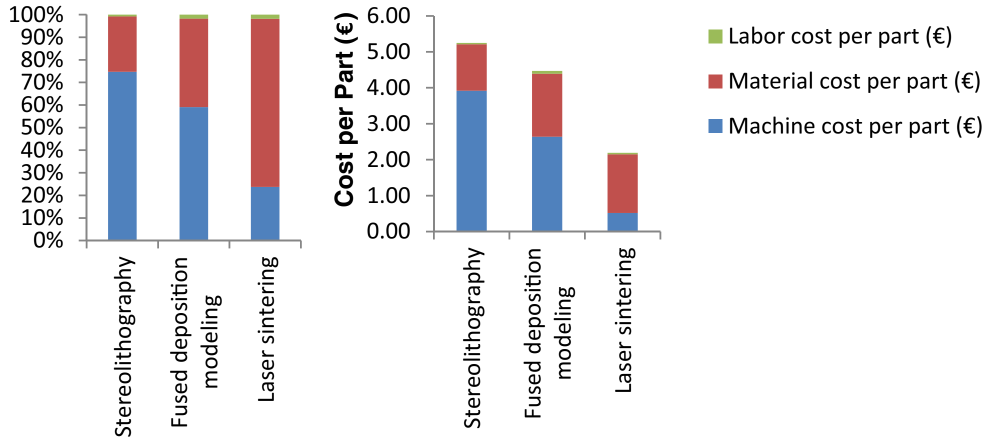
	Material extrusion	Material jetting	Binder jetting	Vat photopoly-merization	Sheet lamination	Powder bed fusion	Directed energy deposition	Additive manufacturing research that includes traditional manufacturing
Polymers, polymer blends, and composites	T.A. Grimm [16][a]; Hopkinson and Dickens [19]; Hopkinson [18]; Baumers [7])	T.A. Grimm [16][a]	T.A. Grimm [16][a]	T.A. Grimm [16][a]; Hopkinson and Dickens [19]; Hopkinson [18]; Li [24])	T.A. Grimm [16][a]	Ruffo, Tuck, and Hague [32]; Baldinger and Duchi [6]; Ruffo and Hague [31]; Hopkinson and Dickens [19]; Hopkinson [18]; Baumers [7]; Zhang and Bernard [38]; Atzeni et al. [4]		Hopkinson [18]; Ruffo, Tuck, and Hague [32]; Ruffo and Hague [31]; Hopkinson and Dickens [19]; Atzeni et al. [4]; [24])
Metals		×	×		×	Rickenbacher et al. [30]; Baumers et al. [8]; Baumers [7]); Baumers et al. [9]; Atzeni, Iuliano and Salmi [2]; Atzeni and Salmi [5]; Lindemann et al. [25]; Lindemann et al. [26]	×	Allen [1]
Graded/hybrid metals					×		×	
Ceramics			×	×		×		
Investment casting patterns		×	×	×		×		
Sand molds and cores	×		×			×		
Paper					×			
Undesignated Material						Khajavi et al. [21]		

Source: Thomas [34]

× indicates possible combinations of materials and processes where no cost literature is identified

[a] 3D Printing

Fig. 1 Cost breakout [19]



of raw material costs and indirect costs. The raw material costs are the price ($P_{material}$), measured in euros per kilogram, multiplied by the mass in kilograms (M). The indirect costs are calculated as the total build time (T) multiplied by a cost rate ($P_{indirect}$). The total cost of a build is then represented as:

$$C = P_{material}{}^{*}M + P_{indirect}{}^{*}T$$

The cost per part is calculated as the total cost of a build (C) divided by the number of parts in the build. Ruffo et al. indicate that the time and material used are the main variables in the costing model. It was assumed that the machine worked 100 h/week for 50 weeks/year (57 % utilization). The estimated indirect cost per hour is shown in Table 3.

There are three different times that are calculated in the model of Ruffo et al.: (1) "time to laser scan the section and its border in order to sinter"; (2) "time to add layers of powder"; and (3) "time to heat the bed before scanning and to cool down slowly after scanning, adding layers of powder or just waiting time to reach the correct temperature." The sum of these times is the build time (T), and the resulting cost model along with Hopkinson and Dickens model is shown in Fig. 3. The Ruffo et al. model has a jagged saw tooth shape to it, which is due to the impact of a new line, layer, or build. Each time one of these is added, average costs increase irregularly from raw material consumption and process time. Ruffo et al. estimates are slightly higher than the Hopkinson and Dickens estimate of €2.20 for laser sintering. Ruffo et al. also conducted an examination where unused material was recycled. In this examination, the per-unit cost was slightly less than the Hopkinson and Dickens estimate.

Many of the cost studies assume a scenario where one part is produced repeatedly; however, one of the benefits of additive manufacturing is the ability to produce different components simultaneously. Therefore, a "smart mix" of components in the same build might achieve reduced costs. In a single part reproduction, the per-part cost for a build is the total cost divided by the number of parts; however, the cost for different parts being built simultaneously is more complicated. Ruffo and Hague

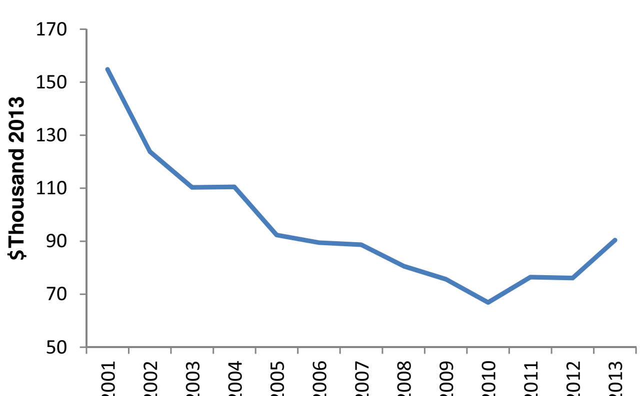


Fig. 2 Average selling price of a professional-grade industrial Additive manufacturing system. Wohlers, Terry. "Wohlers Report [37]: Additive Manufacturing and 3D Printing State of the Industry." Wohlers Associates, Inc. 2014

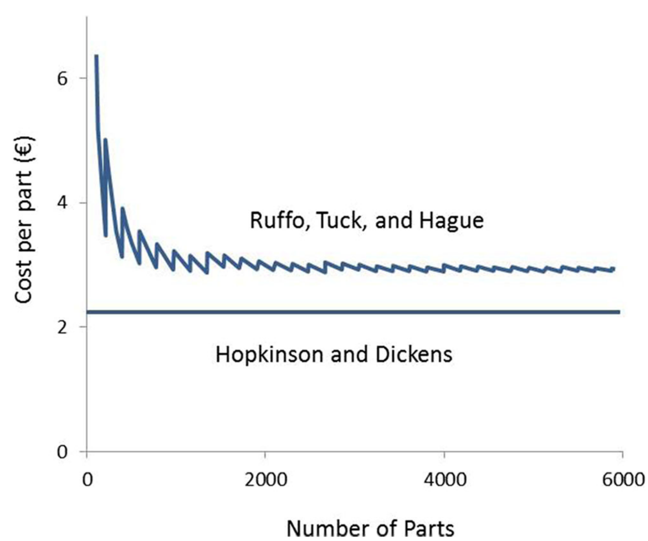


Fig. 3 Cost model comparison (Ruffo, Tuck, and Hague vs. Hopkinson and Dickens). Adapted from Ruffo et al. and Hopkinson and Dickens

Table 3 Indirect cost activities

Activity	Cost/h (€)
Production labor/machine hour	7.99
Machine costs	14.78
Production overhead	5.90
Administrative overhead	0.41

Source: Ruffo, Tuck, and Hague [32]

compare three costing methodologies for assessing this cost [32]. The first method is based on parts volume where

$$Cost_{p_i} = \left(\frac{V_{p_i}}{V_B}\right)*Cost_B$$

Where
$\mathrm{Cos}t_{Pi}$=cost of part i
V_{Pi}=volume of part i
V_B=volume of the entire build

$$\mathrm{Cost}_B = \sum \frac{indirect\_cost}{working\_time}\left(t_{xy}+t_z+t_{HC}\right) + \frac{direct\_cost}{mass\_unit} m_B$$

m_B=mass of the planned production proportional to the object volumes, and the time to manufacturing the entire build t_{xy}=time to laser-scan the section and its border to sinter powder. t_z=time to add layers of powder, t_{HC}=time to heat the bed before scanning and to cool down after scanning and adding layers of powder i=an index going from one to the number of parts in the build $Cost_B$ also equals C from above, which is the total cost of a build. The second method is based on the cost of building a single part and is represented as the following:

$$Cost_{Pi} = \frac{Y_i*\mathrm{Cost}_B}{n_i}$$

where

$$Y_i = \frac{\mathrm{Cost}^*_{P_i} + n_i}{\sum\left(\mathrm{Cost}^*_{P_i}*n_j\right)}$$

Also, i is the index of the part being calculated, j is the index for all parts manufactured in the same bed, n_i is the number of parts identified with i, and $Cost^*_{P_i}$ is the cost of a single part i estimated using the earlier equation for C. The third method is based on the cost of a part built in high volume. It is similar to the second method, only the cost variables in γ_i are calculated using a high number of parts rather than a single part. It is represented as the following:

$$\mathrm{Cost}_{P_i} = \frac{\gamma_i{}^{\infty}*\mathrm{Cost}_B}{n_i}$$

Where

$$\gamma_i{}^{\infty} = \frac{\mathrm{Cost}^{\infty}_{P_i} + n_i}{\sum_j\left(\mathrm{Cost}^{\infty}_{P_i}*n_j\right)}$$

Where $\mathrm{Cost}^{\infty}_{P_i}$ is a hypothetical number, which approaches infinity, of manufactured parts i.

Ruffo and Hague use a case study to evaluate the validity of estimating the per-part cost with the results suggesting that only the third model provides a “fair assignment method.” The other two were identified as being inappropriate due to the result drastically reducing the estimated cost of larger components at the expense of smaller parts.

A number of other papers also examine additive manufacturing costs with many suggesting that additive manufacturing tends to be cost-effective for low batch runs. Hopkinson and Dickens estimates for their sample part that additive manufacturing is cost-effective for volumes of up to between 6000 and 14,000, depending on the additive manufacturing system. Ruffo et al. estimated that the same part was cost-effective for production runs of up to between 9000 and 10,500. Atzeni examined the production of a landing gear assembly and estimated that additive manufacturing is cost-effective for production runs of up to 42 [2].There have been three proposed alternatives for the diffusion of additive manufacturing discussed in the literature. The first is where a significant proportion of consumers purchase additive manufacturing systems or 3D printers and produce products themselves [29]. The second is a copy shop scenario, where individuals submit their designs to a service provider that produces goods [29]. The third scenario involves additive manufacturing being adopted by the commercial manufacturing industry, changing the technology of design and production. One might, however, consider a fourth scenario. Because additive manufacturing can produce a final product in one build, there is limited exposure to hazardous conditions, and there is little hazardous waste [20]. There is the potential to bring production closer to the consumer for some products (i.e., distributed manufacture). For example, currently, a more remote geographic area may order automotive parts on demand, which may take multiple days to be delivered. Additive manufacturing might allow some of these parts or products to be produced near the point of use or even onsite [17]. Further, localized production combined with simplified processes may begin to blur the line between manufacturers, wholesalers, and retailers as each could potentially produce products in their facilities.

Khajavi et al. compare the operating cost of centralized additive manufacturing production and distributed production, where production is in close proximity to the consumer [21]. This analysis examined the production of spare parts for the air-cooling ducts of the environmental control system for the F-18 Super Hornet fighter jet, which is a well-documented instance where additive manufacturing has already been implemented. The expected total cost per year for centralized production was between \$1.0 million and \$1.8 million for distributed production. Inventory obsolescence cost, initial inventory production costs, inventory carrying costs, and spare parts transportation costs are all reduced for distributed production; however, significant increases in personnel costs and the initial investment in additive manufacturing machines make it more expensive than centralized production. Increased automation and reduced machine costs are needed for this scenario to be cost-effective. It is also important to note that this analysis examined the manufacture of a relatively simple component with little assembly. One of the benefits of additive manufacturing is to produce an assembled product rather than individual components. Research by Holmström et al., which also examines spare parts in the aircraft industry, concurs that currently, on demand centralized production of spare parts is the most likely approach to succeed; however, if additive manufacturing develops into a widely adopted process, the distributed approach becomes more feasible [17].

3.2 Societal advantage of additive manufacturing

At the company level, the goal is to maximize profit; however, at the societal level there are multiple stakeholders to consider and different costs and benefits. At this level, one might consider the goal to be to minimize resource use and maximize utility. Dollar values are affected by numerous factors such as scarcity, regulations, and education costs among other things that impact how efficiently resources are allocated. The allocation of resources is an important issue; however, understanding the societal impact of additive manufacturing requires separating issues in resource allocation from resource utilization. This section discusses two approaches to examining additive manufacturing at the societal level. First, it discusses it from a monetary cost perspective. It then provides an approach to measuring it from a resource consumption perspective.

3.2.1 Monetary cost perspective

As discussed by Young, the costs of production can be categorized in two ways [33]. The first involves those costs that are "well-structured" such as labor, material, and machine costs. The second involve "ill-structured costs" such as those associated with build failure, machine setup, and inventory. Many of the current cost studies examine well-structured costs such as material and machine costs, which account for a significant portion of additive manufacturing production. Additionally, these studies tend to examine the production of single parts with those that examine assemblies tending to neglect examining supply chain effects such as inventory and transportation costs; however, many of the benefits may be hidden in inventory and the supply chain. For instance, a dollar invested in automotive assembly takes 10.9 days to return in revenue. It spends 7.9 days in material inventory, waiting to be utilized. It spends 19.8 h in production time and another 20.6 h in downtime when the factory is closed. Another 1.3 days is spent in finished goods inventory. Moreover, of the total time used, only 8 % is spent in actual production. According to concepts from lean manufacturing, inventory and waiting, which constitute 92 % of the automotive assembly time, are two of seven categories of waste. This is just the assembly of an automobile. The production of the engine parts, steering, suspension, power train, body, and others often occur separately and also have inventories of their own. Additionally, all of these parts are transported between locations. The average shipment of manufactured transportation equipment in the USA travels 801 miles. This amounts to 45.3 billion ton-miles of transportation equipment being moved annually. At the beginning of 2013, there were \$605 billion in inventories in the manufacturing industry, which was equal to 10 % of that year's revenue. The resources spent producing and storing these products could have been used elsewhere if the need for inventory were reduced.

Because additive manufacturing can potentially build an entire assembly in one build, it reduces the need for some of the transportation and inventory costs, resulting in impacts throughout the supply chain. Therefore, in order to understand the cost difference between additive manufacturing and other processes, it is necessary to examine the costs from raw material extraction to production and through the sale of the final product. This might be represented as:

$$\begin{aligned} C_{AM} = & \left(MI_{R,\,AM} + MI_{M,\,AM}\right) \\ & + \left(P_{E,\,AM} + P_{R,\,AM} + P_{M,\,AM}\right) \\ & + \left(FGI_{E,\,AM} + FGI_{R,\,AM} + FGI_{M,\,AM}\right) + WT_{AM} \\ & + RT_{AM} + T_{AM} \end{aligned}$$

Where

C_{AM}=cost of producing an additive manufactured product

MI=cost of material inventory for refining raw materials (*R*) and for manufacturing (*M*) for additive manufacturing (*AM*)

P=cost of the process of material extraction (*E*), refining raw materials (*R*), and manufacturing (*M*), inclusts, machine costs, and other relevant costs for additive manufacturing (*AM*)

FGI=cost of finished goods inventory for material extraction (*E*), refining raw materials (*R*), and manufacturing (*M*) for additive manufacturing (*AM*)

WT_{AM}=cost of wholesale trade for additive manufacturing (*AM*)

RT_{AM}=cost of retail trade for additive manufacturing (*AM*)

T_{AM}=transportation cost throughout the supply chain for an additive manufactured product (*AM*)

This could be compared to the cost of traditional manufacturing, which could be represented as the following:

$$C_{Trad} = \left(MI_{R,\ Trad} + MI_{\ I,\ Trad} + MI_{A,\ Trad}\right) + \left(P_{E,\ Trad} + P_{R,\ Trad} + P_{I,\ Trad} + P_{A,\ Trad}\right) + \left(FGI_{E,\ Trad} + FGI_{R,\ Trad} + FGI_{I,\ Trad} + FGI_{A,\ Trad}\right) + WT_{Trad} + RT_{Trad} + T_{Trad}$$

Where

C_{Trad}=cost of producing a product using traditional processes (*Trad*)

MI=cost of material inventory for refining raw materials (*R*), producing intermediate goods (*I*), and assembly (*A*) for traditional manufacturing (*Trad*)

P=cost of the process of material extrtion (*E*), refining raw materials (*R*), producing intermediate goods (*I*), and assembly (*A*), including administrative costs, machine costs, and other relevant costs for traditional manufacturing (*Trad*)

FGI=cost of finished goods inventory for material extraction (*E*), refining raw materials (*R*), producing intermediate goods (*I*), and assembly (*A*) for traditional manufacturing (*Trad*)

WT_{Trad}=cost of wholesale trade for traditional manufacturing (*Trad*)

RT_{Trad}=cost of retail trade for traditional manufacturing (*Trad*)

T_{Trad}=transportation costs throughout the supply chain for a product made using traditional manufacturing (*Trad*)

Currently, there is a better understanding about the cost of the additive manufacturing process cost (P_{AM}) than there is for the other costs for this process. Additionally, most cost studies examine a single part or component; however, it is in an assembled product where additive manufacturing might have significant cost savings. Traditional manufacturing has numerous intermediate products that are transported and assembled, whereas additive manufacturing can complete an assembly in a single build. For example, consider the possibility of an entire engine being made in one build using additive manufacturing compared to an engine that has parts made and shipped for assembly from different locations with each location having its own factory, material inventory, finished goods inventory, administrative staff, and transportation infrastructure among other things. Additionally, the engine might be made using less material, run more efficiently, and last longer because the design is not limited to the methods used in traditional manufacturing; however, many of these benefits would not be captured in the previously mentioned cost model. To capture these benefits one would need to include a cradle to grave analysis.

A partial example of the approach using traditional manufacturing is shown in Table 4, which provides a breakdown of the source of costs for a generic $100 steering/suspension component made in USA. These values were calculated using input–output analysis of benchmark input–output Data from the Bureau of Economic Analysis.[2] It also utilizes labor data from the Bureau of Labor Statistics [10]. This example excludes imported supply chain goods for this component and focuses on domestic resources that are consumed. Imported values are a relatively small percentage of the total US manufacturing activity. In terms of 2009 imported supply chain value added used by a nation's manufacturing industry, USA imported 10.8 % of its supply chain [35]. These imports require natural resources and utilize labor; thus, they are important in regard to a firm's production. However, tracking the resources used for them poses significant challenges.

In Table 4, columns A through H provide compensation data by occupation (listed at the top of the table) by industry category (listed on the left of the table). It is important to note that this is a summary table of the data, as there are over 300 industry categories and over 800 occupation categories, resulting in over 200,000 combinations. In Table 4, column I is the sum of compensation, as indicated at the top of the table (i.e., I=A+B+…H), while column L is the sum of compensation, taxes, and gross operating surplus. The table sums both horizontally and vertically; thus, the total of $100 is at the bottom right of the table. The costs are broken into six stages of production on the left (i.e., raw material extraction, material refining, automotive parts, other manufacturing, and the final stage of producing the vehicle steering/suspension component). The values for each of these stages includes onsite inventory of materials and finished goods along with production. Seven other separate categories of cost are also listed in the table, including transportation and wholesale trade. Transportation costs, including transportation purchased (listed as the seventh row down) and transportation employees (column G "transportation and material moving") is $4.86 (i.e., the sum of 2.02 and 3.65 less 0.80, which is subtracted to avoid double counting) of the steering/suspension component or 4.86 %. Purchased warehousing/storage and wholesale trade was 0.31 and 7.25 %, respectively.

If the generic component shown in Table 4 were produced using additive manufacturing, it might reduce some of the intermediate part costs. For example, it might not require screws, bolts, or intermediate assemblies. This reduction might subsequently eliminate some transportation and wholesale costs, which together amount to 12.1 % of the total.

[2] The methods used are documented in Thomas, Douglas and Anand Kandaswamy. "Tracking industry operations activity: a case study of US automotive manufacturing." NIST Special Publication 1601. Forthcoming. And Thomas, Douglas and Anand Kandaswamy. "Inventory and flow time in the US manufacturing industry." NIST Technical Note. Forthcoming.

Table 4 Average costs for a $100 automobile steering/suspension component using traditional manufacturing methods

Compensation by Category									Value Added and Components			
	A Professional and management	B Building and grounds	C Office and admin	D Construction and extraction	E Installation, maintenance, and repair	F Production occupations	G Transportation and material moving	H Other	I=A+B+…H Compensation of employees	J Taxes on production and imports, less subsidies	K Gross operating surplus	L=I+J+K Value added estimated
Raw material extraction (metals	0.02	0.00	0.00	0.02	0.02	0.01	0.01	0.00	0.08	0.03	0.26	0.37
Material refining	1.20	0.02	0.43	0.15	0.62	3.02	0.32	0.00	5.75	0.38	3.89	10.02
Intermediate parts	1.31	0.02	0.57	0.08	0.19	2.76	0.16	0.00	5.09	0.16	3.30	8.55
Automotive parts	0.73	0.00	0.16	0.04	0.14	1.24	0.10	0.00	2.41	0.08	0.91	3.40
Other manufacturing	1.40	0.01	0.41	0.03	0.20	1.44	0.15	0.00	3.64	0.22	3.12	6.98
Vehicle steering/suspension system	7.36	0.04	1.62	0.40	1.39	12.42	0.97	0.00	24.20	3.57	5.92	33.69
Transportation	0.15	0.00	0.13	0.03	0.10	0.02	0.80	0.00	1.23	0.07	0.72	2.02
Wholesale trade	1.14	0.01	1.65	0.02	0.21	0.12	0.46	0.00	3.61	1.48	2.16	7.25
Retail trade	0.06	0.00	0.16	0.00	0.06	0.00	0.02	0.00	0.31	0.12	0.12	0.54
Warehousing/storage	0.04	0.00	0.05	0.00	0.01	0.01	0.13	0.00	0.23	0.00	0.07	0.31
Nonmanufacturing energy	0.03	0.00	0.01	0.00	0.03	0.01	0.00	0.00	0.09	0.08	0.16	0.33
Other utilities	0.17	0.00	0.09	0.01	0.09	0.02	0.00	0.00	0.39	0.17	0.75	1.31
Other	9.67	0.33	3.33	0.29	0.43	0.27	0.53	0.97	15.82	1.04	8.37	25.22
TOTAL	23.27	0.42	8.63	1.08	3.48	21.33	3.65	0.97	62.83	7.41	29.76	100.00

Breaking out these supply chain costs allows for a better understanding of where large costs are located that might be affected by additive manufacturing. Unfortunately, gathering and estimating the supply chain costs for a specific component can be difficult and cost prohibitive, but these are costs that additive manufacturing may impact.

3.2.2 Resource consumption perspective

The factors of production are typically considered to be land (i.e., natural resources), labor, capital, and entrepreneurship; however, capital includes machinery and tools, which themselves are made of land and labor. Additionally, a major element in the production of all goods and services is time, as illustrated in many operations management discussions. Therefore, one might consider the most basic elements of production to be land, labor, human capital, entrepreneurship, and time. The human capital and entrepreneurship utilized in producing additive manufactured goods is important, but it is a complex issue that is not a focus of this paper. The remaining items land, labor, and time constitute the primary cost elements for production. It is important to note that there is a tradeoff between time and labor (measured in labor hours per hour). For example, it takes 100 people less time to build a house than it takes for 1 person to build a house. It is also important to note that there is also a tradeoff between time/labor and land (i.e., natural resources), as illustrated in Fig. 4. For example, a machine can reduce both the time and the number of people needed for production, but utilizes more energy. The triangular plane in the figure represents possible combinations of land, labor, and time needed for producing a manufactured good. It is important to note that this figure only illustrates that a tradeoff exists between time, labor, and natural resources and the relationship is not actually linear as shown in the figure. For some products, it may be a set of alternatives represented by points, while others may have a sliding scale such as the building of a house. Since there are many possible scenarios, a simple plane is used for this discussion. This tradeoff is a significant issue because productivity increases are often at the cost of natural resources. For example, productivity increases are often achieved by adopting machinery, which consumes natural resources such as raw material and energy; thus, productivity increases while sustainability decreases.

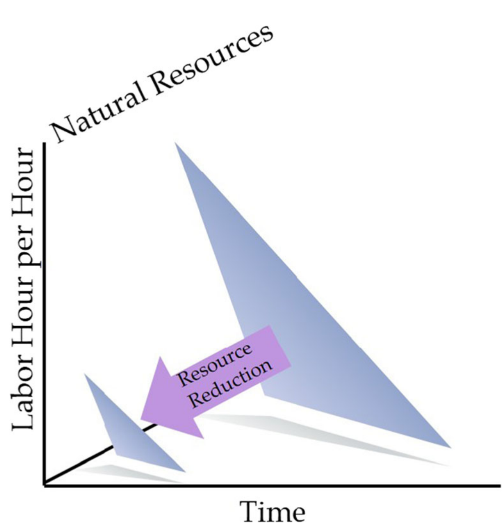


Fig. 4 Time, labor, and natural resources needed to produce a manufactured product

In Fig. 4, moving anywhere along the large plane represents utilizing alternative methods of production that are available at a given point in time. An alternative to selecting a current method is to develop a new method or improved method of production, which results in shifting the plane. From a societal perspective, the ideal shift would result in a reduction in time, labor, or natural resources without increasing the use of other resources, as illustrated in Fig. 4. If the introduction of additive manufacturing results in an ideal reduction in the resources needed for manufacturing, then the plane or some portion of it will move toward the origin. Alternatively, additive manufacturing may result in a tradeoff between time, labor, and natural resources.

In addition to the resources consumed in production, manufactured products often consume resources when they are being utilized. Goods are produced to serve a designated purpose. For example, automobiles transport objects and people; cell phones facilitate communication; and monitors display information. Each item produced is designed for some purpose, and in the process of fulfilling this purpose, more resources are expended in the form of land, labor, and time. Additionally, a product with a short life span results in more resources being expended to reproduce the product. Additionally, the disposal of the old product may result in expending further resources. Additive manufactured products may provide product enhancements, new abilities, or an extended useful life. The total advantage of an additive manufactured good is the difference in the use of land, labor, and time expended on production, utilization, and disposal combined with the utility gained from the product compared to that of traditional manufacturing methods. This can be represented as the following:

$$TA_L = \left(L_{AM,P} + L_{AM,U} + L_{AM,D}\right) - \left(L_{T,P} + L_{T,U} + L_{T,D}\right)$$

$$TA_{LB} = \left(LB_{AM,P} + LB_{AM,U} + LB_{AM,D}\right) - \left(LB_{T,P} + LB_{T,U} + LB_{T,D}\right)$$

$$TA_T = \left(T_{AM,P} + T_{AM,U} + T_{AM,D}\right) - \left(T_{T,P} + T_{T,U} + T_{T,D}\right)$$

$$TA_U = U(P_{AM}) - U(P_T)$$

TA=the total advantage of additive manufacturing compared to traditional methods for land (*L*), labor (*LB*), time (*T*), and utility of the product (*U*)

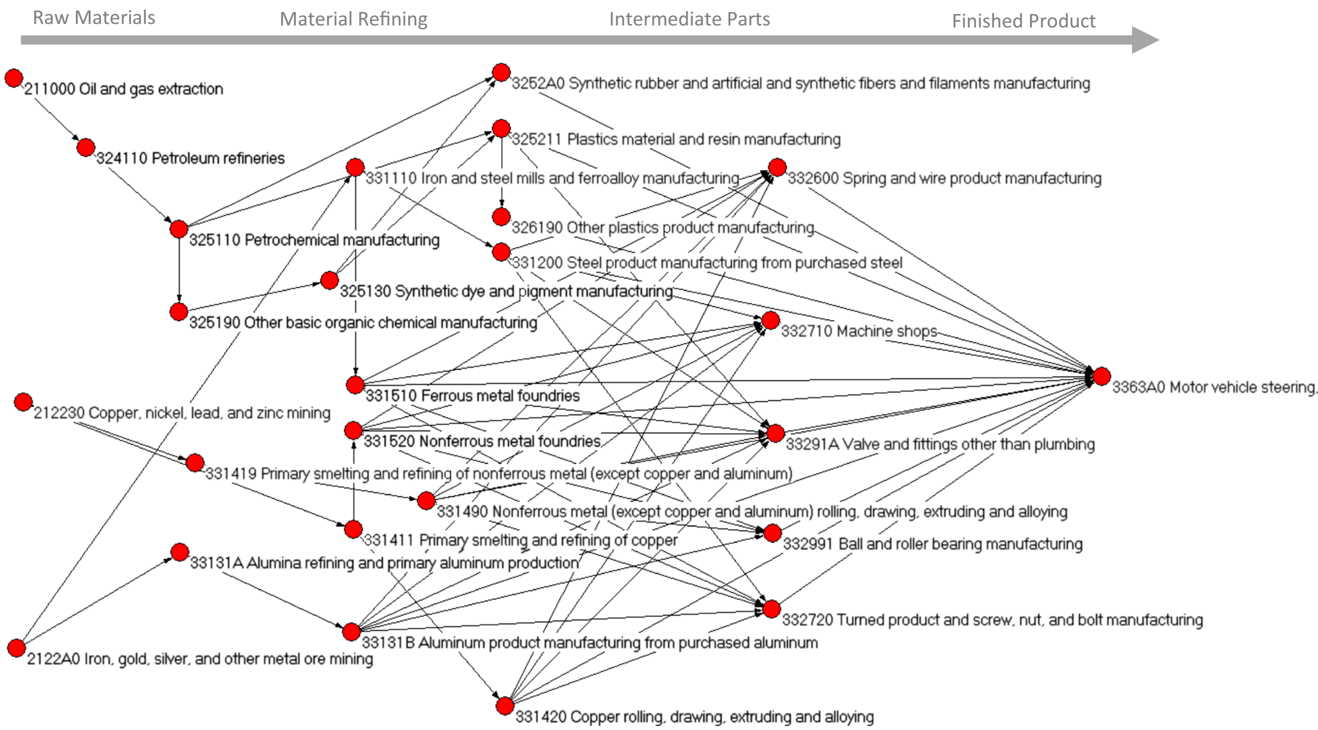


Fig. 5 Material supply chain for motor vehicle steering and suspension component

L=the land or natural resources needed using additive manufacturing processes (*AM*) or traditional methods (*T*) for production (*P*), utilization (*U*), and disposal (*D*) of the product

LB=the labor hours per hour needed using additive manufacturing processes (*AM*) or traditional methods (*T*) for production (*P*), utilization (*U*), and disposal (*D*) of the product

T=the time needed using additive manufacturing processes (*AM*) or traditional methods (*T*) for production (*P*), utilization (*U*), and disposal (*D*) of the product

$U(P_{AM})$=the utility of a product manufactured using additive manufacturing processes, including the utility gained from increased abilities, enhancements, and useful life.

$U(P_T)$=the utility of a product manufactured using traditional processes, including the utility gained from increased abilities, enhancements, and useful life.

In this case, production includes material extraction, material refining, manufacturing, and transportation among other things. Unfortunately, our current abilities fall short of being able to measure all of these items for all products; however, it is important to remember that these items must be considered when measuring the total advantage of additive manufacturing. An additional challenge is that land, labor, time, and utility are measured in different units, making them difficult to compare.

This approach might be partially illustrated using the previously discussed $100 steering/suspension component made using traditional manufacturing methods. Figure 5 provides a map of the supply chain for this generic component, which tracks the materials that makeup the final product; therefore, energy and services are not included in the map. These supply chain connections are based on the BEA benchmark input–output data. Each supply chain entity is labeled with a BEA NAICS code and description. For each of these supply chain components, the time, labor, and natural resources are provided in Tables 5 and 6. It is important to note that these are summary tables as there are over 300 industry categories and 800 labor categories. The time in days in Table 5 is broken into the time items spend in material inventory, work-in-process, work-in-process downtime when the factory is closed, and finished goods inventory. On average, the time spent in work-in-process is 13 % of the total time. The longest flow path through the supply chain is 604.6 days, as outlined in Table 7. Labor hours, shown in Table 6, is shown as per 1000 components. There is approximately 1657.41 h of labor per 1000 components or 1.66 h per component with approximately 0.70 h per component attributed to production activities.

Natural resource use, shown in Table 6, was developed using a suite of environmentally extended input–output databases for Life Cycle Assessments (LCA) developed under contract to NIST by Dr. Sangwon Suh of the Bren School of Environmental Science and Management at the University of California, Santa Barbara.[3] This data has been utilized in a

[3] This work is based on Suh, S. Developing a sectoral environmental database for input–output analysis: the comprehensive environmental data archive of the US, Eco. Sys. Research., 2005, 17: 4, 449–469.

Table 5 Time and labor hours for motor vehicle steering and suspension component

NAICS and Des cription		Time (days)					Labor hours (per 1000 components)					
		Materials and supplies Inventory	Work in process	Work-in-process (downtime)	Finished goods inventory	Total	Construction and extraction occupations	Installation, maintenance, and repair occupations	Production occupations	Transportation and material moving occupations	Other	TOTAL
211000	Oil and gas extraction					8.4	0.28	0.05	0.11	12 1.	05 1.	60
212230	Copper, nickel, lead, and zinc mining					45.6	0.25	0.17	0.10	0.08	0.15	0.76
2122A0	Iron, gold, silver, and other metal ore mining					38.7	0.51	0.35	0.21	0.17	0.32	1.57
324110	Petroleum refineries	7.2	2.3	4.1	10.5	24.1	0.03	0.05	0.25	0.04	0.21	0.58
325110	Petrochemical manufacturing	73.1	7.3	8.9	115.7	205.0	0.01	0.07	0.28	0.04	0.26	0.67
325130	Synthetic dye and pigment manufacturing	27.7	4.9	1.7	31.5	65.8	0.01	0.04	0.15	0.02	0.14	0.35
325190	Other basic organic chemical manufacturing	19.2	5.8	2.0	43.0	69.9	0.01	0.08	0.34	0.05	0.32	0.80
325211	Plastics material and resin manufacturing	15.6	5.5	0.7	37.9	59.7	0.02	0.19	0.99	0.08	0.65	1.93
3252A0	Synthetic rubber and artificial/synthetic fibers/filaments	13.9	4.5	1.4	31.8	51.7	0.01	0.07	0.37	0.03	0.24	0.73
326190	Other plastics product manufacturing	19.3	2.8	2.4	24.2	48.6	0.07	0.84	8.56	1.68	3.30	14.45
331110	Iron and steel mills and ferroalloy manufacturing	70.1	23.6	14.1	48.4	156.2	0.86	3.72	9.39	1.87	3.61	19.45
331200	Steel product manufacturing from purchased steel	37.4	9.7	5.8	24.3	77.3	0.23	0.84	5.86	1.02	2.32	10.27
33131A	Alumina refining and primary aluminum production	45.6	11.2	4.0	19.5	80.3	0.06	0.29	1.36	0.32	0.47	2.50
33131B	Aluminum product manufacturing from purchased aluminum	21.7	–	–	15.9	74.9	0.03	0.17	0.81	0.19	0.28	1.49
331411	Primary smelting and refining of copper	8.3	39.7	14.2	15.7	77.8	0.00	0.02	0.14	0.02 0.	07	0.25
331419	Primary smelting and refining of nonferrous metal	40.2	14.0	17.1	32.6	103.9	0.01	0.05	0.27	0.03	0.13	0.48
331420	Copper rolling, drawing, extruding and alloying	21.8	13.3	16.2	38.5	89.7	0.09	0.46	2.70	0.30	1.30	4.85
331490	Nonferrous metal rolling, drawing, extruding and alloying	42.3	28.6	34.8	28.6	134.4	0.04	0.22	1.27	0.14	0.61	2.27
331510	Ferrous metal foundries	16.9	4.9	5.9	19.3	46.9	0.71	5.13	46.30	2.57	11.18	65.88
331520	Nonferrous metal foundries	14.2	5.0	7.4	10.7	37.3	0.36	2.59	23.40	1.30	5.65	33.30
332600	Spring and wire product manufacturing	24.4	4.3	5.3	35.2	69.2	0.02	0.08	1.26	0.12	0.54	2.01
332710	Machine shops	16.8	13.2	16.5	28.2	74.7	0.37	1.56	42.53	1.43	13.07	58.94
332720	Turned product and screw, nut, and bolt manufacturing	19.2	7.6	15.6	30.2	72.5	0.09	0.61	12.50	0.79	4.53	18.52
33291A	Valve and fittings other than plumbing	48.1	11.9	24.6	54.7	139.3	0.25	0.75	10.48	0.83	5.55	17.86
332991	Ball and roller bearing manufacturing	80.9	31.1	64.1	90.3	266.3	0.24	0.73	10.18	0.81	5.39	17.35
3363A0	Motor vehicle steering, suspension component	15.7	2.4	3.3	11.1	32.5	7.14	30.03	370.27	31.57	139.55	578.56
Other		–	–	–	–	–	12.64	40.93	150.23	96.74	499.42	799.97
Total		–	–	–	–	–	24.34	90.12	700.28	142.4	700.3	1657.41

Table 6 Natural resources for motor vehicle steering and suspension component (per million components)

NAICS	and description	Natural resources: global warming (kg) CO2 eq	Acidification H+ moles eq	HH criteria air (kg) PM10 eq	Eutrophication (kg) N eq	Ozone depletion air (kg) CFC-11 eq	Smog air (kg) O3 eq	Ecotox CTUe	HH cancer CTUHcan	HH noncancer CTUHnoncan	Primary energy consumption thousand BTU	Land use acre	Water consumption (kg)
211000	Oil and gas extraction	552,006	444,763	4241	351.57	0.26	220,117	49,623	0.00	0.01	8,180,035	39.88	49,685,052
212230	Copper, nickel, lead, and zinc mining	310,483	128,873	1636	60.50	0.03	33,576	428,242	0.00	0.06	3,165,034	5.53	27,748,203
2122A0	Iron, gold, silver, and other metal ore mining	1,342,887	825,048	6376	555.65	0.29	303,504	255,411	0.01	0.65	13,473,405	49.41	101,762,902
324110	Petroleum refineries	3,571,065	894,161	5577	576.08	0.99	351,666	110,904	0.00	0.03	28,625,079	67.62	92,727,645
325110	Petrochemical manufacturing	3,571,065	894,161	5577	576.08	0.99	351,666	110,904	0.00	0.03	28,625,079	67.62	92,727,645
325190	Other basic organic chemical manufacturing	2,758,593	470,496	2363	272.78	8.70	132,908	821,667	0.00	0.06	20,533,192	246.18	134,150,922
325211	Plastics material and resin manufacturing	2,995,857	555,348	1990	312.79	10.08	170,901	432,648	0.00	0.06	23,549,720	139.59	105,192,646
3252A0	Synthetic rubber and artificial/synthetic fibers/filaments	686,048	181,366	797	95.49	7.79	46,876	2,744,030	0.00	0.03	5,822,165	85.61	79,930,826
326190	Other plastics product manufacturing	1,840,696	443,358	1366	223.19	5.86	123,899	387,733	0.00	0.05	18,600,448	358.11	108,528,689
331110	Iron and steel mills and ferroalloy manufacturing	41,256,498	5,232,727	18,555	2648.14	5.14	1,470,125	2,013,016	0.01	0.88	154,785,941	604.92	728,521,199
331200	Steel product manufacturing from purchased steel	4,135,777	577,469	1989	296.46	0.93	164,749	304,118	0.00	0.11	18,752,403	93.48	97,721,859
33131A	Alumina refining and primary aluminum production	2,635,347	1,137,465	2329	270.81	0.73	148,383	754,920	0.00	0.41	17,968,234	59.57	138,301,090
33131B	Aluminum products from purchased aluminum	850,696	228,222	553	73.27	0.28	42,156	149,880	0.00	0.07	5,596,641	30.51	35,845,552
331411	Primary smelting and refining of copper	407,842	294,493	685	56.95	0.12	32,010	376,739	0.00	0.06	4,021,522	17.01	25,382,540
331419	Primary smelting and refining of nonferrous metal	262,391	228,269	353	38.00	0.25	23,429	65,034	0.00	0.05	1,939,752	17.83	13,357,862
331420	Copper rolling, drawing, extruding and alloying	1,626,240	654,629	1608	217.60	1.15	121,750	856,309	0.00	0.13	15,130,516	132.15	104,287,435
331490	Nonferrous metal rolling/drawing/extruding/alloying	1,209,461	348,656	838	105.82	2.22	60,603	189,006	0.00	0.13	6,653,605	115.47	45,079,110
331510	Ferrous metal foundries	8,246,938	1,886,674	11,823	782.09	5.96	458,034	1,968,665	0.01	0.79	61,073,241	377.42	421,871,564
331520	Nonferrous metal foundries	6,065,393	338,273	3536	444.28	2.90	247,031	2,478,935	0.00	0.43	37,263,097	298.88	252,446,624
332600	Spring and wire product manufacturing	204,890	37,599	119	19.13	0.12	10,505	42,741	0.00	0.01	1,330,660	10.56	8,408,733
332710	Machine shops	1,897,401	442,575	1229	193.65	1.22	107,015	280,437	0.00	0.07	16,477,895	107.69	115,393,004
332720	Turned product and screw, nut, and bolt manufacturing	1,969,006	399,711	1079	183.21	1 3.42	101,723	206,029	0.00	0.06	13,581,277	90.65	94,911,029
33291A	Valve and fittings other than plumbing	1,447,527	352,711	980	150.03	1.30	83,372	312,036	0.00	0.06	11,121,964	94.17	83,019,622
332991	Ball and roller bearing manufacturing	1,268,995	271,775	731	121.94	1.28	68,305	104,649	0.00	0.03	9,754,647	54.66	66,775,836
3363A0	Motor vehicle steering, suspension component	9,309,671	2,113,683	6701	1068.71	11.75	541,141	3,590,903	0.00	0.36	68,423,211	1400.53	526,222,383
Other		76,598,365	25,137,039	83,314	13,277.52	87.38	6,896,372	36,779,393	0.04	2.44	727,347,560	33,900.59	5,597,988,981
Total		175,337,238	45,054,679	162,702	22,658.01	165.79	12,109,583	55,920,212	0.10	7.10	1,310,525,830	38,473.07	9,116,822,012

Table 7 Longest flow route for a $100 generic steering/suspension component

NAICS and description	Time (days)				
	Materials and supplies inventory	Work-in-process	Work-in-process (downtime)	Finished goods inventory	Total
211000 Oil and gas extraction					8.4
324110 Petroleum refineries	7.2	2.3	4.1	10.5	24.1
325110 Petrochemical manufacturing	73.1	7.3	8.9	115.7	205.0
325190 Other basic organic chemical manufacturing	19.2	5.8	2.0	43.0	69.9
325130 Synthetic dye and pigment manufacturing	27.7	4.9	1.7	31.5	65.8
325211 Plastics material and resin manufacturing	15.6	5.5	0.7	37.9	59.7
33291A Valve and fittings other than plumbing	48.1	11.9	24.6	54.7	139.3
3363A0 Motor vehicle steering/suspension	15.7	2.4	3.3	11.1	32.5
TOTAL	206.5	40.1	45.2	304.4	604.6

number of environmental efforts, including NIST's Building for Environmental and Economic Sustainability (BEES) and Building Industry Reporting and Design for Sustainability (BIRDS) tool. This data utilizes TRACI impact factors; therefore, there are 12 measures of environmental impacts: global warming, primary energy consumption, human health air pollutants, human health—cancer, water consumption, ecological toxicity,[4] eutrophication,[5] land use, human health—noncancer, smog formation, acidification, and ozone depletion. Other examinations may use alternative measures of natural resources, which may have different implications.

Producing the steering/suspension component using additive manufacturing may impact or eliminate multiple supply chain components. For example, it may eliminate or reduce the use of machine shops, screws and nuts, and valves and fittings in the supply chain for this component. Although it may be difficult or costly to track and compare the costs of an individual component through an entire supply chain, these items are potentially impacted by the adoption of additive manufacturing; therefore, a comprehensive understanding of the impacts necessitates examining these issues.

In this illustration, the time and labor required for the utilization of the product (i.e., driving time and driving labor) would be unchanged; therefore, it would be unnecessary to include it. However, an additive manufactured product may be lighter and requires less maintenance, thus there may be an increase in fuel efficiency and a decrease in maintenance. Table 8 provides the resources preserved from a potential 0.1 % increase in fuel efficiency and a 0.1 % decrease in maintenance for the production of 100 k automobiles with 25 mpg fuel efficiency. As much as 22,900 labor hours are preserved as a result of this moderate increase in efficiency. Some amount of natural resources are preserved, including impacts on the environment; however, the time is unchanged, as the time that it takes to drive from point A to point B would be unchanged from the adoption of additive manufacturing for this steering/suspension product.

To apply the method previously discussed, the per component labor hours would be calculated from Table 5 for traditional manufacturing (1.66 h per component) and added to the calculated per component labor hours from Table 8 (42.6 h per component for fuel plus 18.7 h for maintenance). This would equal the labor hours, which are potentially impacted by additive manufacturing, for production and utilization of this component. Similar calculations could be made for natural resources. This item could then be compared to that for additive manufacturing. The difference between the two would reveal the labor resources and natural resources that are preserved as a result of adopting additive manufacturing. Measuring time is slightly different since some activities occur in series while others are parallel, as seen in the map of the supply chain in Fig. 5; therefore, measures of time for each activity cannot simply be added together. Operations managers often examine the longest flow time, which for this case is shown in Table 7. Reducing this flow time would reduce the total time for producing this component. The time for utilizing this product (i.e., driving) is unchanged; thus, it is not examined. The utility experienced by the user (i.e., driver) for a steering/suspension component made using traditional methods provides the same utility as that of an additive manufactured component, as it does not change the driving experience; therefore, it is unnecessary to examine differences in utility.

4 Adoption and diffusion of additive manufacturing

In order to create products and services, a firm needs resources, established processes, and capabilities [22].

[4] The potential of a chemical released into the environment to harm terrestrial and aquatic ecosystems.

[5] The addition of mineral nutrients to the soil or water, which in large quantities can result in generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity

Table 8 Resource preservation for a 0.1 % increase in fuel efficiency and a 0.1 % reduction in maintenance

	Resources consumed for fuel production (100 k vehicles)[a]	Resources consumed for auto maintenance (100 k vehicles)[b]	Resources preserved per 100 k vehicles from fuel preservation[c]	Resources preserved per 100 k vehicles from maintenance reduction[d]	TOTAL resources preserved per 100 k vehicles
Natural Resources					
Global warming (kg) CO_2 eq	4,911,639,588	759,422,277	4,889,895	757,318	5,647,212
Acidification H+ moles eq	1,436,517,465	219,695,064	1,430,474	219,135	1,649,610
HH criteria air (kg) PM10 eq	9,364,747	607,214	9325	606	9931
Eutrophication (kg) N eq	958,507	99,719	954	99	1054
Ozone depletion air (kg) CFC-11 eq	1859.16	649.62	1.852	0.648	2.501
Smog air (kg) O_3 eq	581,746,689	52,726,498	579,293	52,600	631,893
ecotox CTUe	312,945,937	248,720,966	312,064	248,216	560,279
HH Cancer CTUHcan	3.2078	0.3608	0.003	0.000	0.004
HH Noncancer CTUHnoncan	59.3112	24.6879	0.059	0.025	0.084
Primary Energy BTU (1000s)	42,848,770,625	8,654,744,390	42,665,393	8,628,625	51,294,018
Land use (acre)	169,269.63	111,131.64	169	111	279.69
Water consumption (kg)	160,863,596,850	58,769,507,047	160,221,899	58,604,744	218,826,644
Labor (h)	4,261,302	18,683,499	4257	18,683	22,941
Production (h)	634,660	–	634	–	634
Maintenance/repair (h)	–	6,446,971	–	6,446,971	6,446,971
Other (h)	3,626,642	12,236,528	3623	12,237	15,860
Time (days)	–	–	0.00	0.00	0.00

[a] Calculated for a vehicle with 25 MPG fuel efficiency, 200 k mile lifespan, and an average fuel price of $2.77 per gallon

[b] Calculated for a vehicle with a 200 k mile lifespan, an average maintenance cost of $0.046 per mile as calculated by the American Automobile Association [3, 11]

[c] Reduction from a 0.1 % increase in fuel efficiency

[d] Reduction from a 0.1 % decrease in maintenance

Resources include natural resources, labor, and other items needed for production. A firm must have access to resources in order to produce goods and services. The firm must also have processes in place that transform resources into products and services. Two firms may have the same resources and processes in place; however, their products may not be equivalent due to quality, performance, or cost of the product or service. This difference is due to the capabilities of the firm, its ability to produce a good or service effectively. Kim and Park present three entities of capabilities (see Fig. 6): controllability, flexibility, and integration [23]. Controllability is the firm's ability to control its processes. Its primary objective is to achieve efficiency that minimizes cost and maximizes accuracy and productivity. Flexibility is the firm's ability to deal with internal and external uncertainties. It includes reacting to changing circumstances while sustaining few impacts in time, cost, or performance. According to Kim and Park, there is a tradeoff between controllability and flexibility; that is, in the short term, a firm chooses combinations of flexibility and controllability, sacrificing one for the other as illustrated in Fig. 7. Over time, a firm can integrate and increase both flexibility and controllability through a number of means, including technology or knowledge advancement. In addition to the entities of capabilities, there are categories of capabilities or a chain of capabilities, which include basic capabilities, process-level

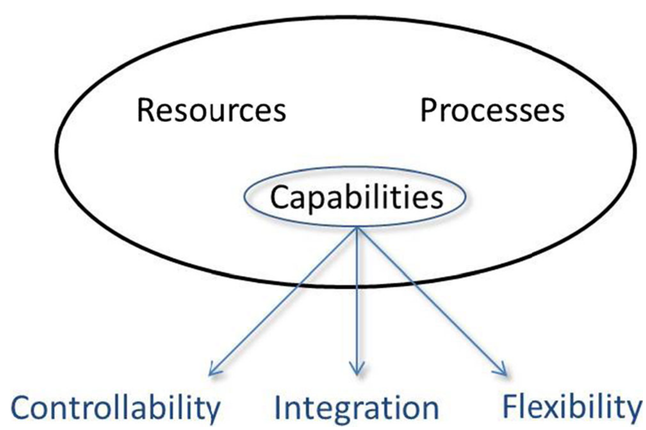


Fig. 6 Necessities of a firm. Adapted from Kim, Bowon and Chulsoon Park. [23]. "Firms' integrating efforts to mitigate the tradeoff between controllability and flexibility." International Journal of Production Research. 51(4): 1258–1278

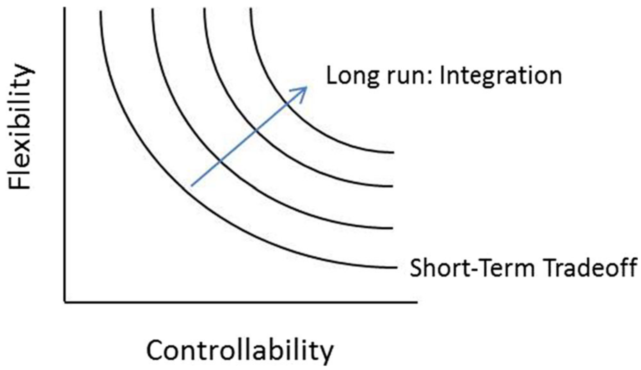


Fig. 7 Flexibility and controllability. Adapted from Kim, Bowon and Chulsoon Park. [23]. "Firms' integrating efforts to mitigate the tradeoff between controllability and flexibility." International Journal of Production Research. 51(4): 1258–1278

capabilities, system-level capabilities, and performance. As seen in Fig. 8, basic capabilities include overall knowledge and experience of a firm and its employees, including their engineering skills, safety skills, and work ethics among other things. Process-level capabilities include individual functions such as assembly, welding, and other individual activities. System-level capabilities include bringing capabilities together to transform resources into goods and services. The final item in the chain is performance, which is often measured in profit, revenue, or customer satisfaction among other things.

Adopting a new technology, such as additive manufacturing, can have significant impacts on a firm's capabilities. As discussed in the previous sections, in some instances, the per unit cost can be higher for additive manufacturing than for traditional methods. The result is that a firm sacrifices controllability for flexibility; thus, it makes sense for those firms that seek a high flexibility position to adopt additive manufacturing. In some instances, however, additive manufacturing can positively affect controllability. Additive manufacturing can reduce costs for products that have complex designs that are costly to manufacture using traditional methods. As the price of material and systems comes down for additive manufacturing, the controllability associated with this technology will increase, making it attractive to more firms.

In addition to the tradeoff between flexibility and controllability, additive manufacturing can also directly impact a firm's chain of capability, including the basic, process-level, and system-level capabilities. At the basic level, additive manufacturing requires new knowledge, approaches, and designs. These new knowledge areas can be costly and difficult to acquire. At the process-level, a firm that adopts additive manufacturing is abandoning many of its current individual functions to adopt a radically new production method. Former functions might have required significant investment in order to fully develop. Many firms may be apprehensive in abandoning these capabilities for a new process, which itself may require significant investment to fully develop. Finally, additive manufacturing can impact the system-level capability, as it is not only a process that affects the production of individual parts but also the assembly of the parts. All of these changes can make it costly and risky for a business to adopt additive manufacturing technologies and can result in reducing the rate at which this technology is adopted.

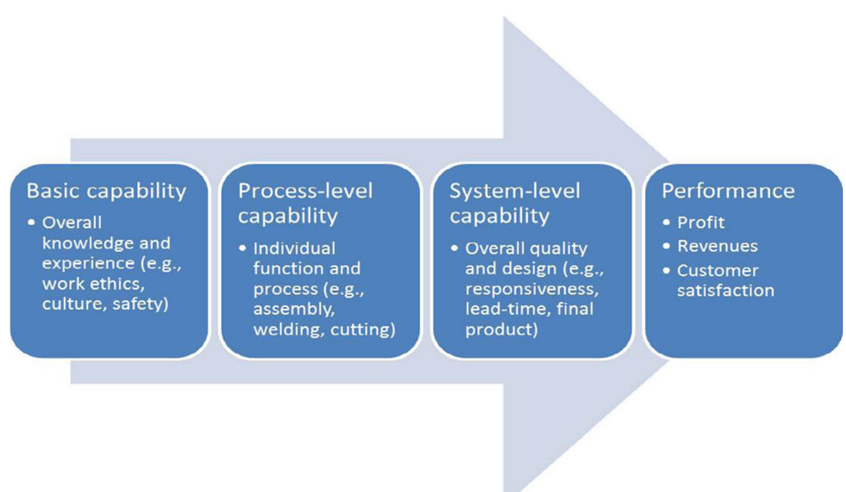
The future of additive manufacturing is unknown; however, it might be advantageous to conjecture about future adoptions using the trend in past adoptions. Using the number of domestic unit sales, [36] the growth in sales can be fitted using least squares criterion to an exponential curve that represents the traditional logistic S-curve of technology diffusion. The most widely accepted model of technology diffusion was presented by Mansfield [27]:

$$p(t) = \frac{1}{1 + e^{\alpha - \beta t}}$$

Where

$p(t)$=the proportion of potential users who have adopted the new technology by time t

Fig. 8 Chain of capability. Adapted from Kim, Bowon and Chulsoon Park. [23]. "Firms' integrating efforts to mitigate the tradeoff between controllability and flexibility." International Journal of Production Research. 51(4): 1258–1278



α=location parameter

β=shape parameter (β>0)

In order to examine additive manufacturing, it is assumed that the proportion of potential units sold by time t follows a similar path as the proportion of potential users who have adopted the new technology by time t. In order to examine shipments in the industry, it is assumed that an additive manufacturing unit represents a fixed proportion of the total revenue; thus, revenue will grow similarly to unit sales. The proportion used was calculated from 2014 data. The variables and β are estimated using regression on the cumulative annual sales of additive manufacturing systems in USA between 1988 and 2014. US system sales are estimated as a proportion of global sales. This method provides some insight into the current trend in the adoption of additive manufacturing technology. Unfortunately, there is little insight into the total market saturation level for additive manufacturing, that is, there is not a good sense of what percent of the relevant manufacturing industries (shown in Table 1) will produce parts using additive manufacturing technologies versus conventional technologies. In order to address this issue, a modified version of Mansfield's model is adopted from Chapman [12], National Institute of Standards and Technology:

$$p(t) = \frac{\eta}{1 + e^{\alpha - \beta t}}$$

Where

η=market saturation level

Because η is unknown, it is varied between 0.03 and 100 % of the relevant manufacturing shipments, as seen in Table 9. Figure 9 illustrates six of the trend estimates using the model. The R^2 value ranges between 0.95 and 0.97; thus, between 95 and 97 % of the variation in the growth of additive manufacturing is explained using this model. This suggests that additive manufacturing is, to some extent, following the S-curve model of diffusion. For this technology to exceed \$4.4 billion in 2020, \$16.0 billion in 2025, and \$196.8 billion in 2035, it would need to deviate from its current trends of adoption, as these are the maximum estimates in Table 9.

4.1 Summary and discussion

Globally, there is an estimated \$667 million in value added produced using additive manufacturing, which equates to 0.01 % of total global manufacturing value added. US value added for additive manufacturing is estimated as \$241 million. Current research on additive manufacturing costs reveals that this technology is cost-effective for manufacturing small batches with continued centralized manufacturing; however, with increased automation, distributed production may become cost-effective. Due to the complexities of measuring additive manufacturing costs, current studies are limited in their scope. Many of the current studies examine the production of single parts, and those that examine assemblies tend not to examine supply chain effects such as inventory and transportation costs along with decreased risk to supply disruption. Currently, research also reveals that material costs constitute a major proportion of the cost of a product produced

Table 9 Potential US additive manufacturing shipments based on past trends, by varying market saturation levels

Market potential of relevant manufacturing (percent of shipments)	Market potential, shipments (\$billions 2014)	Shipments in 2020 (\$billions 2014)	Shipments in 2025 (\$billions 2014)	Shipments in 2030 (\$billions 2014)	Shipments in 2035 (\$billions 2014)	R^2
100.00	\$2287.4	4.4	16.0	57.5	196.8	0.95
75.00	\$1715.5	4.4	16.0	57.0	191.3	0.95
50.00	\$1143.7	4.4	15.9	56.1	181.3	0.95
45.00	\$1029.3	4.4	15.9	55.8	178.1	0.95
40.00	\$914.9	4.4	15.9	55.4	174.4	0.95
35.00	\$800.6	4.4	15.8	54.9	169.8	0.95
30.00	\$686.2	4.4	15.8	54.3	164.0	0.95
25.00	\$571.8	4.4	15.7	53.5	156.5	0.95
20.00	\$457.5	4.4	15.6	52.3	146.5	0.95
15.00	\$343.1	4.4	15.4	50.4	132.4	0.95
10.00	\$228.7	4.3	15.1	47.0	111.1	0.95
5.00	\$114.4	4.3	14.2	39.0	74.8	0.95
1.00	\$22.9	3.8	9.6	16.6	20.7	0.95
0.50	\$11.4	3.3	6.8	9.7	10.9	0.95
0.15	\$3.4	2.0	2.9	3.3	3.4	0.95
0.05	\$1.1	1.0	1.1	1.1	1.1	0.96
0.03	\$0.7	0.6	0.7	0.7	0.7	0.97

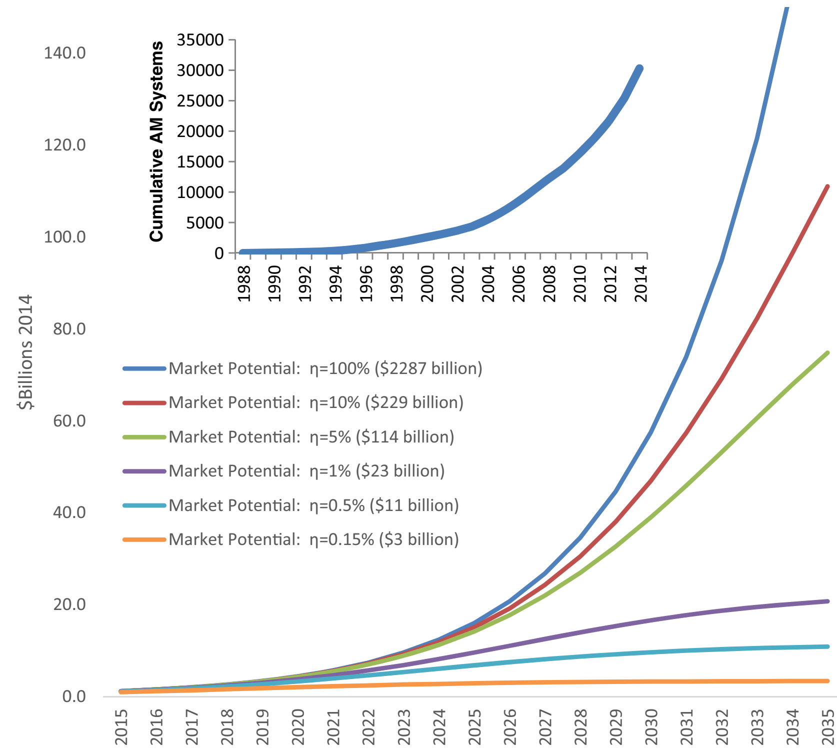


Fig. 9 Potential US additive manufacturing shipments based on past trends by varying market saturation levels

using additive manufacturing; however, technologies can often be complementary, where two technologies are adopted alongside each other and the benefits are greater than if they were adopted individually. Increasing adoption of additive manufacturing may lead to a reduction in raw material cost through economies of scale. The reduced cost in raw material might then propagate further adoption of additive manufacturing. There may also be economies of scale in raw material costs if particular materials become more common rather than a plethora of different materials. The additive manufacturing system is also a significant cost factor; however, this cost has continually decreased. Between 2001 and 2011, the average price decreased by 51 % after adjusting for inflation.

Additive manufacturing not only has implications for the costs of production but also the utilization of the final product. This technology allows for the manufacture of products that might not have been possible using traditional methods. These products may have new abilities, extended useful life, or reduce the time, labor, or natural resources needed to use these products. For example, automobiles might be made lighter to reduce fuel costs, or combustion engines might be designed to reduce cooling needs. For this reason, there is a need to track the land (i.e., natural resources), labor, and time expended on production, utilization, and disposal along with the utility gained from new designs. This paper discussed a supply chain approach to examining costs from a monetary cost perspective and a resource consumption perspective. The cost perspective examines supply chain costs in monetary values, while the resource perspective examines the time, labor, and natural resources used in production, utilization, and disposal of a product. The two approaches were illustrated, in part, using input–output analysis of a generic $100 steering/suspension component.

The adoption of additive manufacturing has increased significantly in recent years; however, in some instances, the per unit cost can be higher for additive manufacturing than for traditional methods. The result is that a firm sacrifices controllability for flexibility; thus, it makes sense for those firms that seek a high flexibility position to adopt additive manufacturing. In some instances, however, it is possible for additive manufacturing to positively affect controllability as well, as this technology can reduce costs for products that have complex designs that are costly to manufacture using traditional methods. As the price of material and systems comes down for additive manufacturing, the controllability associated with this technology will increase, making it attractive to more firms. In addition to the tradeoff between flexibility and controllability, additive manufacturing can also directly impact a firm's chain of capability, including the basic, process-level, and system-level capabilities. At the basic level, additive manufacturing requires new knowledge, approaches, and designs. These new knowledge areas can be costly and difficult to acquire. Examining current trends in adoption provides some limited insight. For this technology to exceed $4.4 billion in 2020, $16.0 billion in 2025, and $196.8 billion in 2035, it would need to deviate from its current trends of adoption.

Compliance with ethical standards

Disclaimer Certain trade names and company products are mentioned in the text in order to adequately specify the technical procedures and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

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