

› TNO: THE IMPACT OF 3-D PRINTING ON SUPPLY CHAIN MANAGEMENT

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› INTRODUCTION



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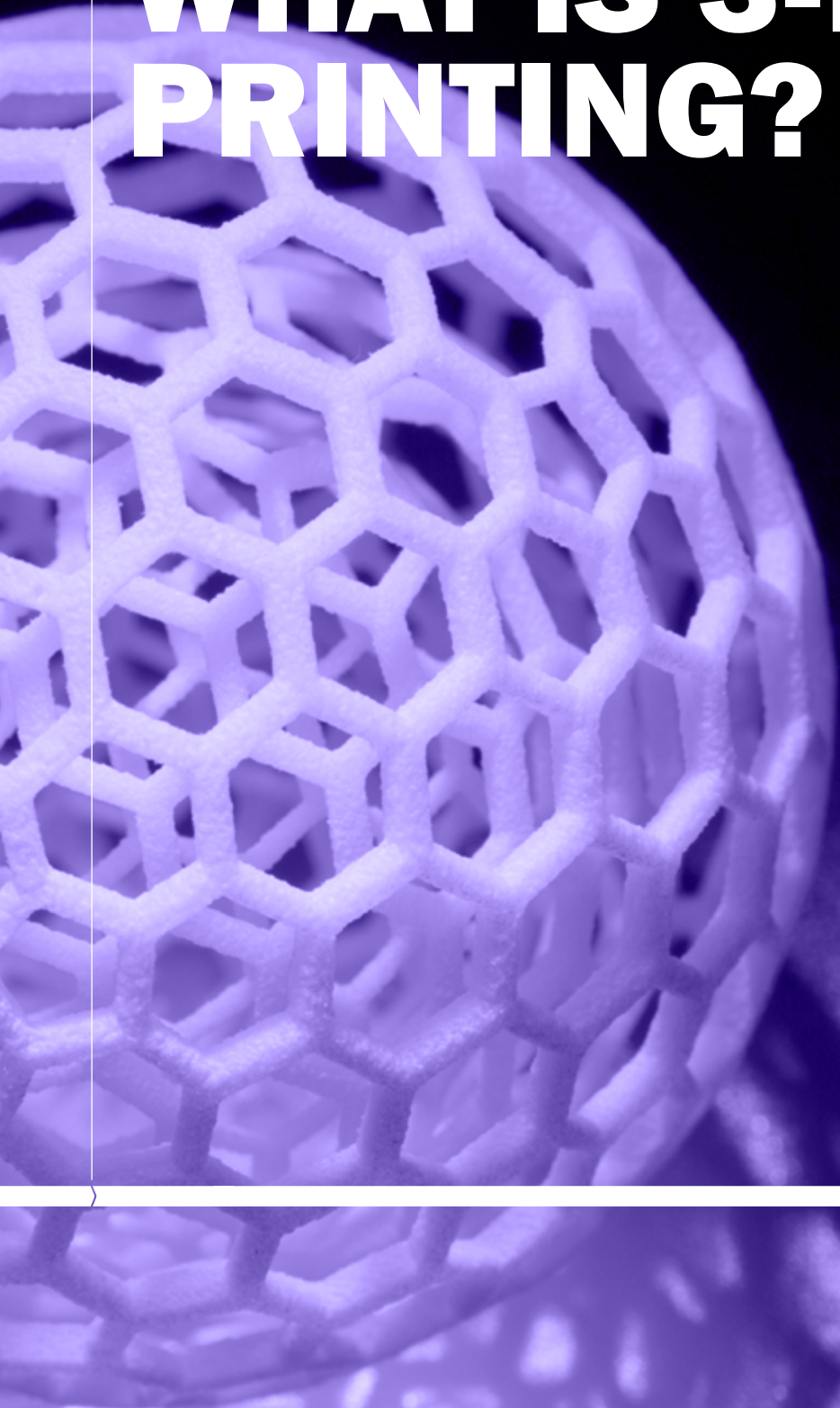
It is said that 3-D printing, officially known as additive manufacturing, has the potential to become the biggest single disruptive phenomenon to impact global industry since mass production lines were introduced early in the twentieth century. McKinsey Global Institute¹ named 3-D printing as one of the twelve disruptive technologies that will transform life, business and the global economy by 2025. With 3-D printing an idea can go directly from a design file to a product, skipping many traditional manufacturing steps. And manufacturing can take place anywhere in the world where the right printers are available. This might cause new businesses to emerge and well-established businesses to fail².

Manufacturing products using 3-D printing technology change the traditional approach to manufacturing completely, for instance by eliminating the need for expensive component assembly and the freedom to change product designs on the fly. Consequently, logistics operations and supply chain design will see pervasive changes. Consider, for example, where to stock materials if manufacturing can take place anywhere in the world. Or how operations processes will become much less complex if there's no need for component assemblies, but raw materials can be readily transformed to finished products instead. And how large quantities of 'containerized' sub-assemblies and components used as input materials are substituted for bulk-transported raw materials.

In this TNO White Paper we explore how 3-D printing impacts the design and management of global supply chains.

At TNO, we have years of experience in 3-D Printing. We rely on scientific expertise, process technology knowhow, and supply chain and economics intelligence to research and consult on 3-D Printing. For more detailed information: check out our website or read our TNO White Papers about 3-D Printing, available free of charge.

› WHAT IS 3-D PRINTING?



3-D printing is the “process of joining materials to make objects from 3-D model data, usually layer upon layer.”³ The digital model is generated using computer-aided design (CAD) software or 3-D scanners. The resulting model is then printed as a three-dimensional object in a 3-D printer from raw materials in either liquid or particle form. The 3-D printer deposits microscopically thin layers of the raw material, and the print gradually materializes as the layers are built up step by step. The amount of detail possible in a 3-D print is determined by the thinness of the layers, and the raw material can be anything from plastics, synthetic resin, to ceramic powder, metal, or even glass. Some 3-D printers can also combine various materials together in one end product.

Although Additive Manufacturing is the official term, it is more often referred to as 3-D printing and actually a multitude of different printing technologies are aggregated under the 3-D printing catchphrase.

In essence, 3-D printing is an innovation in manufacturing technology. Traditionally, products are produced using machining techniques which mostly rely on the removal of material by methods such as cutting, drilling, grinding, and sanding – these methods are considered subtractive processes. Also, component assembly is traditionally required to construct the full end-product. 3-D printing is achieved using an additive process, where successive layers of material are laid down in different shapes, adding the material on a layer upon layer basis. 3-D printing can successfully construct a product from a single piece of material, circumventing the need for component assembly. Even moving parts can be 3-D printed.

Finally, 3-D printing distinguishes itself by its inherent appeal of ‘home manufacturing’. For years 3-D printers came with a price tag that made them unaffordable to anyone outside big business, however this trend is quickly changing. As 3-D printers become gradually cheaper, consumers can buy a 3-D printer and design and produce one-off products from the comfort of their homes.

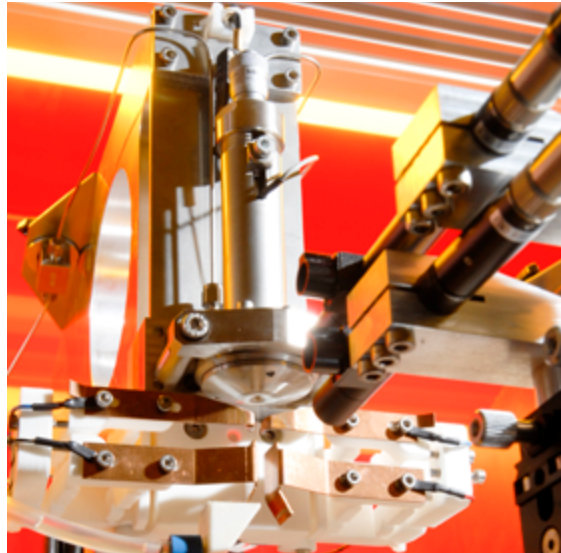
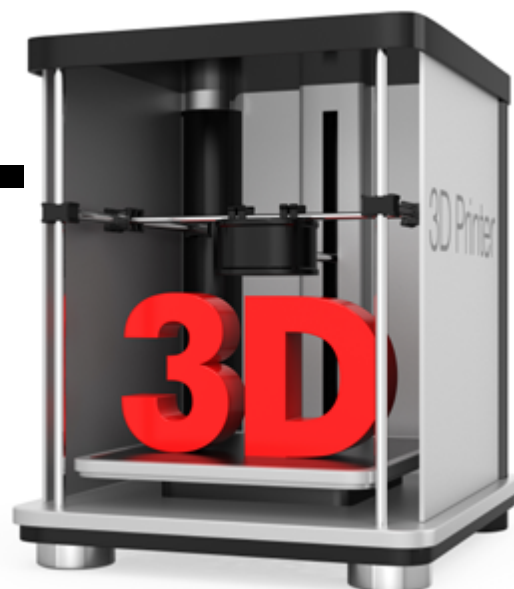


Figure 1: Inkjet Technology for 3-D printing (Source: TNO)

ADVANTAGES OF 3-D PRINTING

There are a number of elements which make 3-D printing an attractive production process:

1. **Economical product customization** – 3-D printing permits cost-effective production of very small batches. Every single product can therefore be tailor-made to the customer’s exacting specifications, something not possible with traditional production processes for which expensive tooling and molds have to be acquired and redesign is expensive.
2. **Freedom of design** – 3-D printing allows for freedom of design because standard CAD software can be used to design and redesign products. The CAD drawing can be directly printed into a physical part and redesigns can be implemented with ease. Designs can be created by anyone skilled in computer-aided design anywhere in the world.





Source: Hollandse Hoogte

- 3. **Complex product manufacturing** – 3-D printing enables fairly easy production of products that were hard or even impossible to produce in the traditional way. Complex products can be printed at once, resulting not only in less waste and lighter products, but also in time savings. Although the process of printing is still very time-consuming, the ability to consolidate several machining steps into a single manufacturing step, reduces overall manufacturing time for complex products.
- 4. **Decentralized manufacturing** – products designed in standard CAD software environments can be produced literally anywhere in the world, as long as compatible 3-D printers are available. Since 3-D printers are spreading throughout the world, this enables the manufacturing process to be physically closer to its customers. Time-to-market can be reduced by outsourcing manufacturing to globally-dispersed 3-D printing service providers⁴.

Due to the ability to cost-effectively produce single products, 3-D printing is very useful for prototyping and modelling. This is nowadays still the largest application of additive manufacturing. However, due to improved printing technologies the quality of the products produced by a 3-D printer increased over the last years, thereby allowing

produced parts to fulfill the higher quality standards of the end-parts and final products market. Examples of end-parts are aviation components and examples of final products are medical devices such as orthotics or hearing aids. Combined with the limited market for prototypes⁵, the end-parts and final products have taken a more prominent part in the market, as can be seen in Figure 2.

DRAWBACKS OF 3-D PRINTING

3-D printing technologies can be very flexible and efficient for small production runs but there are some limitations to product quality and large-scale production runs that have to be taken into account. At the time of writing, 3-D printed products cannot yet compete with the production quality and scale efficiency of products produced with other (subtractive) processes such as injection molding technologies. Currently, the main drawbacks are:

- 1. **Limited product dimensions:** 3-D printers typically have a relatively small print bed limiting the maximum dimensions of the final product, especially in the home segment market. Large products have to be manufactured by other technologies.
- 2. **Reduced choice for materials:** there is a limited but growing amount of raw materials that can be used for 3-D printing, which limit the choice of materials, colors, and surface finished compared to subtractive technologies.
- 3. **Lower precision:** 3-D printing technologies have not yet reached the same level of industrial engineering precision associated with other technologies.
- 4. **Limited strength:** due to the layered additive process, products have limited strength, restrained resistance to heat and moisture, and compromised color stability.

RECENT MARKET DEVELOPMENTS IN 3-D PRINTING

3-D printing: inflated expectations or value-adding technology?

3-D printing promises many innovations. It's therefore no surprise that the market hype revolving around 3-D printing has reached its peak. Technology research organization Gartner included enterprise 3-D printing and consumer 3-D printing in its yearly Hype Cycle of 2013. As can be seen in the figure, consumer 3-D reached the top of the hype cycle in 2013. But enterprise 3-D printing is already on its way to

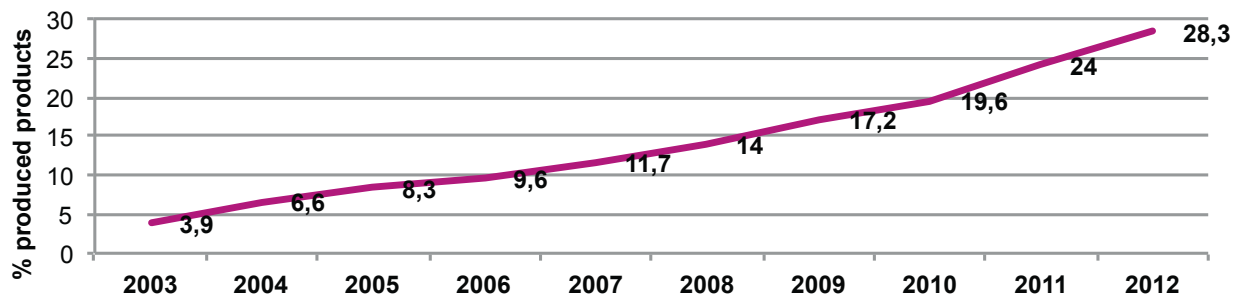


Figure 2: Produced end-use parts and final products in 3-D market as percentage of total products produced. (Source: Wohlers Associates⁶)

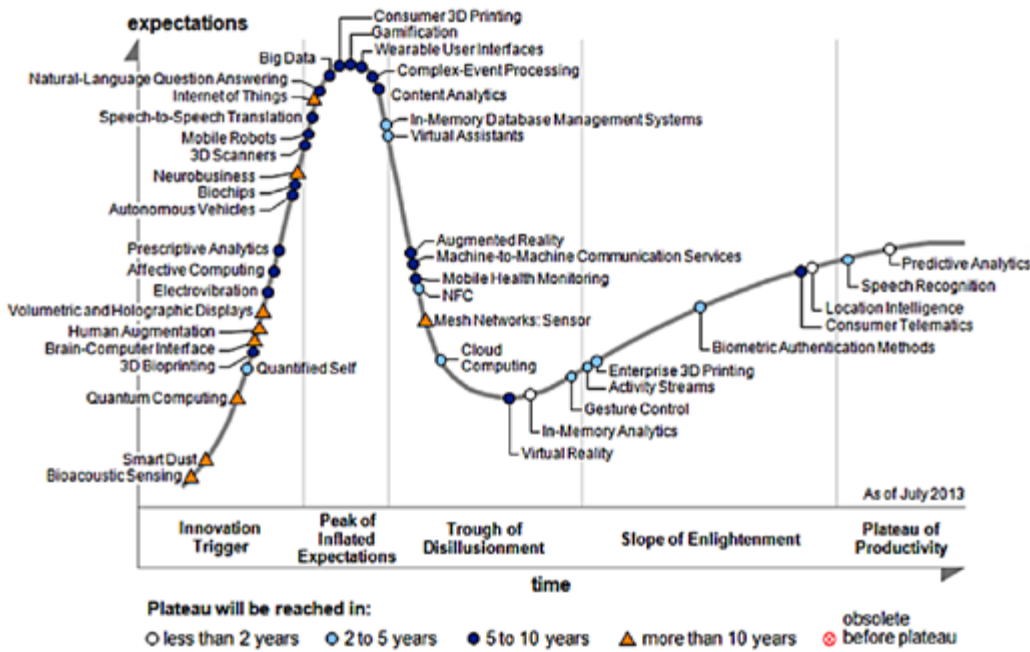


Figure 3: 3-D printing on the Gartner Hype Cycle of 2013⁷

become a value-adding reality. Enterprise 3-D printing is expected to reach the 'plateau of productivity' in 2 to 5 years and first-movers are already reaping the benefits of the technology.

MARKETS OF 3-D PRINTING: APPLICATIONS OF 3-D PRINTING TECHNOLOGY

So which industries and sectors have gone the furthest in applying 3-D printing technology?

- 1. Consumer products/electronics** – 3-D printing is mostly used in the consumer products/electronics sector and it has been for the last eight years. There is a large variety of products within the consumer markets, including toys, fashion and jewelry.
- 2. Automotive industry** - the automotive industry sees many applications of 3-D printing technology. Within this sector, 3-D printing is mainly used for prototyping by design engineers, but in the near future customized devices are expected. At the same time, custom parts can be produced in order to serve customers in the car tuning and luxury car segments.
- 3. Medical and dental** – the medical and dental sectors have been the third largest sector for over the past twelve years 3-D printing techniques have been applied within the medical and dental arena for the creation of assistive, surgical and prosthetic devices, surgical implants, and scaffolds for tissue engineering.⁸ More than half of the hearing aids and orthotics are already produced using 3-D printing⁹. Very recently, a Dutch patient received a completely new skull, printed using 3-D printing technology, at the University Medical Center Utrecht.¹⁰

- 4. Industrial/business machines and aerospace** make up the fourth and fifth largest sectors using 3-D printing. Especially the aerospace market is quite varied in the use of 3-D printing, with many examples of niche components being made and supplied using various forms of 3-D printing. Here, 3-D printing reduces the Buy-to-Fly ratio due to the possibility of substituting multiple heavy parts by a single lightweight 3-D printed component, its high material use efficiency, and ability to process aerospace grade titanium and nickel alloys.¹¹

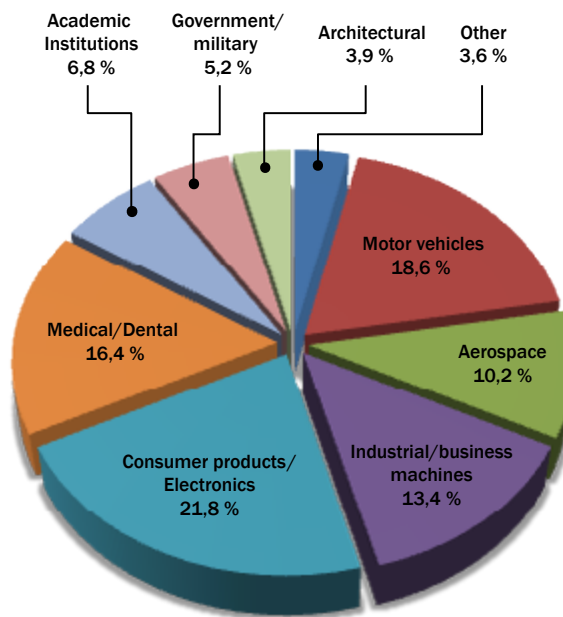


Figure 4: Market share of sectors using 3-D printing. Source: Wohlers Associates¹²

› SUPPLY CHAIN MANAGEMENT AND 3-D PRINTING





3-D printing holds great promises for manufacturing flexibility and the ability to economically manufacture small batches of products. As soon as manufacturing firms adopt 3-D printing technologies for parts of their manufacturing operations, supply chain design and logistics operations will change.

DEFINITION AND FRAMEWORK OF SUPPLY CHAIN MANAGEMENT

To discuss the consequences of 3-D printing on supply chain management, we need to be precise and use a well-established framework and definition of supply chain management.

Definition

We employ a truncated version of the Council of Supply Chain Management Professionals¹³ definition of supply chain management:

“Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. In essence, supply chain Management integrates supply and demand management within and across companies. It includes logistics management activities, as well as manufacturing operations, and it drives coordination of processes and activities with and across marketing, sales, product design, finance and information technology.”

Framework

The Supply Chain Operations Reference model (SCOR, Figure 5) is the de facto standard tool for supply chain management. The SCOR Model describes the extended supply chain, spanning from the supplier's supplier to the customer's customer. In the SCOR Model five main processes are defined that we will consider in light of 3-D printing:

1. **Make** – Processes that transform product to a finished state to meet planned or actual demand.
2. **Source** – Processes that procure goods and services to meet planned or actual demand.
3. **Deliver** – Processes that provide finished goods and services to meet planned or actual demand, typically including order management, transportation management, and distribution management.
4. **Return** – Processes associated with returning or receiving returned products for any reason. These processes extend into post-delivery customer support.
5. **Enable** – Processes associated with enabling the main processes Plan, Source, Make, Deliver, Return and product design, finance, information technology.
6. **Plan** – Processes that balance aggregate demand and supply to develop a course of action which best meets sourcing, production, and delivery requirements.

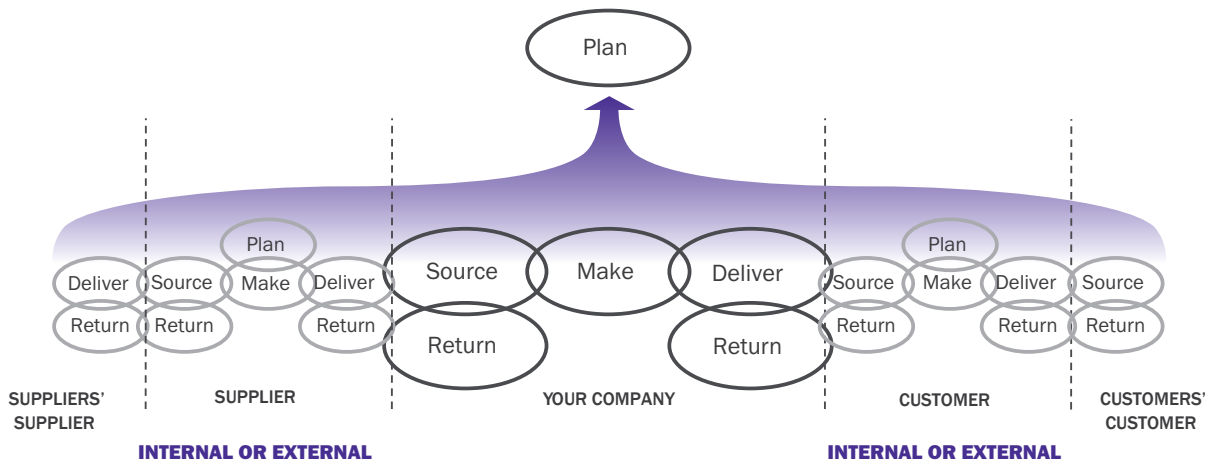


Figure 5: SCOR Reference Model 'Supply Chain'¹⁴

SUPPLY CHAIN MANAGEMENT PROCESSES: MAKE, SOURCE, DELIVER, RETURN, ENABLE AND PLAN

In short, supply chain management is an integrating function with primary responsibility for linking major business functions and business processes within and across. It addresses manufacturing operations, sourcing, distribution, returns, planning and it enables coordination of processes and activities with and across marketing, sales, product design, finance and information technology. We investigate the consequences of 3-D printing for all these supply chain processes and activities, across the entire value chain (Figure 6).

PLAN FOR 3D PRINTING

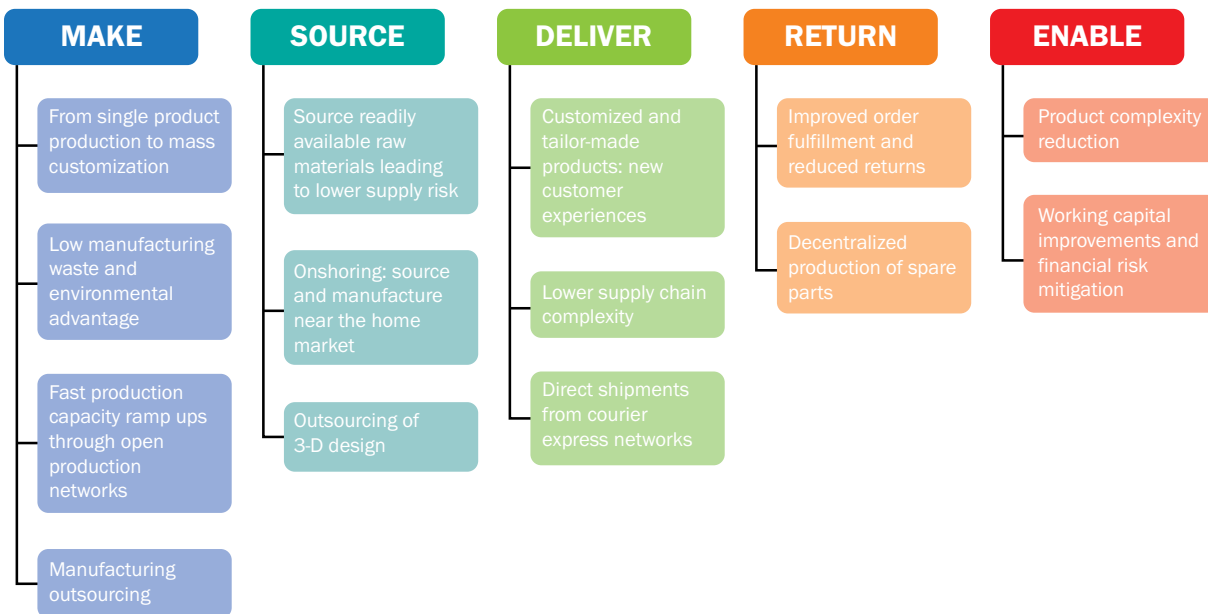


Figure 6

MAKE MANUFACTURING AND OPERATIONS**3-D printing: from single product production to mass customization**

If mass production is the goal, injection molding technologies are the de facto standard. Injection molding, a subtractive process, allows large quantities of products to be produced against very low per-unit costs. Costs are relatively high for small batches but costs per unit decrease quickly as scale increases, which is a major benefit of injection molding technologies. Mass customization – tailoring a product to the specific wishes of a single customer – is not something that comes easy with injection molding technologies, as speed and standardization are the name of the game here. New designs are very costly to implement as expensive new molds and tools have to be manufactured and the setup and change-over of machines is slow costly.

In contrast, 3-D printing is very well suited for mass customization. It enables firms to economically build custom products in small batches as there is no need for the crafting of tools and molds and machine setup and change-overs are virtually non-existent. That means that cost-effective production of single product batches become feasible with each and every product customized to the customer's requirements.

As batch sizes increase, 3-D printing can be used successfully for bridge manufacturing. Bridge manufacturing occurs for medium size batches where mass production technologies such as injection molding still lack the desired flexibility and costs of change-overs are considered too high.

One drawback of 3-D printing though, is that production costs do not decrease significantly with an increase in scale. The costs for the first product are effectively the same as for the 10,000th product.

Current 3-D printing technologies are still relatively inefficient and time-consuming. Mass production with additive manufacturing is often not feasible compared to injection molding technologies. But TNO's PrintValley system breaks these constraints, with 3-D printing speed improvements of 10 up to 100 times faster.

Low manufacturing waste and environmental advantage

With traditional subtractive production processes material waste is typically high, as excess product is milled, scrapped and sanded away. Even though these waste materials may be recycled, this requires an additional processing step to make it ready for manufacturing again. 3-D printing technologies have an environmental advantage here, as because of adding the material on a layer-by-layer

basis, 3-D printing reduces material usage and process waste. 3-D printing machines, depending on the technology used, go about very efficiently with the input materials and so resource utilization can beat traditional CNC milling processes.¹⁵

**Fast production capacity ramp ups through open production networks**

Traditionally, it takes quite some time for a firm to start production of a new product or new revision of a product. Machines need to be adapted, new tooling needs to be made, and production schedules have to be developed. And when finally production is up and running, process quality may be below par and product redesign is required. This can be a cumbersome and costly process. 3-D printing technologies, however, utilize standardized production procedures and standard machinery. The digital model designs can be shared and downloaded all over the world. This means that production capacity can be easily ramped up at multiple sites simultaneously, anywhere in the world.

Manufacturing outsourcing

In many regions of the world, clusters of 3-D printing service providers start to emerge. Essentially, they supply the same kinds of service that traditional 2D paper-and-printed-matter copy centers have provided for decades, simply adding the third dimension to their offer.

Also specialized 3-D printing service providers start to emerge everywhere in the business landscape. These service providers have various high capacity printers to respond to all kinds of demands for 3-D printed products. This, however, reduces the need for many firms to have their own assets that can manufacture additively, and consequently firms may outsource their demand of those services and free capital locked up in property, plant and equipment (PP&E) assets. Considering the growth of these so-called Print Valleys and individual service providers, chances increase that there is a specialized service provider locally available.

SOURCE PROCUREMENT AND OUTSOURCING

Source readily available raw materials leading to lower supply risk

Traditional production relies on a combination of using raw materials and a number of components and sub-assemblies. With 3-D printing, a product can be made out of a single raw material or a combination of multiple raw materials, eliminating the need for sourcing expensive sub-assemblies and components.

3-D printing uses raw materials as input materials such as nylons, plastics, metal, clay, silicone, and porcelain among other. These materials are readily available and in terms of supply risk, this decreases tremendously as there are many suppliers available for these materials, all over the world.

Also, the raw materials can be sourced in bulk and the materials represent relatively low value which makes inventory minimization less of an issue, which in turn can improve availability and reduce the probability of stockouts. In essence, the raw materials for 3-D printing exhibit some of the properties of typical leverage items: materials that have a high profit impact but only low supply risk. Purchasers can use their full buying purchasing power, easily switch between abundant commodity suppliers and place high-volume orders, raking in quantity discounts.

Onshoring: sourcing and manufacture near the home market

Traditionally, production is outsourced to lower-wage countries if the lower wages can compensate for the transportation and handling costs. This is usually the case for production with a proportion of low-skilled manual labor. However, 3-D printing is a very automated and standardized process, and therefore requires a lower proportion of low-skilled workers in the overall production process. As a result, sourcing and/or manufacturing in lower-wage countries becomes of less importance. This enables 3-D printing centers to be located in close proximity to home markets in high-wage areas such as Europe and the United States, decreasing the length and complexity of the supply chain and improving the time-to-market.

Outsourcing of 3-D design

The success of 3-D printing relies heavily on the direct link between design and manufacturing in order enable product customization. If, however, a firm does not have the capabilities to design new products in-house, there are plenty of service providers and design networks available, offering their 3-D design services. Thanks to the high level of standardization achieved by using off-the-shelve CAD-software tools, design and subsequent manufacturing can have very low turnaround times.

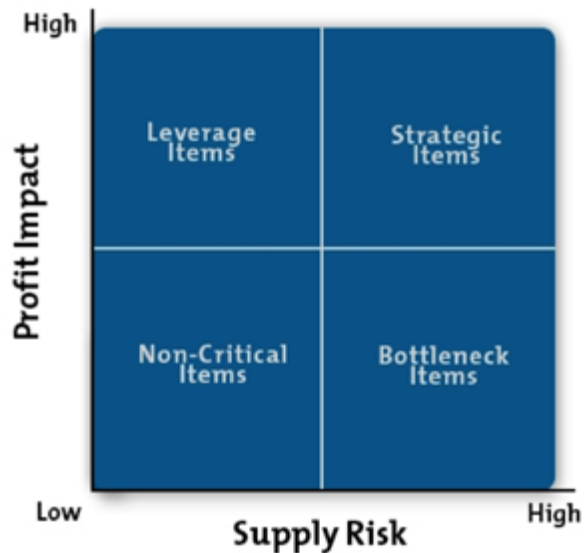


Figure 7: Kraljic Purchasing Portfolio ¹⁶ – 3-D printing involves low-risk, high-impact Leverage items



DELIVER SALES AND DISTRIBUTION

Customized and tailor-made products: new customer experiences

The most obvious benefit of using 3-D printing technologies, of course, resides in the ability to customize the products based on the customer's requirements and wishes. Customers can even add the modifications and customizations to the products themselves, with a little help and knowledge of 3-D design principles and software. Next to regular market channels of undifferentiated 'off the shelf' products, firms can now offer an additional channel. The new channel is characterized by a value proposition in which customers take part in designing the product to their exacting specifications and for which a premium price can be charged. Essentially, 3-D can help to avoid the dreaded commodity trap.

Lower supply chain complexity

3-D printing holds the promise to significantly decrease the complexity of existing supply chain networks (Figure 8 and Figure 9). 3-D printing, for instance, allows manufacturing firms to create single products that previously would have required multiple components to be assembled together. This eliminates the assembly phase of production and thus potentially a significant reduction in labor costs, storage, handling and logistics costs.¹⁷ In fact, the supply chain for such a product becomes quite uncluttered: a manufacturing firm directly sources the raw materials for the product, prints the design in-house and the next step is the distribution to the final customer or even a direct shipment. Obviously, such a shorter supply chain may incur lower transactions costs and lower logistics costs.

Direct shipments from courier express networks

For specific sectors, namely courier express networks, the impact of 3-D printing cannot be overstated. Many courier express companies such as UPS, DHL, FedEx and TNT Express, have complex supply chain networks that excel in

transporting parcel-sized packages all over the world, using well-established links to all transportation modes available. Most 3-D printers are limited to relatively small form factors, so the products printed on 3-D printers typically have parcel-sized dimensions (though not exclusively, as 3-D printed houses and car dashboards are in fashion as of late).

Imagine a regional courier hub or European Distribution Center to be outfitted with advanced 3-D printing facilities. The courier itself can provide 3-D printing services to their customers, or ally with an on-site 3-D printing service provider that offers an e-commerce store for designing and ordering 3-D printed products.

Products ordered through the courier or e-commerce store can be made-to-order directly, using common raw materials and shipped off instantly to the customers in the European service area, piggy backing on the extensive distribution network already in place.

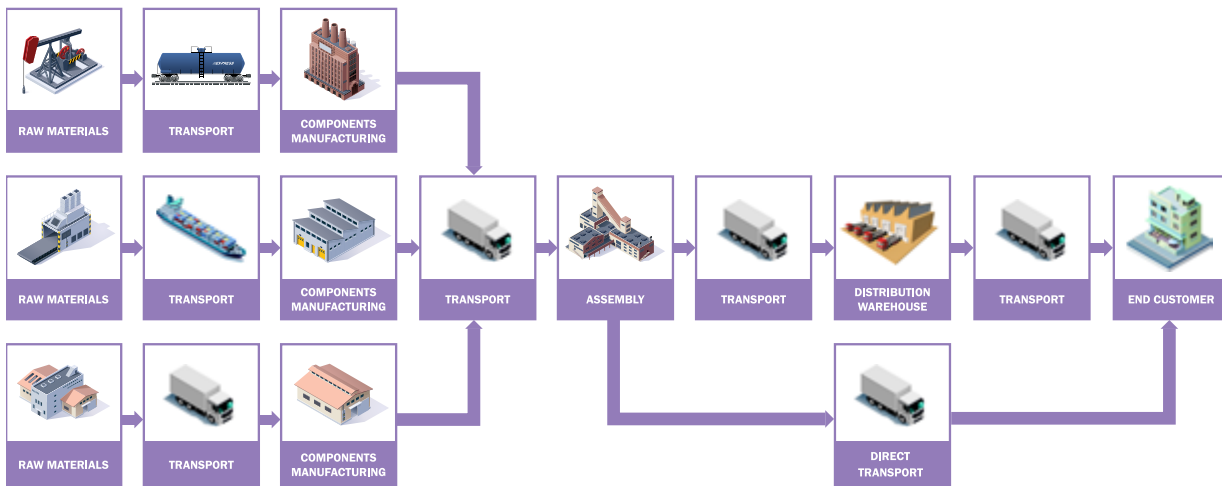


Figure 8: Simplified traditional supply chain network structure

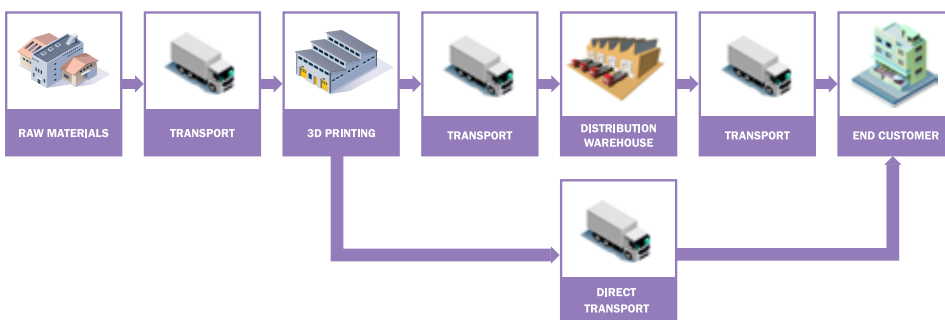


Figure 9: Supply chain network structure with 3-D printing competence

RETURN REVERSE LOGISTICS AND AFTER SALES**Improved order fulfillment and reduced returns**

With 3-D printing, the production process is initiated by the actual customer demand. As the products can be fully specified and tailor-made, this will reduce the number of returns as consumers can be expected to be more satisfied with the product specifications and quality if they had a say in the initial product specification.



Figure 10: 3-D printed orthopedic insole

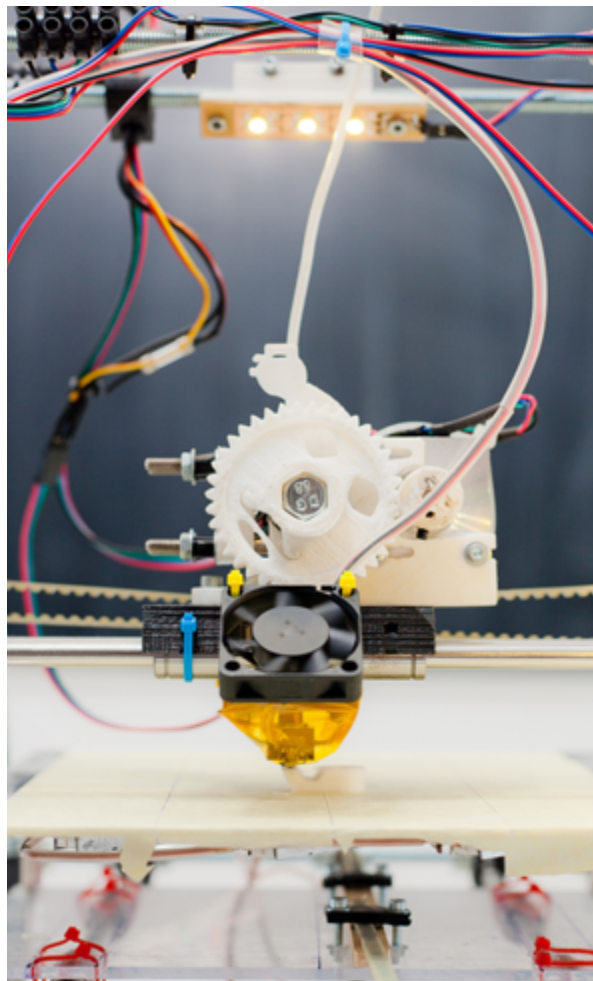
Complex products, that usually require numerous iterative production and adjustment process steps, can be error-free produced using 3-D printing. Consider for instance orthopedic insoles: specially-designed custom-made footwear to relieve discomfort associated with many foot and ankle disorders.

Traditionally, production and delivery of an orthopedic insole required frequent contact between the client and the orthopedist. The orthopedist would take a foam print of the client's foot, which he would send to the insole manufacturer for it to fabricate the insole. As the sole is finished, it is sent to the orthopedist who will perform the final fit with the customer. The sole is sent back and forth from producer to orthopedist to optimize the fitting, as the fitting is never perfect the first time around. This production and reprocessing process can take up four to six weeks.

When soles are fabricated by means of 3-D printing, on the side of the customer there will now be only one moment of contact between client and orthopedist during which the foam print is made. The orthopedist can choose to scan the foam print on location, or to send the print to a scan service, which will send the 3-D-scan to a 3-D print service provider. When 3-D printed, no additional handling or readjustment is needed as the product will provide a perfect fit. The customer can decide to collect the insole at orthopedist, or to have the final product sent straight to his home address.

Decentralized production of spare parts

Many firms face difficulties in determining where to build inventories of spare parts. Having spare parts readily available is important in many industries, but the costs of holding these inventories of finished products can be staggering. Spare parts, for example, have relatively high value but volumes are quite small and logistics take up a considerable portion of the total landed cost. Firms therefore usually decide to store a limited inventory of spare parts at a central location far away from customers, because stocking inventories at multiple decentralized locations closer to customers is a very expensive endeavor. However, using 3-D printing, firms can choose to keep zero inventory of spare parts and simply produce spare parts using 3-D printers at decentralized locations near customers. Since product designs can easily be shared over the Internet and printed using broadly available standardized 3-D printing technology, costs for spare parts fulfillment will go down. The unit cost of a 3-D printed spare part may be higher, but this is offset by the fact that expensive warehouses full of slow moving volumes of spare parts are not required anymore.



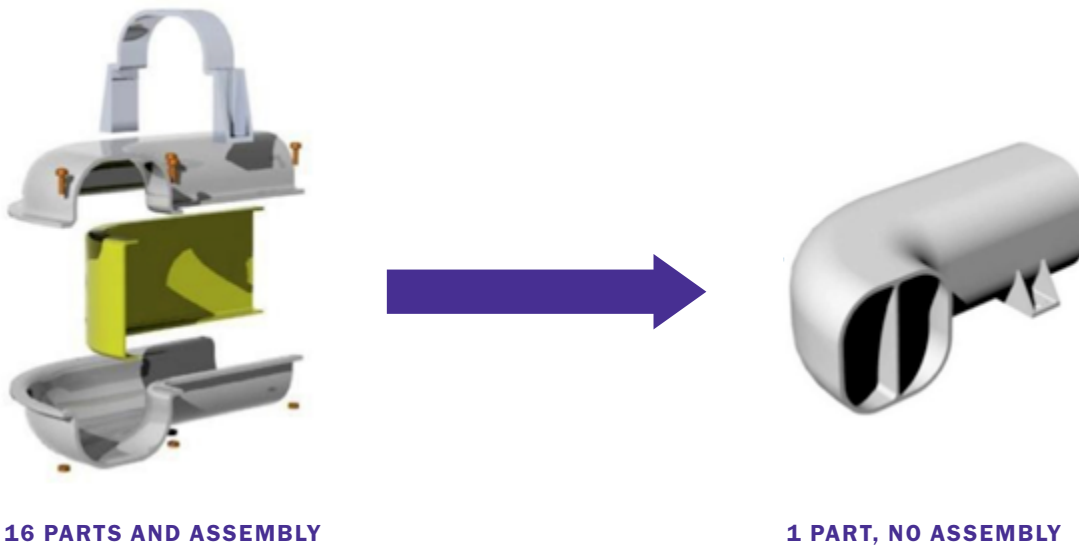


Figure 11: Reduced product complexity through 3-D printing for aircraft air duct. Source: 3-D Systems (2013)

ENABLE PRODUCT DESIGN AND FINANCE

Product complexity reduction

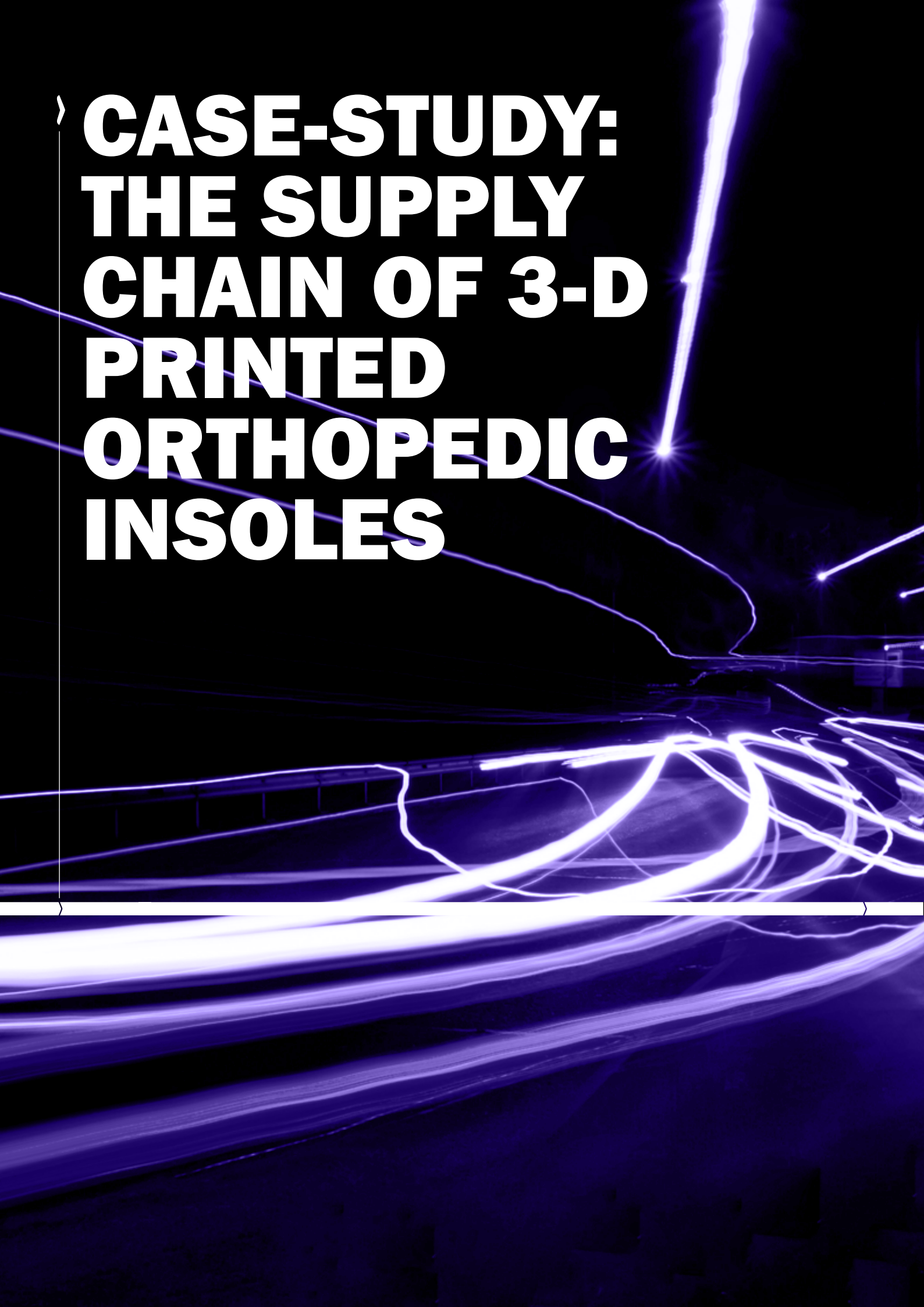
3-D printing has already gained a solid foothold in the aerospace construction industry. Even though 3-D printed parts can have below-average quality in many applications, in aerospace construction they have found that products can become much less complex. Instead of a multi-component assembly, products can be printed from a single part which saves material and weight. Also, this reduces the logistics complexity, because the need for multiple components to be available at exactly the same time is alleviated.

Figure 11 shows the reduced product complexity of an 3-D printed air duct used in aircrafts. Originally, the air duct consisted of 16 parts assembled together, but using additive manufacturing the product can be engineered and manufactured in one part. This reduces the weight of the product, increases the strength and thus improves buy-to-fly ratio.

Working capital improvements and financial risk mitigation

In many cases, products manufactured using 3-D printing technologies will have customization or tailor-made components, as non-customized 'off-the-shelve' products can still be more economically produced using regular subtractive processes like injection molding. Because products are customized and tailor-made, products are typically paid for before actually being manufactured, effectively reducing working capital, cash flows and improving operational liquidity.

And as soon as manufacturing is completed, products will be shipped off instantly to the customer. This means no capital is held up in expensive inventories of components, subassemblies or finished goods. Again, working capital is reduced, and reduces the risk of customer defaults.



**CASE-STUDY:
THE SUPPLY
CHAIN OF 3-D
PRINTED
ORTHOPEDIC
INSOLES**

Orthopedic insoles are typical products that can be produced using traditional methods, but for which 3-D printing provides broad advantages. We highlight some changes to the supply chain design if 3-D printing is used for producing orthopedic insoles.



Figure 12: Foam Scan

The traditional supply chain of orthopedic insoles
 Many consumers regularly purchase orthopedic insoles for health reasons to help deal with defects in the natural shape of the foot or positioning of the foot during standing or walking.

The insoles are usually partly machined and partly handcrafted. The insole manufacturer holds inventories of cork, plastic and leather, which are the main components for the insole. Cork and plastics are used for the basis of the insole, while a leather top-layer is often assembled at the end of the production process. The cork and plastics cannot be used right away, but need pre-production before they can serve as input materials for the final assembly of the insole.

Traditionally, purchase of an orthopedic insole requires frequent contact between the client and an orthopedist, and resultantly the insole manufacturer (see Figure 13).

The orthopedist takes a foam print or plaster cast from the client's foot and determines which physical adjustment the client needs. Then he sends the scan, along with his notes, to the insole manufacturer.

The insole manufacturer receives the customer's foam scan from the orthopedist, interprets the orthopedist's notes and it fabricates the sole using CNC manufacturing technology.

After the sole is finished, it is send to the orthopedist who will perform the final fitting with the customer. Most client's, however, are not satisfied with the product the first time around and usually adjustments to the insole are needed. The insole is send back and forth from manufacturer to orthopedist to optimize the fitting, and the customer has to visit the orthopedist every time for fitting. The total process easily takes up four to six weeks and costs of the final product are around €200.

THE 3-D PRINTED ORTHOPEDIC INSOLE SUPPLY CHAIN

Orthopedic insoles can also be manufactured using 3-D printing technology. When soles are fabricated by means of 3-D printing, the supply chain changes significantly as fewer types of materials are used and production quality increases.

The orthopedist, again, takes a foam print from the client's foot, adds the required adjustments to the model. However, the orthopedist can also take a direct 3-D scan from the client's foot, digitally add the required adjustments and send the digital model to the 3-D printing manufacturer. The manufacturer produces the insole straight from the design. This time around, there's less room for human-induced error. The strict integration between 3-D scan and 3-D print ensures that a single moment of contact between

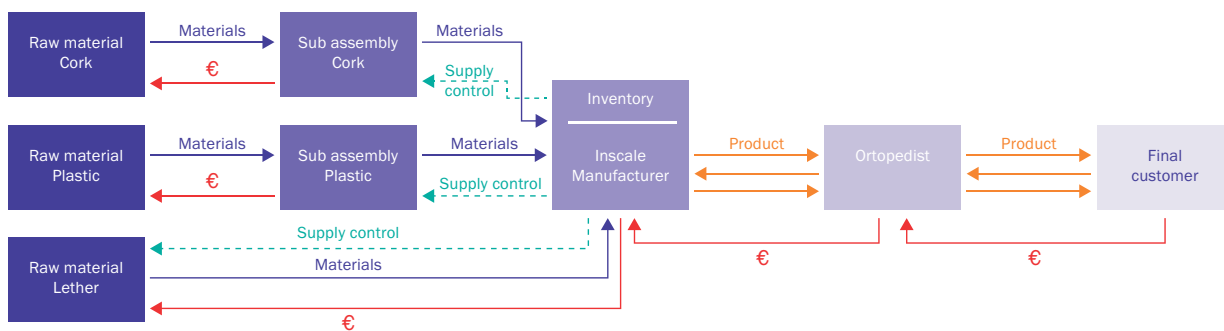


Figure 13: Traditional supply chain for orthopedic insoles

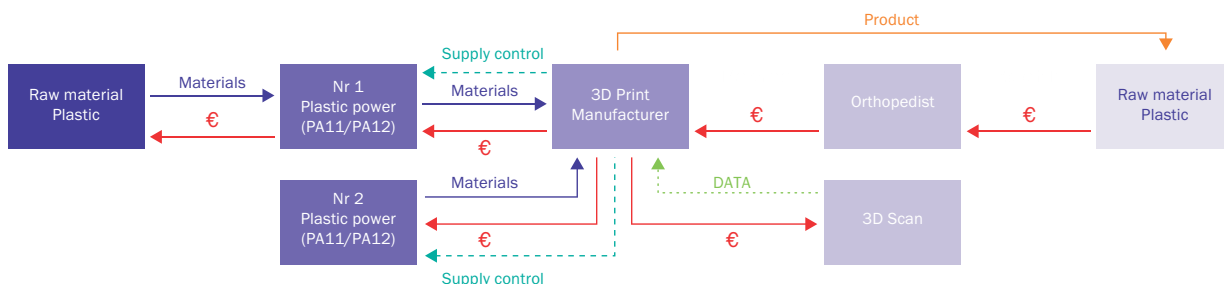


Figure 14: 3-D printed orthopedic insoles

THE SUPPLY CHAIN OF ORTHOPEDIC INSOLES

SUPPLY CHAIN DESIGN	TRADITIONAL SUPPLY CHAIN	3-D PRINTING SUPPLY CHAIN	EXPLANATION
MAKE: MANUFACTURING AND OPERATIONS			
Production order trigger	Make-to-order (MTO)	Make-to-order (MTO)	
Production process capacity	High	Increase	Using standardized 3-D printers, available production capacity is virtually limitless
Number of materials in final product (BOM complexity)	3	Decrease	Insoles can be 3-D printed using only 1 or 2 raw materials
Lead-time production and assembly	4-6 weeks	Decrease	Due to higher 'First time right' production with 3-D printing, total lead-time decreases
Number of manufacturing errors	Average	Decrease	3-D printing allows higher quality of production with less re-manufacturing required. The involvement of human error is reduced by working only digitally.
Quality control	Lots of manual finishing	Decrease	Traditionally, manufacturer and orthopedist have to do lots of manual finishing, with 3-D printing allows a much better specified product.
Workforce skill level required for production	Average	Decrease	Lower skilled employees can operate 3-D printers
Manufacturing outsourcing	Low	Increase	Traditionally, orthopedists will do business with only a relatively low number of manufacturers. However, if they have a standard 3-D scan of the client's foot, they can outsource the production anywhere they want.
DELIVER: SALES AND DISTRIBUTION			
Market stability	Stable	No change	
Price per product	High, about EUR 200,= per pair	Decrease	Price depends on the type of insole, but 3-D printing insoles can generally be competitive and sometimes even cheaper than traditional methods.
Inventory of end-products	None	No change	Insoles are manufactured on a per-order basis (make-to-order), with no accumulation of end products inventory
Logistics operations design	Parcel express networks	No change	Initially, we don't expect any changes to the logistics organization behind the insole. However, as soon as parcel express networks start to offer generic 3-D printing facilities on a grand scale, direct shipping becomes an option.
SOURCE: PROCUREMENT AND OUTSOURCING			
Used input materials	Cork, plastics, leather	PA11/PA12 plastics	
Inventory of components	Low	Decrease	There are no pre-assembled components needed as products are instantaneously manufactured in the 3-D printer. This also makes forecasting less error-prone.
Supply chain network complexity	7 to 8	Decrease	The decrease in bill of materials complexity also reduces the number of parties in the supply chain network, effectively reducing the alignment and coordination required.
Dependency on suppliers (scarcity of raw materials)	Low	Decrease	With 3-D printing, manufacturers can source readily available supplies of plastics, reducing their dependency on suppliers.
Sourcing input materials	Bulk, small volumes	No change	
3-D design execution	Orthopedist	Clients	Traditionally, orthopedists will develop the plaster casts for usage as the mold/template for the insole. Using smartphones, clients can now produce 3-D scans from their feet themselves, ordering prints straight at the 3-D printing manufacturer.

SUPPLY CHAIN DESIGN	TRADITIONAL SUPPLY CHAIN	3-D PRINTING SUPPLY CHAIN	EXPLANATION
RETURN: REVERSE LOGISTICS AND AFTER SALES			
Influence of customer on product specification (CODP)	Upstream	No change	
Importance of after-market services	High	Decrease	Often, client's are not satisfied with their orthotics straight from the workshop. Re-manufacturing and close customer contact remains important. Using 3-D printing, the initial product feels better for customers, limiting the amount of rework needed.
Order fulfillment cost	High	Decrease	Due to higher initial production quality and less re-manufacturing required, the number of returns decreases and total fulfillment costs decrease
ENABLE: PRODUCT DESIGN AND FINANCE			
Product complexity reduction	Low	Decrease	The insoles become slightly less complex, because of the number of input materials required in the final insole.
Product structure strength	High	Increase	Due to using "unibody" 3-D prints, the product's structural strengths actually increases compared to traditional assemblage processes.

Figure 15: changes in supply chain design and operations for orthopedic insoles



client and orthopedist should be enough for a correct fitting. The client can even decide to collect the insole at the production location, or to have the final product sent to his home address, omitting the fitting process at the orthopedist at all.

In terms of the impact of 3-D printing on supply chain management, Figure 15 lists some of the changes in supply chain design that 3-D printing technology brings about for production of orthopedic insoles.

For starters, the number of materials used in the insole is reduced. Instead of cork, a nylon powder is used. The polyamides have the advantages that the materials are widely available, reducing sourcing challenges and dependence on suppliers. At the same time, insoles can become thinner but stronger using these materials. Also, customization can move beyond the level of customization offered by traditional methods. For instance, color and finishing of the insole can be determined by client, as he or she might want bright colored insoles with his or her initials carved into the basis.

When using 3-D printing, the cost for one pair of insoles can be competitive with traditional methods, or be even cheaper. And 3-D allows for a much shorter total lead-time, thanks to the "First Time Right" 3-D printing process.

FUTURE 3-D PRINTED ORTHOPEDIC INSOLES

3-D printed insoles are already happening. A start-up company called Sols (www.sols.co) offers two business models to distribute its 3-D printed insoles: the regular channel in which the client visits an orthopedist who makes the 3-D scan. The alternative is an innovative channel in which a client can make the 3-D scan herself, using an iPad and an app, using a process called photogrammetry. The insole is printed at a 3-D printing supplier of Sols and directly shipped off to the client for approximately \$ 100. In short, using 3-D printing for orthopedic insoles can improve the initial production quality, improve material strength, reduce the complexity of the supply chain, decrease cost, and even allows for differentiation and customization of the product at levels beyond the traditional processes.

› CONCLUSIONS: PLAN



As part of strategic decision-making, firms have to make decisions on how and where to manufacture products, which channels to use to distribute a product, where to source raw materials and/or components, and whether to do the physical distribution themselves or outsource to a service provider.

We have shown that the introduction of 3-D printing impacts all supply chain management processes: Make, Source, Deliver, Return, Enable and Plan.

With the rush in enterprise 3-D printing already underway and in the dawn of consumer 3-D printing, companies have to plan for the widespread adoption of 3-D printing. One could argue that 3-D printing innovations are currently enjoying a lot of market roar, however the changes to how firms manufacture – or indeed, outsource manufacturing to 3-D printing service providers – will impact many sectors and industries and supply chain network design.

3-D printing technology brings about changes in supply chain management. In summary, firms can:

- Manufacture product to precise customer's specifications;
- Economically produce one-off series and small batches of customized products;
- Enjoy higher material and resource efficiency in production processes;
- Ramp-up global production capacity through exercising standardized 3-D printing processes;
- Outsource manufacturing to specialized service providers;
- Alleviate material constraints by sourcing widely available raw materials;
- Bringing back sourcing and manufacturing operations to the home market;
- Utilize 3-D design capabilities from all over the world;
- Benefit from customer-centric product delivery experiences;
- Reduce supply chain network complexity by disintermediation of multiple supply chain linkages;
- Exploit courier express networks' density and effectiveness by integrating 3-D manufacturing operations;
- Improve order fulfillment: on-time in full with no errors (OTIFNE)
- Substitute expensive spare parts inventory for on-time decentralized spare parts production
- Cut product complexity and benefit from resulting logistics simplification
- Improve working capital and cash flow

As with any new and exciting innovation, we have just touched the tip of the iceberg of potential applications of 3-D printing and its resulting consequences on supply chain management.



Figure 16: (Future) applications of 3-D printing. Source: Wohlers Associates¹⁸

ENDNOTES

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