

Additive Manufacturing Principles and Capabilities Cards

These cards are designed to be used as an education and creativity aid for Additive Manufacturing (referred to as AM throughout the deck). The front of each card includes textual and visual descriptions of the principle or capability. The backside of the cards have a visual example; an application in a real situation.

Traditional

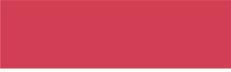


Principled



The front of each card has a simple example or illustration intended to convey the general idea of the AM principle of capability

Categories



Process Capabilities: These cards describe new or interesting operational models that are enabled by AM



Manufacturability Improvements: These cards suggest best practices for ensuring quality 3D prints



Best Known Design Practices: These cards demonstrate principles for how AM can enhance a product's design.



Design Process Improvements: These cards suggest how AM can be used to enhance the Design Process.

The back side of each card has images and a description of an example where the AM principle or capability has been applied in the real world.



These cards were created through a collaboration between the United States Air Force Academy, in Colorado Springs, Colorado and the SUTD-MIT International Design Centre in Singapore.

These cards are built on the findings of the following works:

[1] Perez, K.B., Otto, K.N., and Wood, K.L., "Crowd-sourced Design Principles for Leveraging the Capabilities of Additive Manufacturing," International Conference on Engineering Design (ICED), Milan, IT, July 2015, ICED15-396

[2] Fu, K., Yang, M., and Wood, K.L., "Design Principles: Literature Review, Analysis, and Future Directions," ASME Journal of Mechanical Design, Vol. 138, No. 10, 2016, doi:10.1115/1.4034105



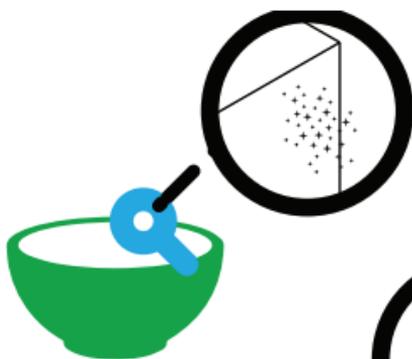
Preserve Small features

Preserve small features and surface finish

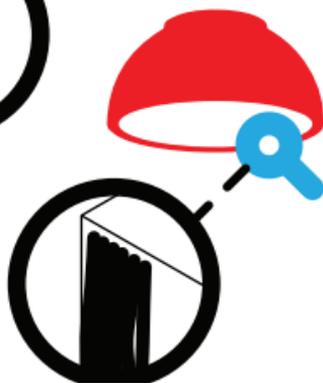
BY

printing parts in an orientation which requires
no support material

Traditional



Principled



Small features can be lost during support material removal. Orienting a part so it does not require support material improve prinability by precenting this.

See other side for a more in-depth example

Preserve Small features



In this example, the designer is using additive manufacturing to create a customized wax seal. Because the detail in the seal is critical, we orient the seal upwards so it does not require support material to preserve the small features.





Minimize Warping

Prevent part warping

BY

Reducing cross sectional area in the layers to minimize residual stresses

Traditional



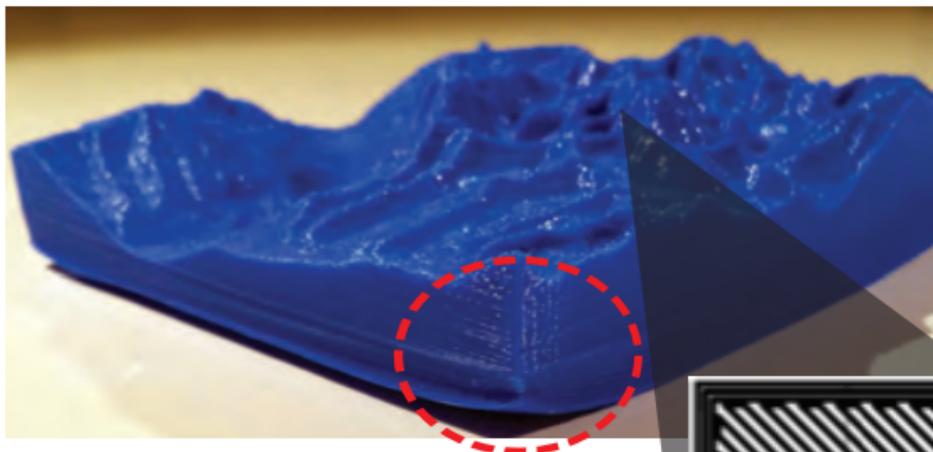
Principled



Warping is caused by a build up of residual stress in each layer as it cools. This effect is less intense when the cross sectional area is reduced.

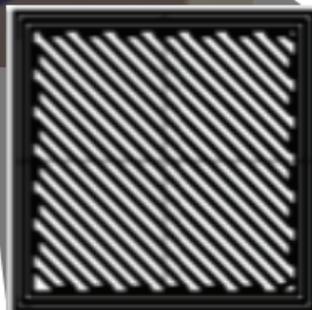
See other side for a more in-depth example

Minimize Warping



Warping

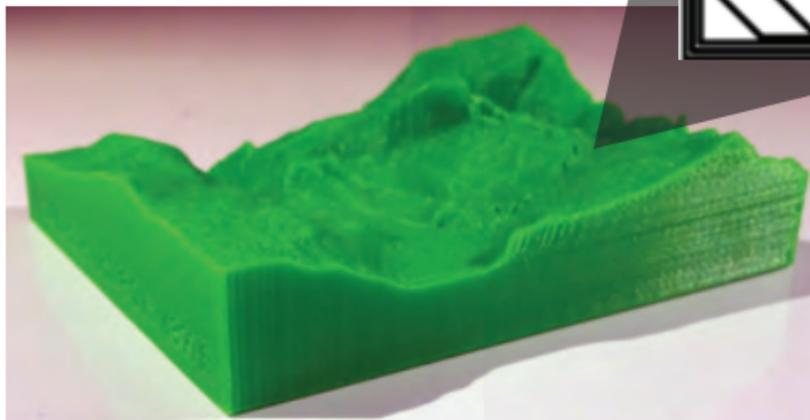
The example here uses a less dense infill in order to reduce the cross sectional area of the part. Since there is less polymer in each layer that is contracting as the part cools, there is less residual stress in the layers and thereby less warping.



75% Infill



25% Infill





Minimize Vertical Aspect Ratio

Improve print success

BY

Orienting or redesigning a part to have a lower vertical aspect ratio

Traditional

Principled



Tall prints can be unstable on the printbed. Orienting it such that the vertical aspect ratio is smaller can remedy this issue.

See other side for a more in-depth example

Minimize Vertical Aspect Ratio



In this example, the designer found it necessary to split the chess pieces in half to make them more stable during printing. While the piece can feasibly be printed as a whole, its aspect ratio and small base made the print unstable during printing. Splitting the figure and the bottom hemisphere upside down helps to improve print success.





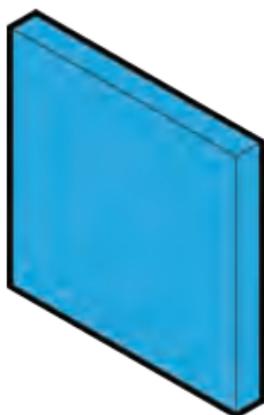
Leverage Cellular or Lattice Structures

Reduce weight, material cost, and preserve structural stability

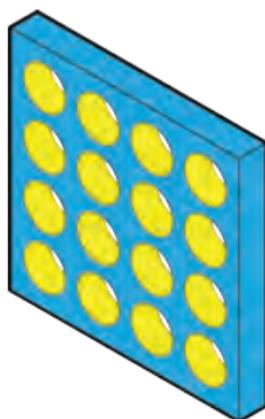
BY

Replacing solid volumes with cellular structures

Traditional



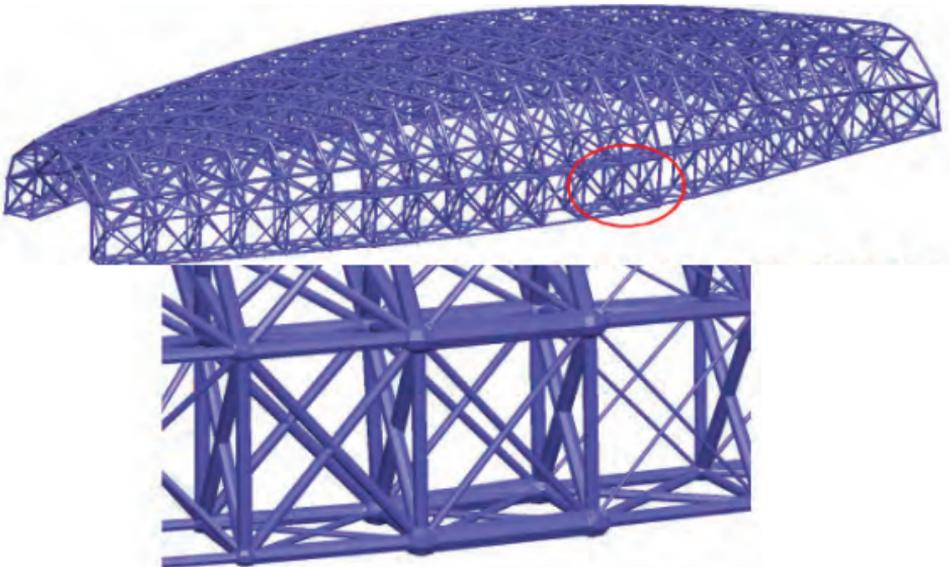
Principled



In this example, a solid panel is instead created from cellular structures rather than being fully dense.

See other side for a more in-depth example

Leverage Cellular or Lattice Structures



Rosen, D. W. (2007). Computer-aided design for additive manufacturing of cellular structures. *Computer-Aided Design and Applications*, 4(5), 585-594. Chicago

In these examples, lattice structures are created to reduce weight but preserve structural stability. The above example shows cellular structures in an airframe design for light weighting. Below are cellular structures applied to bicycle helmet applications to absorb energy in the event of impact.





Create Functional Joints and Interfaces

Eliminate assembly steps and time

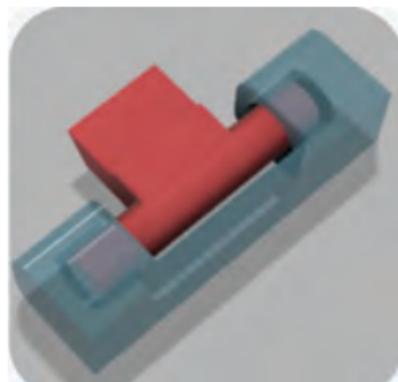
BY

Printing functional joints and interfaces directly

Traditional



Principled



In this example, a hinge is designed to be printed as a single part compared to the traditionally assembled hinge shown on the left.

See other side for a more in-depth example

Create Functional Joints and Interfaces



This dress is fully printed using an SLS Printing Process. Because the printed material is rigid, the individual triangles are connected to each other using rotational hinges so that the dress can move freely.





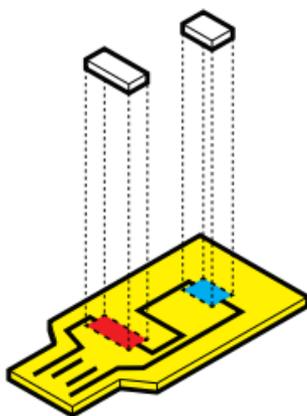
Integrate Functions and Components

Integrate additional functions,
reduce component size, and
reduce interfaces

BY

Printing functional components and features
into a single part

Example



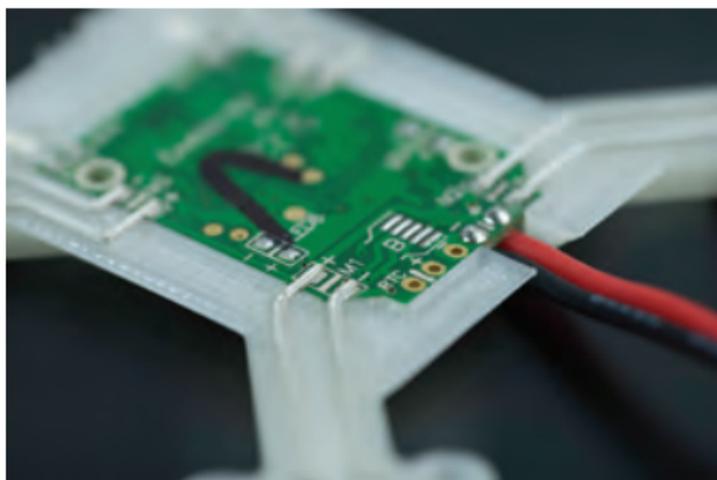
In this example, a USB drive is designed to be printed as a single part with the integrated circuit components directly embedded onto the part.

See other side for a more in-depth example

Integrate Functions and Components



This UAV is designed with a printed structure as well as printed conductive traces. The Circuit board is embedded inside the print and the motors are attached post-print.





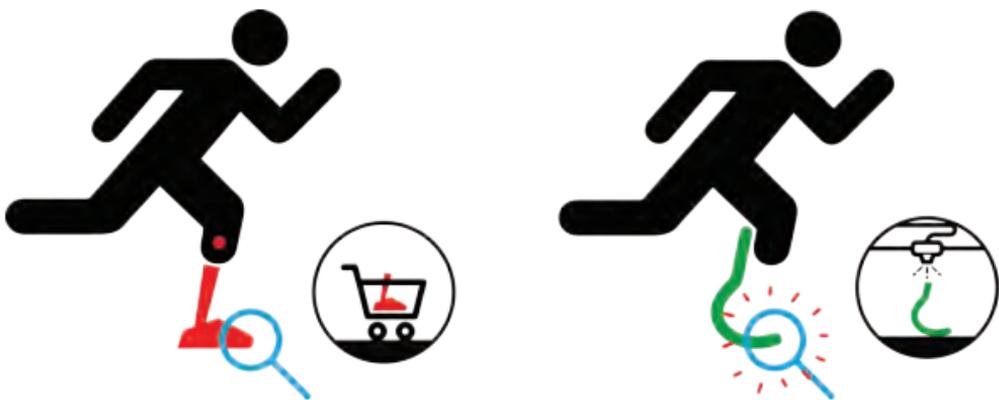
Customize Designs Rapidly

Enable custom products and processes (i.e. low-medium volume production)

BY

Identifying features that are complex or require high levels of user-based customization to meet customer needs

Example



In this example, AM is used to create custom prosthetics tailored to a user rather than a generic prosthetic that might not fit as well.

See other side for a more in-depth example

Customize Designs Rapidly



Align technologies ships thousands of custom orthodontic trays to users every two weeks that are designed from a 3D-scan of a patient's dental geometry. That is thousands of unique products every two weeks. AM provides the geometric flexibility to run such a diverse production line (below).





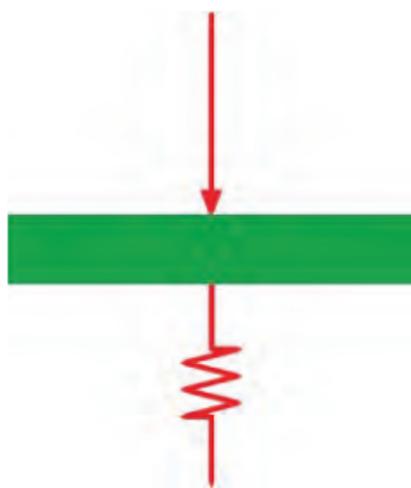
Leverage the Structure for Function

Achieve desired mechanical properties

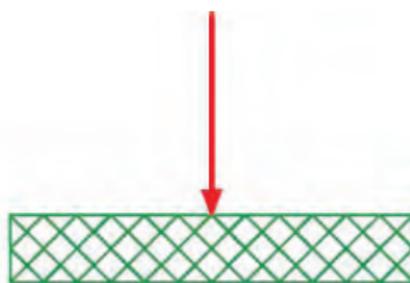
BY

Tailoring the geometry of the structure itself

Traditional



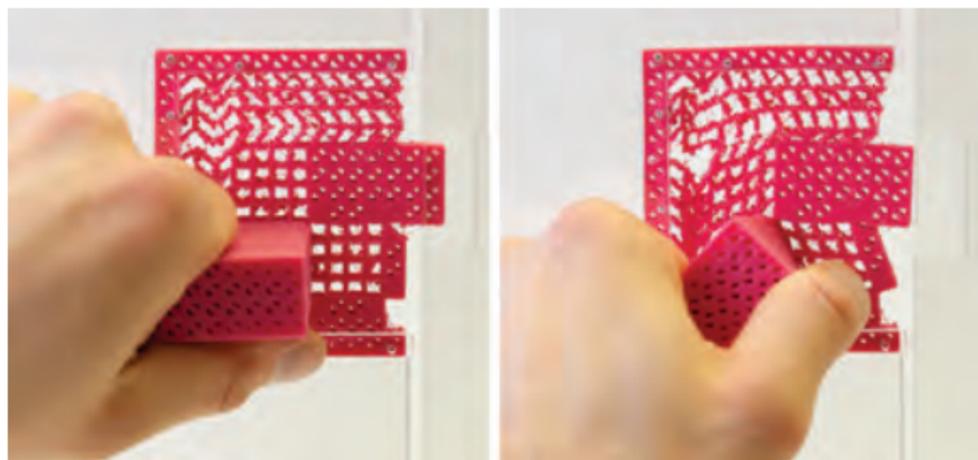
Principled



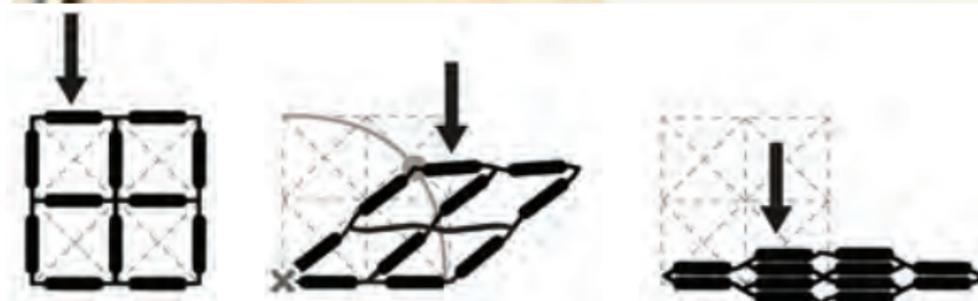
In this example, instead of a rigid beam and spring for displacement, the beam is design to also be the spring by leveraging the overall structure.

See other side for a more in-depth example

Leverage the Structure for Function



The door knob/latch and plier examples here leverage the structure and its ability to rotate within itself to create machines that would typically require multiple components to achieve the desired functions.





Reduce Print Time

Reduce print time

BY

Orienting the shortest dimension parallel to the
slowest fabrication direction

Traditional



Principled



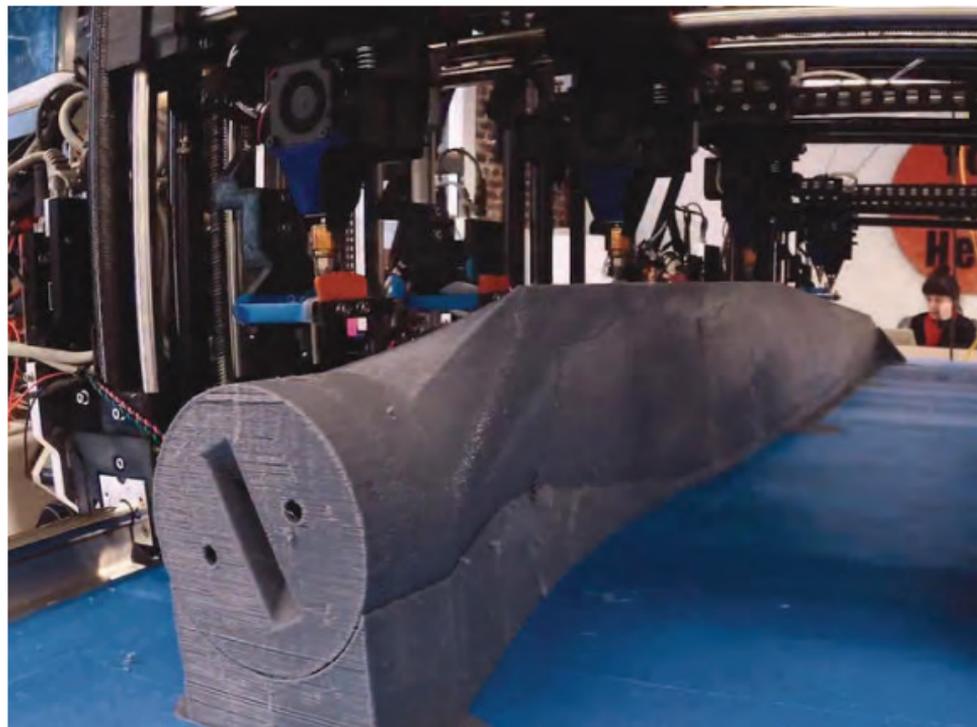
Many AM technologies like FDM are much slower in the vertical direction so reorienting the part to be horizontal makes the print faster and more stable

See other side for a more in-depth example

Reduce Print Time



Printing this airfoil could take days if it were oriented vertically, but few printers are large enough to print it on its side. The time savings of printing such an object on its side is so intriguing that companies have created printers specifically to do that.





Scale for Requirement

Satisfy different parametric requirements

BY

Scaling the design

Traditional

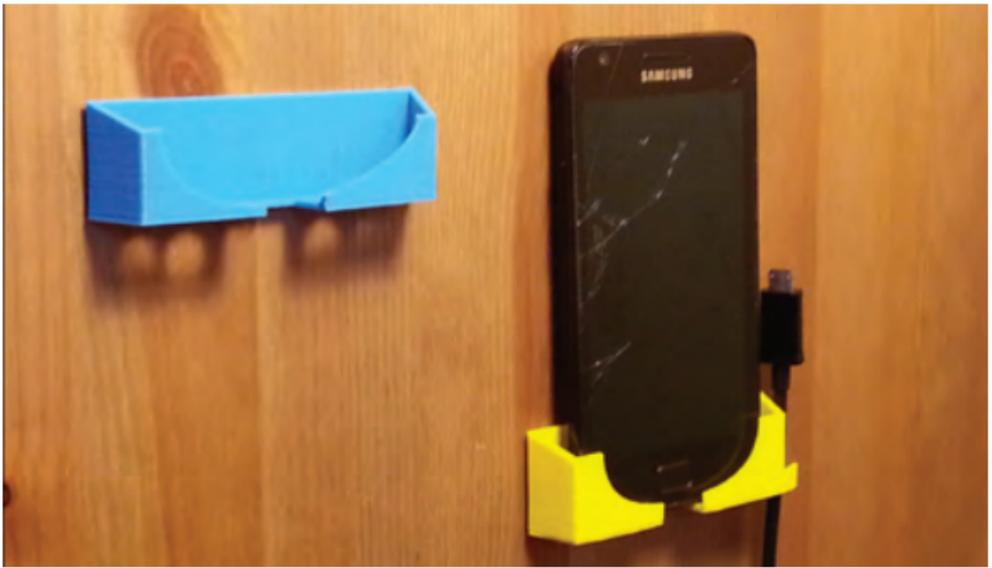
Principled



For example, one could take the design for an ordinary spoon, scale it to be larger and create a spoon for serving. This would save the time of creating a new design

See other side for a more in-depth example

Scale for Requirement



In this example, a parametric customization tool is used to change the dimensions of this mobile phone wall holder/mount. The parametric design tool allows the user to adjust or scale the dimensions of the original part to accommodate their own phone as there are many different makes and models.

parameters

Phonewidth
82

Phonedepth
14

Hight
28

Thickness
1.5

Basethickness
1

<http://www.thingiverse.com/app> Copy View Source Create Thing

<http://www.thingiverse.com/thing:1475333>



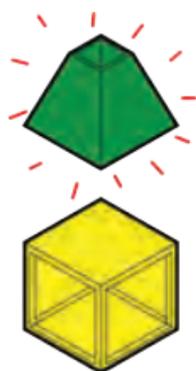
Reuse Digital Geometries

Minimize design time and effort

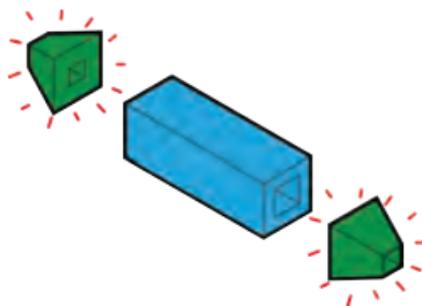
BY

Reusing already-designed component geometry where CAD data is already available

Traditional



Principled



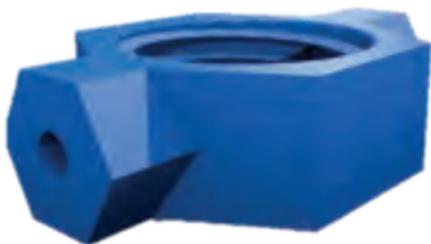
When designing a new component, time and effort may be saved if certain geometries can be reused from previous designs and existing CAD data.

See other side for a more in-depth example

Reuse Digital Geometries



In this example, a user wanted to create a different accessory for a dremel tool. Rather than measuring and sizing the attachment thread on a dremel, the User leveraged an existing thread design to create their accessory.





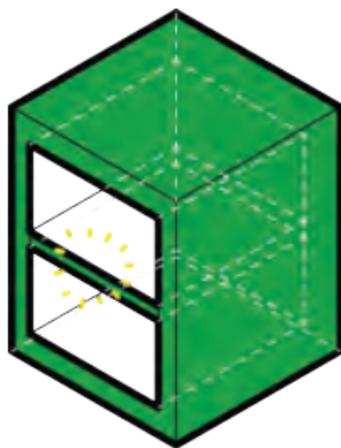
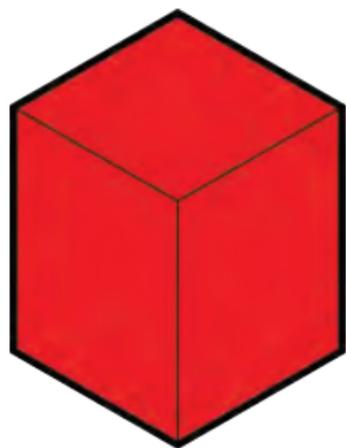
Incorporate Internal Functionality

Add function(s) to designs

BY

Incorporating functional features into non-functional or aesthetic models or components

Example



In this example, shelves are added to an otherwise non-functional part of a structure, increasing its utility by incorporating a storage function.

See other side for a more in-depth example

Incorporate Internal Functionality



NASA leveraged additive manufacturing to create this copper rocket engine part. The image below shows the conformal cooling channels that were able to be designed into the wall along the profile of the engine.



<https://www.nasa.gov/marshall/news/nasa-3-D-prints-first-full-scale-copper-rocket-engine-part.html>



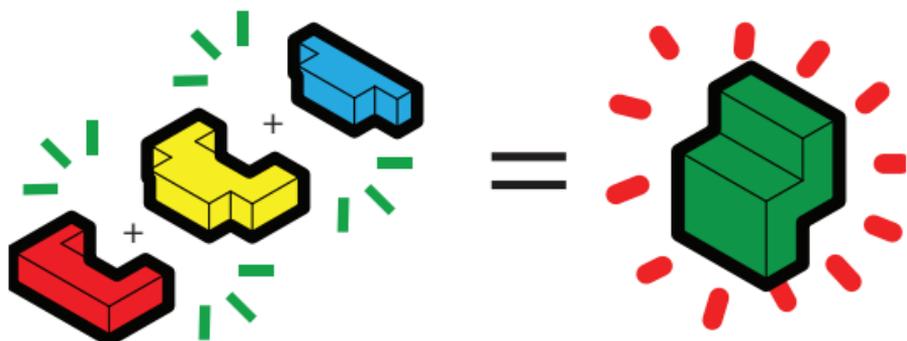
Incorporate Snap Fits (Quick Connects)

Minimize assembly time and number of components

BY

Incorporating snaps fits when possible

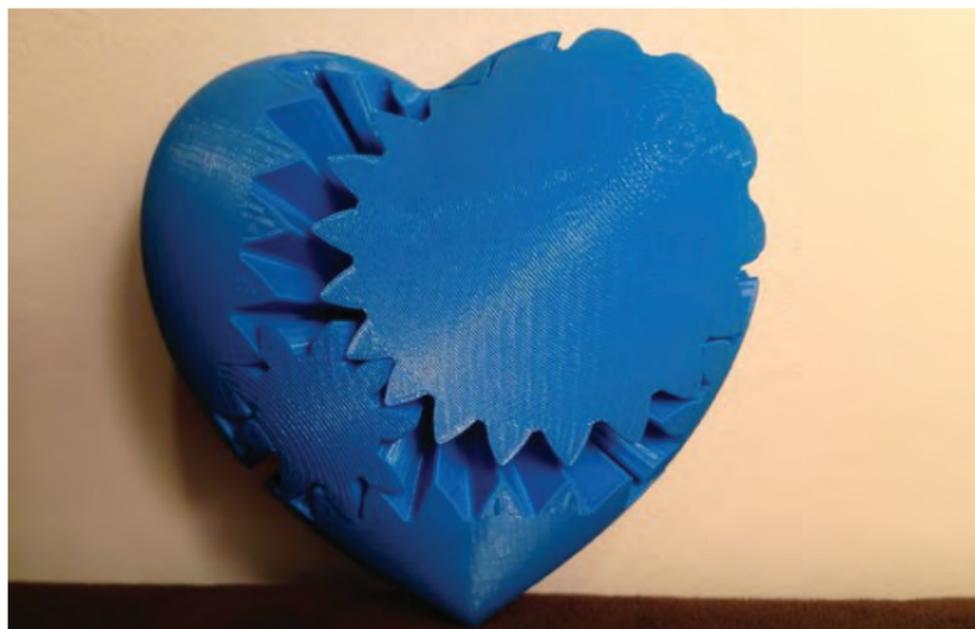
Example



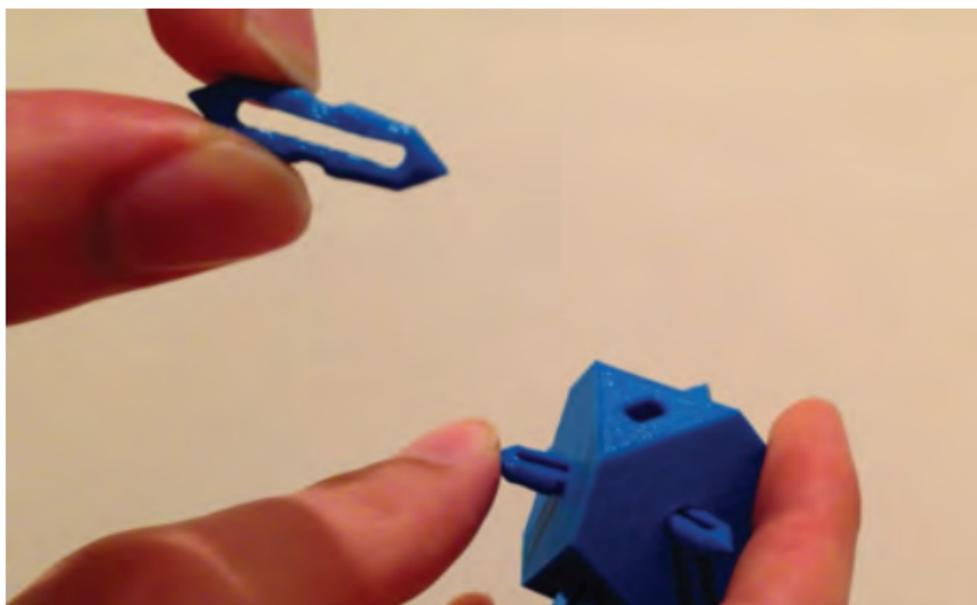
Use snap fits (quick connects) in a design instead of adding fasteners to an assembly if the assembly is more than one piece

See other side for a more in-depth example

Incorporate Snap Fits (Quick Connects)



In this example, the designer implements snap fitting shafts to connect the gears of the assembly to the central hub. By doing this, the use of fasteners is avoided and all parts are created using a single machine.





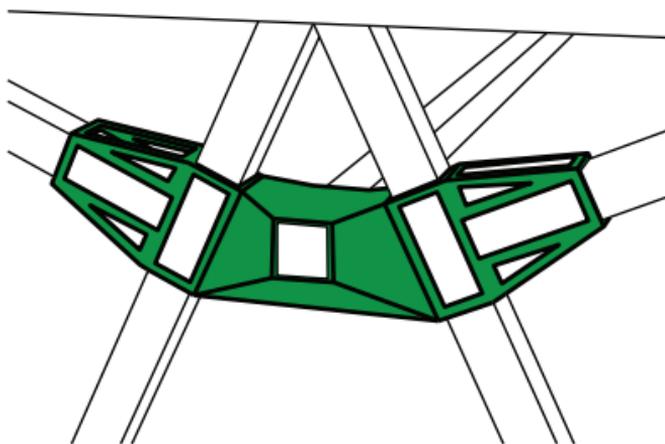
Incorporate Standard Interfaces

Incorporate existing low-cost components

BY

Integrating the necessary standard interfaces

Example



Incorporate standard interfaces for things like fasteners or common materials that might be too large to print or that satisfy constraints such as strength, rigidity, and cost better than the AM materials.

See other side for a more in-depth example

Incorporate Standard Interfaces



<http://www.thingiverse.com/thing:17612>

In this example, the quadcopter above has been redesigned to accommodate metal rods instead of being printed entirely. This may be done because the build volume is not large enough to print the entire vehicle. It may also be because the metal rods are stronger or more cheaply and readily available.



<http://www.thingiverse.com/thing:20581>



Segment Large Artifacts

Improve manufacturability

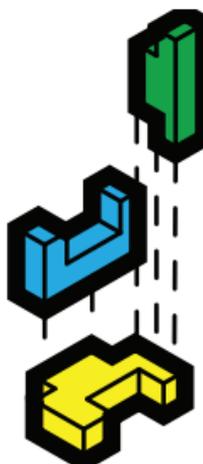
BY

Dividing an artifact into smaller components

Traditional



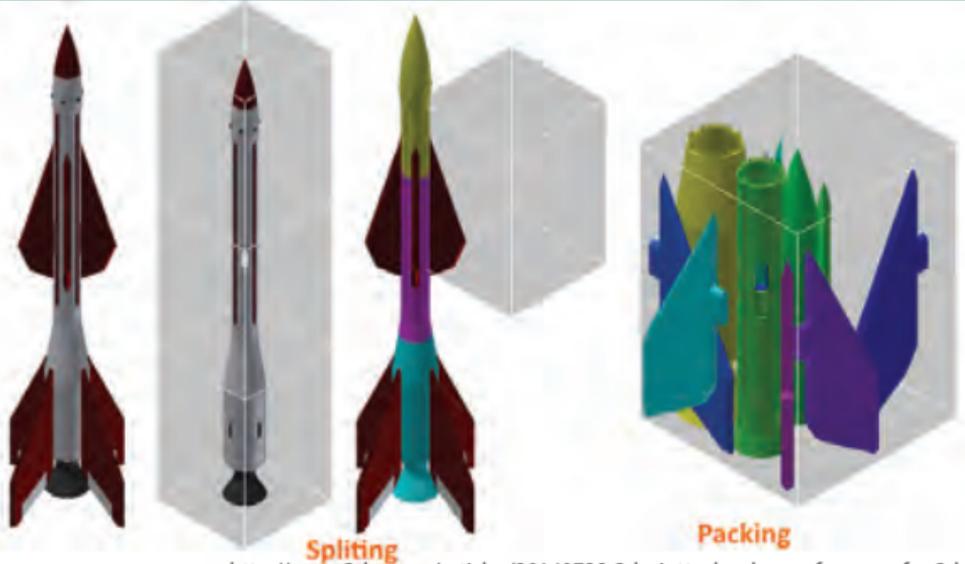
Principled



If a part is too large for the build volume of the selected AM process, it can be divided into smaller parts and assembled after being manufactured.

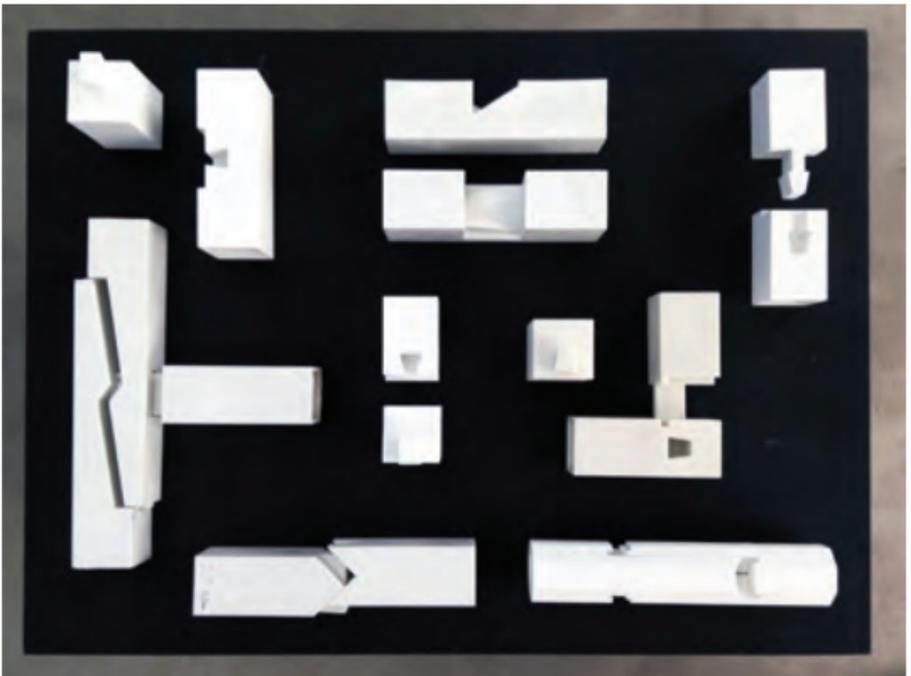
See other side for a more in-depth example

Segment Large Artifacts



<http://www.3ders.org/articles/20140728-3dprinttech-releases-free-app-for-3d-printing-objects-larger-than-build-volume.html>

The above image shows a rocket designed to be split into multiple components to fit into a single build tray. The example below shows how japanese wood joinery techniques can be implemented using additive manufacturing to join parts together.



<https://idc.sutd.edu.sg/>



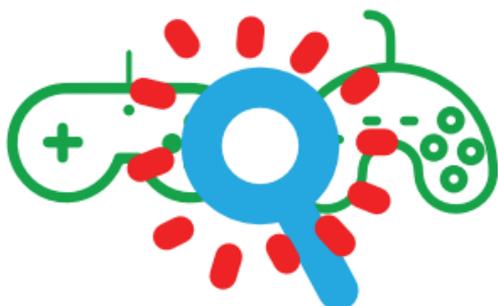
Enable Printed Perturbation Studies

Improve learning in prototypes

BY

Printing several variations of a design and
comparing them

Example



Leverage AM to print variations of the same
concept all at once to quickly compare many
different options.

See other side for a more in-depth example

Enable Printed Perturbation Studies



In this example, researchers developed a new concept for a spoon specifically for feeding babies. As the tip's design was critical to the product's effectiveness, the team leveraged AM to design, manufacture, and test many different variations of the spoon's geometry.





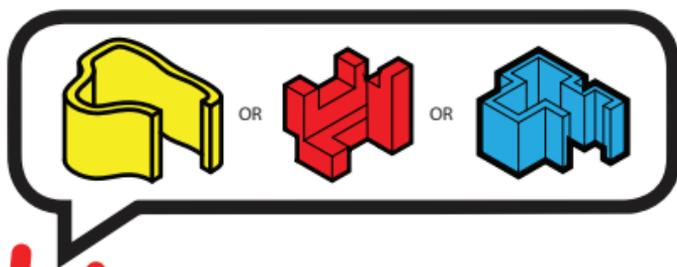
Enhance Concept Generation

Improve the concept generation process and outcomes

BY

Printing simple prototypes of a design or its subsystems

Example



Use AM to rapidly produce ideas during concept generation to help communicate ideas

See other side for a more in-depth example

Enhance Concept Generation



Design requires iteration. AM allows for the rapid development of prototypes from as early as ideation. Use AM to validate ideas early on and refine them as the design team progresses. These examples show the sheer number of iterations undertaken to develop a final product. All are enabled by AM.





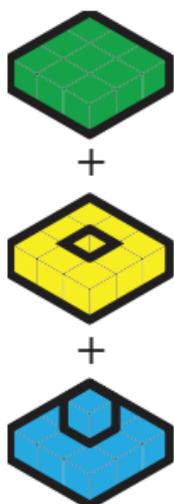
Combine Parts or Components

Reduce assembly time and product complexity

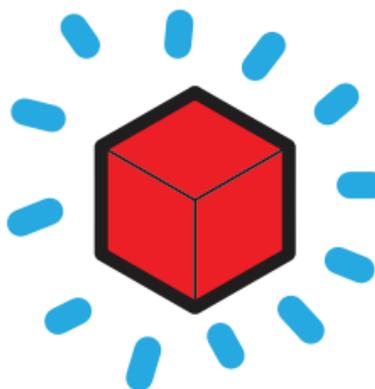
BY

Integrating multiple pieces of an assembly into
a single printed component

Traditional



Principled



Instead of assembling multiple components to create a single product, AM has the capability to print several components directly.

See other side for a more in-depth example

Combine Parts or Components



In this example, AM is used to reduce the complexity of this air duct's assembly. Instead of an assembly of four pieces using four fasteners, it is printed as a single piece with zero fasteners.





SUTD-MIT
INTERNATIONAL
DESIGN
CENTRE (IDC)

Innovation Ready Design



U.S. Air Force Academy
Engineering Mechanics

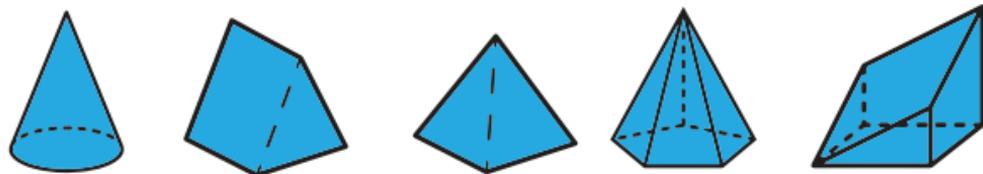
Rapidly Prototype for Assessment

Improve design outcomes

BY

Using AM to create prototypes to assess form,
feel, aesthetics, and/or functionality

Example



Use AM to rapidly prototype different design
concepts for validation.

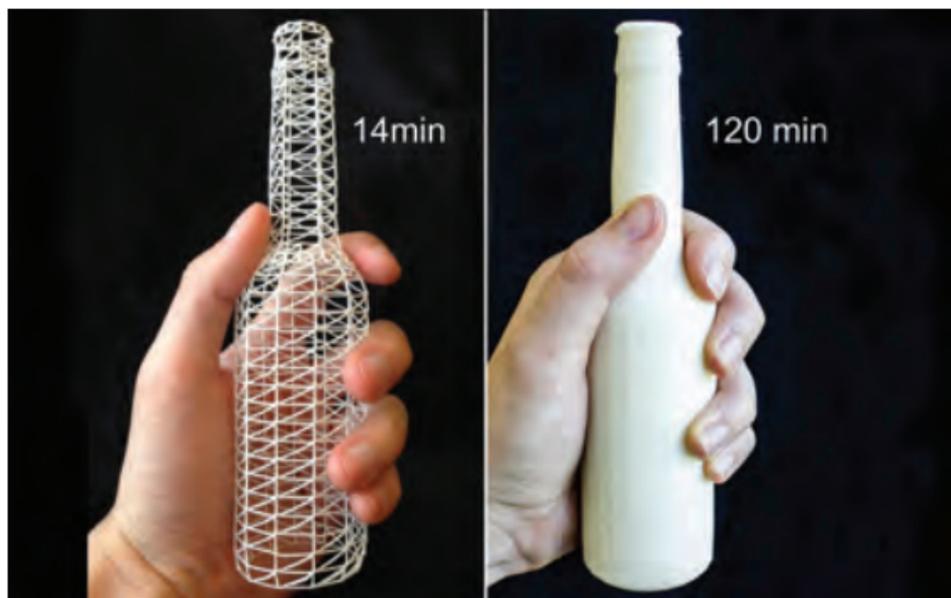
See other side for a more in-depth example

Rapidly Prototype for Assessment



<https://www.ascentaerosystems.com/>

AM can help designers prototype and test quickly. AM has helped to create early prototypes for market validation. Researchers from Cornell University created a system to rapidly print wire frames of objects for form and feel testing, a valuable prototyping tool.



<http://www.cs.cornell.edu/projects/wireprint/>



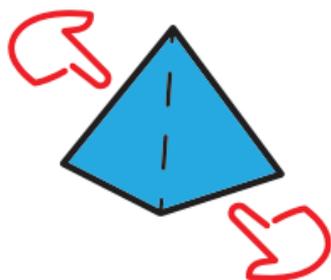
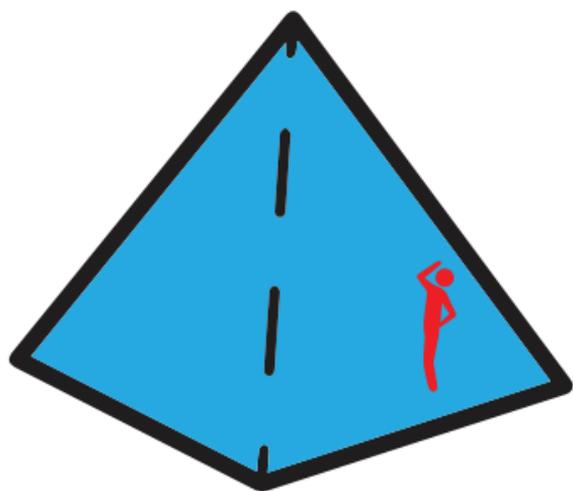
Perform Scaled Testing

Reduce testing time and cost

BY

Additively manufacturing scaled models of a design before creating a full-sized version

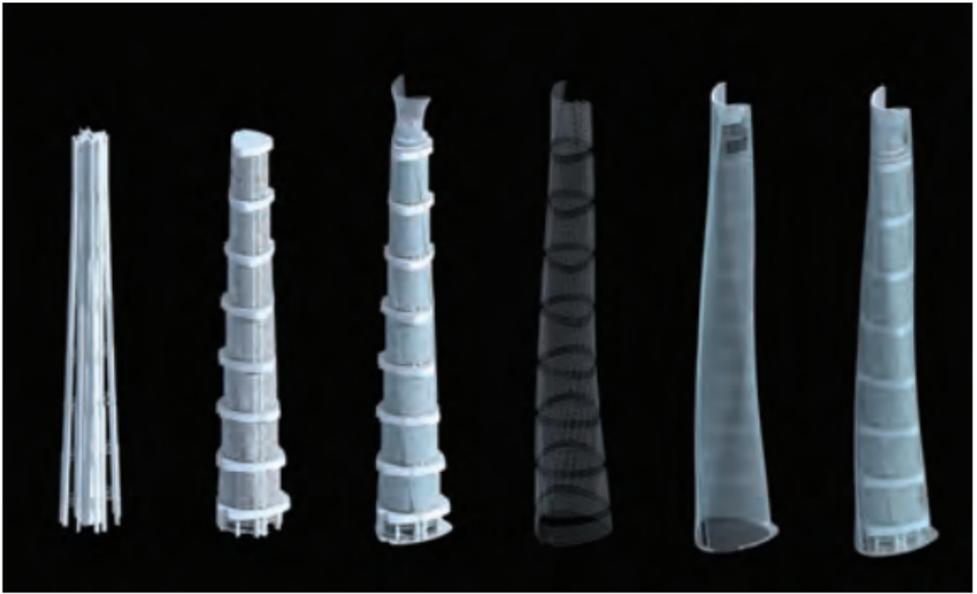
Example



For example, a design team might print and test this scale model of a larger model verify its functionality before building a full sized version.

See other side for a more in-depth example

Perform Scaled Testing



During the design of the Shanghai Tower, scaled models of the tower were first implemented in wind tunnel tests to validate the idea that a spiral configuration would reduce wind side loads. The models above are only a few feet tall.





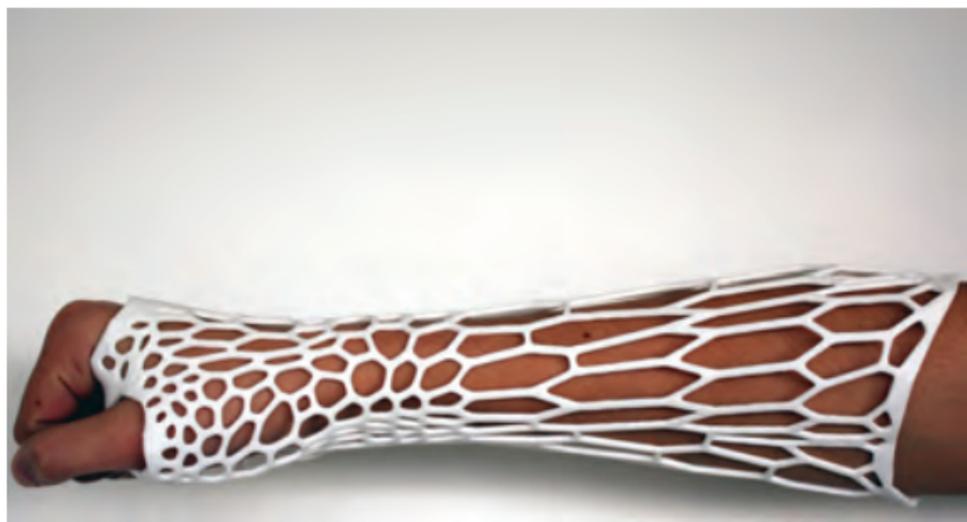
Enable 3D Scanned Personal Interfaces

Enable individualized products

BY

Creating designs that accomodate customized geometries derived from the user

Example



Use AM to create designs which include custom interfaces for customer use like this cast.

See other side for a more in-depth example

Enable 3D Scanned Personal Interfaces



Bespoke Innovations used a mirrored 3D Scan of a patient's remaining leg to create the geometry of the prosthetic fairing for the missing limb. This is unique to every user and made possible with AM.





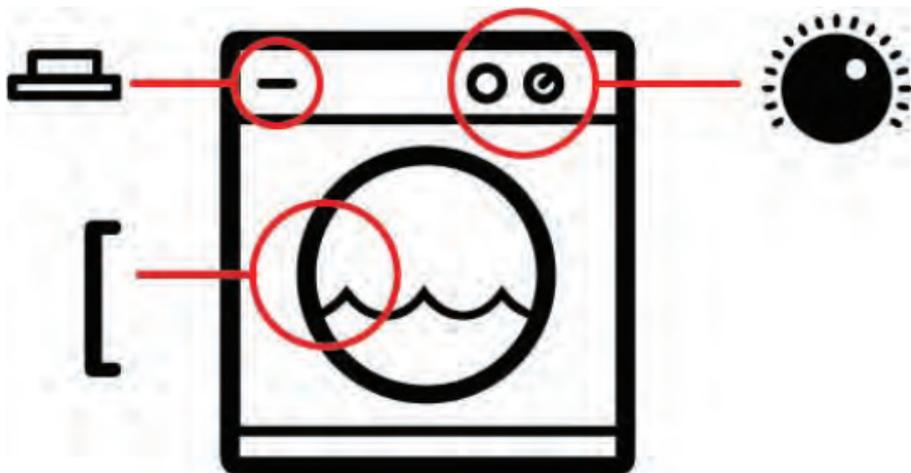
Produce Rapid Replacements

Reduce product downtime and supply chain costs

BY

Using AM to produce replacement parts

Example



Use AM to create rapid replacements rather than relying on traditional supply chains.

See other side for a more in-depth example

Produce Rapid Replacements



Synthesizer company Teenage Engineering provides STL versions of spare parts to enable on-site manufacture and repair of their products by the end-user



acc stl STRAP SCREW 1

by | Found This



From:
\$2.91



acc stl OP CRANK ASS...

by | Found This



From:
\$2.51



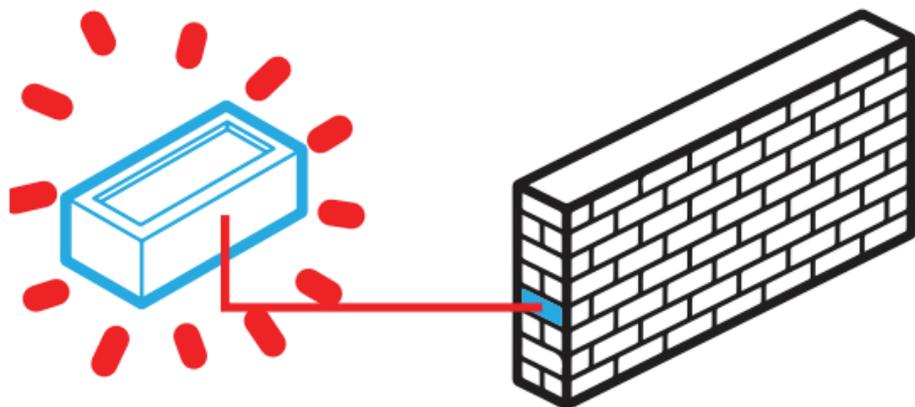
Design Modular Components

Improve product flexibility

BY

Designing modular components that recombine
to achieve different functionality

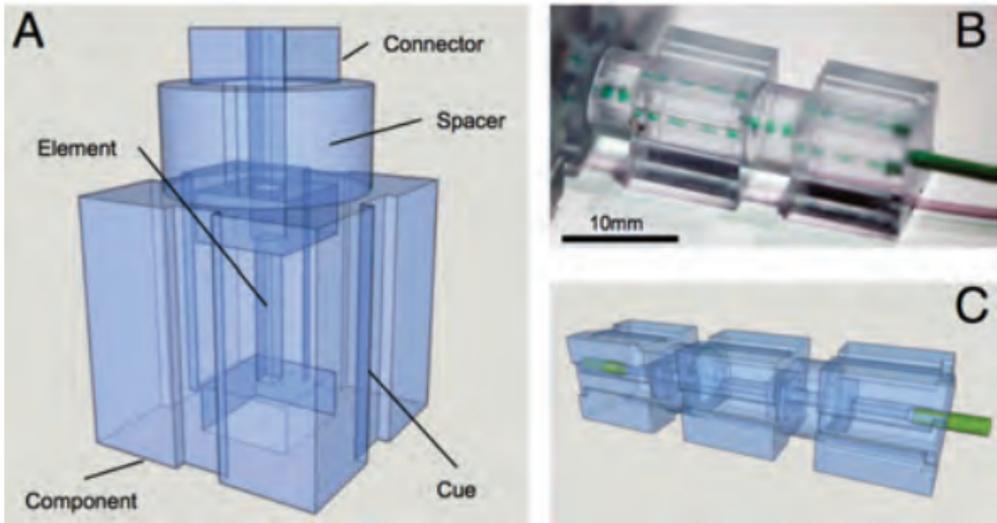
Example



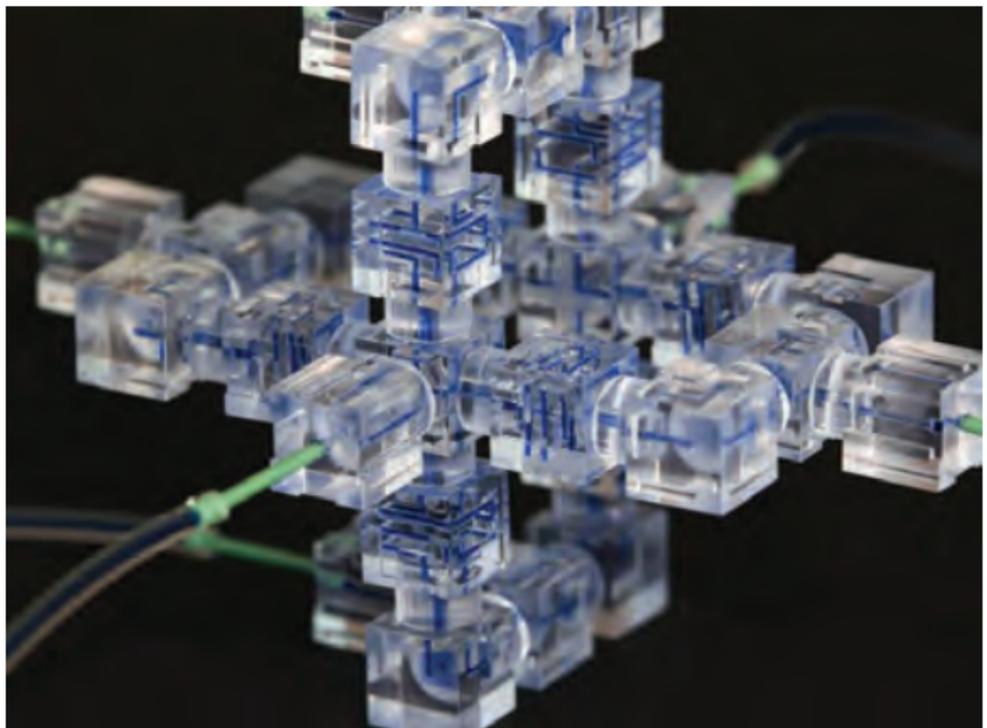
Modularity allows for the replacement or parts for
both repair and for altering the functionality of a
product.

See other side for a more in-depth example

Design Modular Components



In this example, additively manufactured microfluidic modules are design to be assembled together to created much more complex microfluidic circuits for investigation of different fluid behaviors and functions



Bhargava, K. C., Thompson, B., & Malmstadt, N. (2014). Discrete elements for 3D microfluidics. *Proceedings of the National Academy of Sciences*, 111(42), 15013-15018.



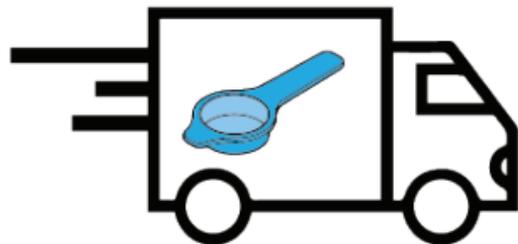
Produce at the Point of Consumption

Reduce supply chain logistics

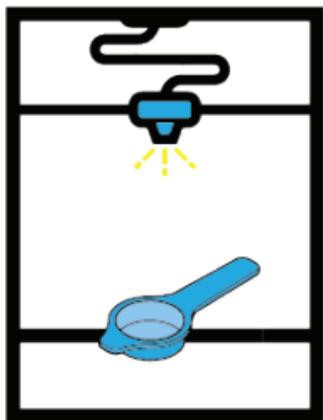
BY

Using AM to create parts at or near their point of consumption/use

Traditional



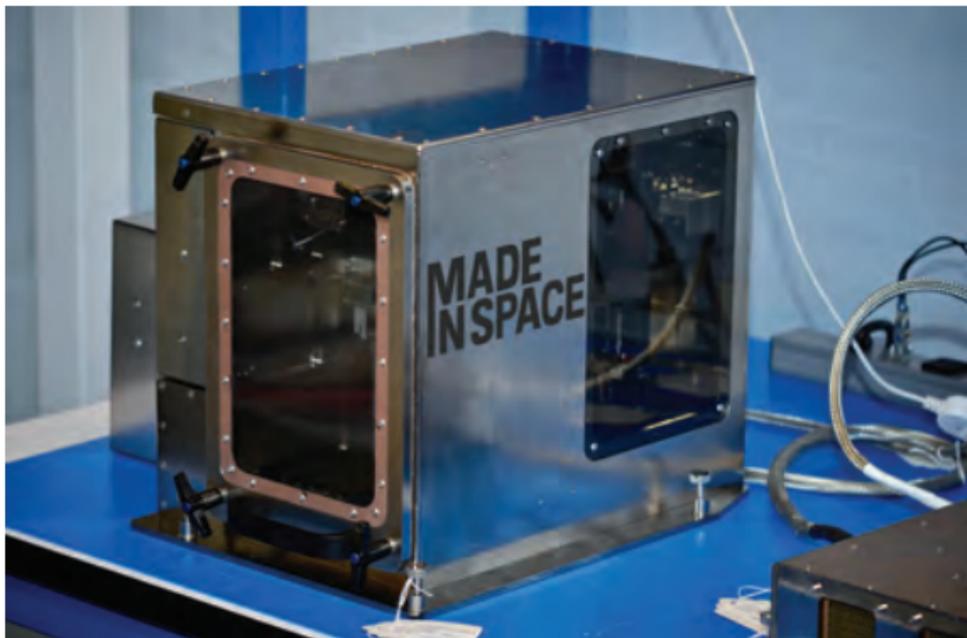
Principled



AM provides the ability to produce parts where they are needed when the user cannot wait for normal shipping lead times of more complex supply chains.

See other side for a more in-depth example

Produce at the Point of Consumption



Because taking every tool that astronauts might need into space violates cost and weight restrictions, Made In Space aims to launch a smaller volume of raw materials which can be used to print tools as they are needed based on the mission or problems encountered



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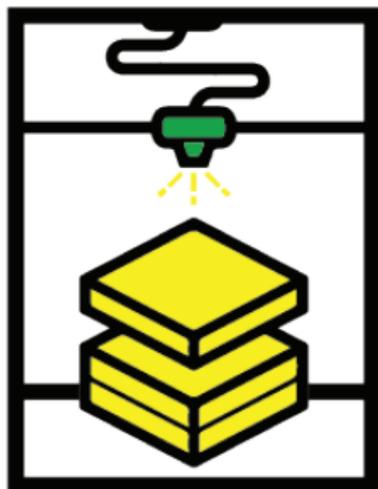
Reduce Part Obsolescence

Improve product lifetime

BY

Additively manufacturing replacement parts
that are no longer in production

Example



Use AM to recreate parts for products that may
no longer be available through traditional
markets.

See other side for a more in-depth example

Reduce Part Obsolescence



In these examples, AM is used to create a car's dial cluster that is no longer in production. Below, components are printed to replace parts to construction sets no longer in production. (They also help to interface different brands of construction toys!)





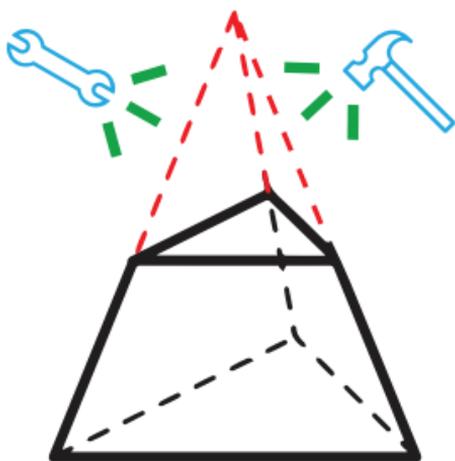
Enable Rapid Repairs

Improve product lifetime

BY

Using AM to replace material at points where it
has worn away

Example



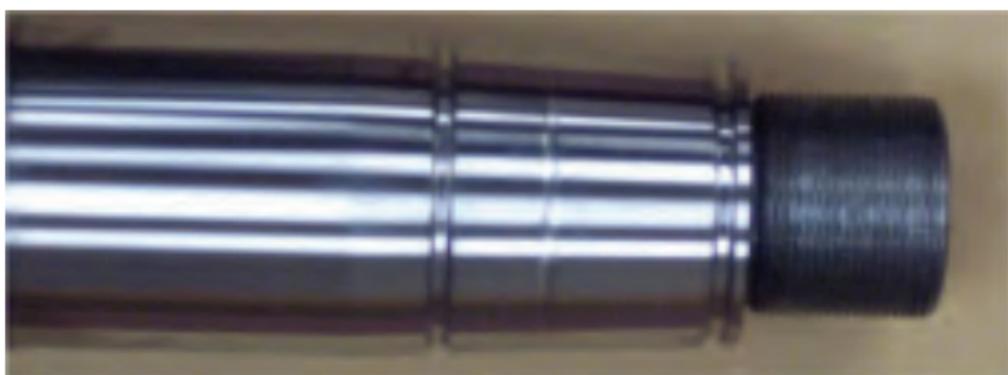
Instead of waiting on a replacement part, use AM to repair a part. This is especially useful in situations where replacements or downtime are very expensive

See other side for a more in-depth example

Enable Rapid Repairs



In this example, a worn shaft first undergoes a laser cladding process to build up bulk metal around the worn area. Following the laser cladding, excess metal is machined away leaving a part that is in like-new condition. This process eliminates waste and saves time.





Use Computationally Driven Designs

Optimize design parameters

BY

Using computationally driven designs from
software

Traditional



Principled



In this example, software is used to optimize material placement in a bracket's design.

See other side for a more in-depth example

Use Computationally Driven Designs



The frame of this bicycle is redesigned using computationally driven structures. These structures are not feasibly manufactured with conventional machining. The geometric flexibility of AM allows for its implementation here.

