Manufacturing Distinction

Gaining access to Mass Customization in the Production of Architecture

by
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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Gaining access to Mass Customization in the Production of Architecture

Contemporary architecture often finds itself challenging the physical constraints of the previous era and typically aims to be one of a kind. This thesis views architecture as the accumulation of design and construction and considers both from the view of constructibility. The design of architecture relies upon the formal desire, its materiality, function, direction of which parts are needed and how they can be constructed. The construction of architecture focuses on the coordination, fabrication and assembly of these parts. The industry of construction has three primary constraints: time, cost, and labour. To ease the construction process ideals have been borrowed and implemented from manufacturing to allow streamlining and moved away from the world of bespoke construction.

We sit in a system of construction based upon the manufactured part. Manufacturing operations follow one essential formula, the transformation of raw material through the addition of machinery, tools, energy, and labour, to provide the desired product with greater function and value. All consumer items are created through these methods individually or in some combination, having to navigate the complex order of procedures which transform simple materials into everyday objects. The constraints of material play a significant role in the manufacturing operation available to produce any given object and its subsequent performance in an architectural application.

Architecture is much more than the manufacturing of a single object. Similar to the production of bikes, cars and other consumer products, architecture utilizes what is known as a system of production. With increased product demand the system of production has naturally transformed as well. Improvements can be seen in areas of logical flow (the division of labour and interchangeable parts), physical flow (the assembly line, mechanization, and digitalization), and controls (tolerances and standards). The constraints of a product play a large role in the appropriateness of a system of production for that object, subsequently impacting the feasibility of any object being economically produced. Manufacturing processes are moving towards digital management and flow as a way of offering unique options within the production of manufactured parts. Overall, architecture strives for a way to be unique within the boundaries of manufactured elements, achieving this through different means such as distilling the function of a space to the elements that construct it, constructing with modular elements, and componentized customization.

The transition towards digital design of objects within the industry allows a physically ‘free’ environment to create within; additive manufacturing offers the processing counterpart by digitally shaping physical objects from ‘nothing’. Moving architecture into the digital realm shifts it into a place to easily integrate digital design data into the manufacturing process. Having the ability to bypass the challenges of how we make items, why we choose specific materials, why we produce at specific volume runs, and ties into existing digital production processes. The potentials stand out in the area of producing objects with unique physical constraints or meeting the demands of small product runs.

Acknowledgments

To Josiah and Isaac, the best source of inspiration for understanding the world. To Jacquelyn many thanks for helping me pull through the final drafts. To my parents, I would not be the person I am today without your guidance support and love,

To my professors and peers for guiding my understanding of the world around me: the flow of processes, materials, and labour in a complex and ever-changing industry.

Thank You,

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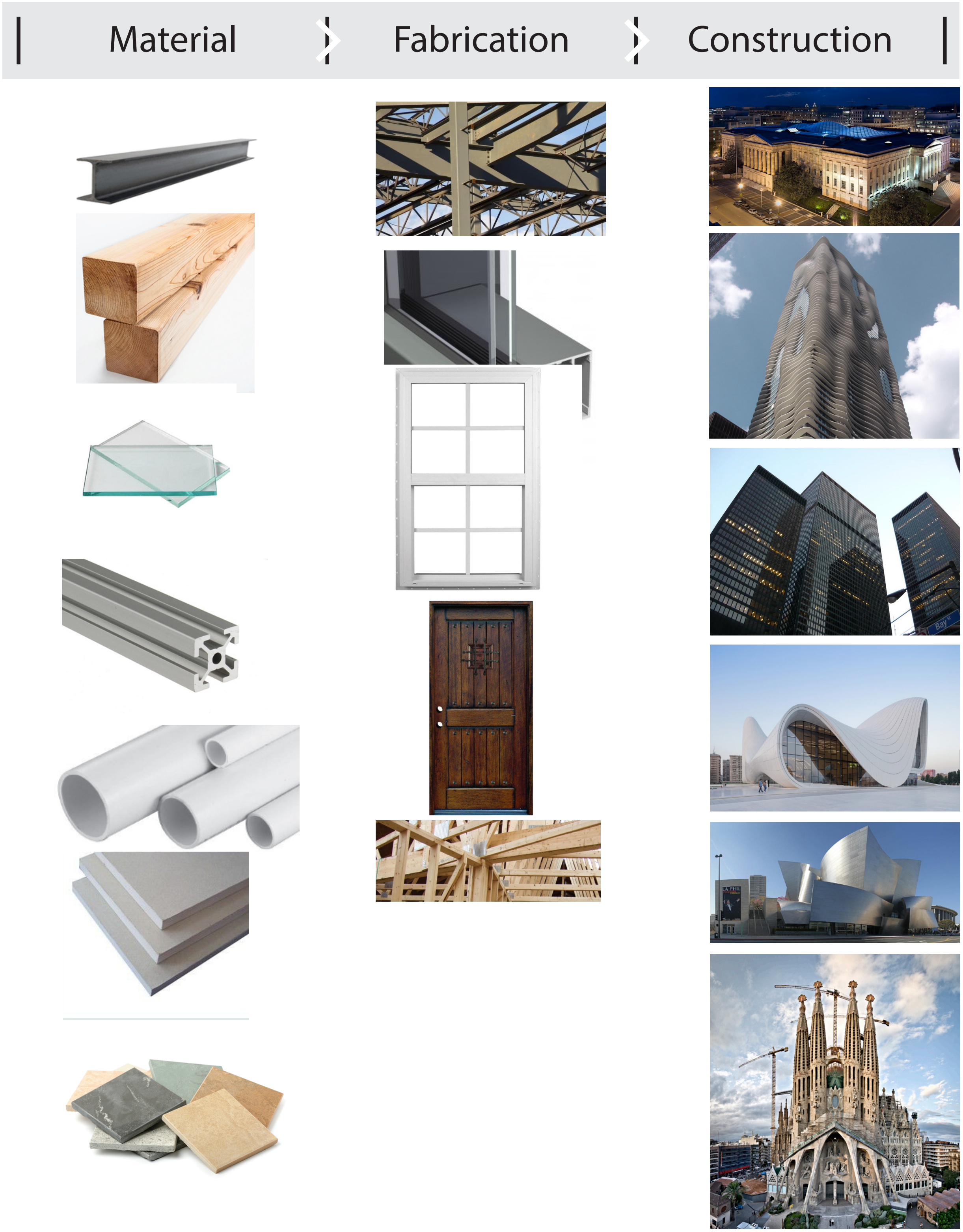


Figure 00.1 • Production of Architectural Objects

As architecture is composed of many different objects it relies on the production of said items. These items have entire series of processes to first pass through. From mining, manufacturing, fabricating, and finally being ready for construction.

oo: Introduction

oo.1 Objective

This thesis will cover the production of objects in context to Architecture. It will review digital design, and how it enables a workflow geared towards three-dimensional printing technology today and in the near future. It will then examine its competition among other manufacturing methods and their systems of production, and critically consider the performance of three-dimensional printed artefact's in architecture. The thesis aims to answer whether three-dimensional printing can open up new realms of design not currently possible, offer a better alternative to established manufacturing methods, and break down barriers in communication between industry tiers.

oo.2 Scope

Architects strive for distinction in an industry where the product is commonplace. The built form is intrinsically a part of every person's life and as such sits in the juxtaposition of being easy to relate to through its multiplicity and difficult to break down into its individual composition. This distinction can be achieved through various approaches, but the possibilities are limited by external pressures such as economics, cultural history, and technical performance. These pressures make the translation from ideal to physical difficult placing great weight on the ability to navigate them. In response, the technology we use to construct buildings has been transformed and adapted over the years to keep up with increased demands of economic performance and product distinction. Production has become streamlined and moved away from the world of bespoke construction, to one of componentized and manufactured parts.

Additive manufacturing, also known as three-dimensional printing, is the latest step in this evolution of manufacturing technology. The name derives from the similarities to the commonly used ink-jet printer where a print head deposits material in a particular position and pattern. 3D printers use a variety of materials in place of ink, with the head mounted on a gantry that can move in three directions. The "ink" can be comprised of plastic, metal and ceramic with a variety of benefits to each. This emerging technology will inevitably impact the field of architecture, with the depth of these changes yet to be analyzed. The following will explore the challenges the built form brings, the challenges architects have translating form, and the potential benefits of three-dimensional printing (3D printing, 3DP).

oo.2.1 The challenges with construction

The industry of architecture currently exists within the reality that:

- A custom solution is required for each project.
- Many stakeholders are part of the final product.

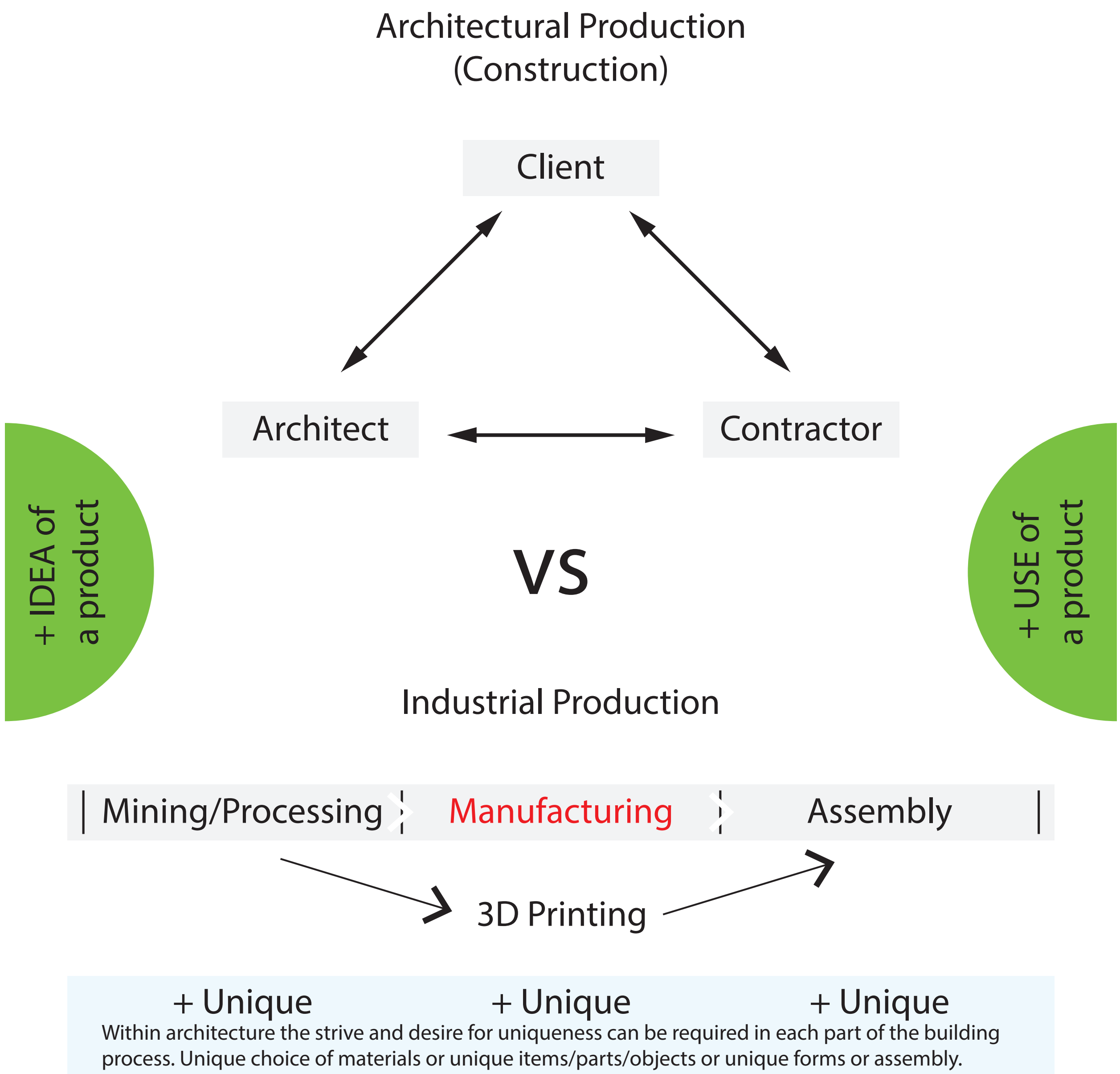


Figure 00.2 • Production Cycles: Architecture vs Industrial

Translation of an Idea 3D printing allows for a manufacturing style which does not rely heavily on knowledge of material properties or manufacturing processes - this allows an added freedom when looking for uniqueness.

- Componentized assembly requires that parts progress through tiers:
  Material > Fabrication > Construction
- Communication is difficult between tiers:
  Material <> Fabrication <> Construction

On the journey of a project's inception to construction, architecture must respond to real-world constraints; these include site conditions, functional program, local regulations and market constraints. Site conditions are physical limits that provide fundamental restrictions for the building to meet, such as; climate zone, sun, wind, soil type, and seismic zones. The functional program can provide constraints in two ways: first, it must meet the needs of the client; secondly, it can inform aesthetic design decisions for the project. Local regulations establish the limits a building must meet to achieve the desired performance level and may impact location, size, materials, construction options, and aesthetic choices. Markets impact the affordability of a project, one of the final barriers for a project on its path to a built form. Projects approach these hurdles during the design phases and continue to fine-tune solutions right through to construction administration.

Similar to manufacturing, construction is the creation of an object, but has outlying constraints which prove to make execution vastly different from the manufacturing industry. (see Figure 00.1). Industrial production hinges around the ability to produce many objects at the cheapest price for a consumer market. Objects typically come off the line identical, or at most with slight changes. Architectural production focuses on one building which responds to unique conditions and provides value to a client while interacting with society at large. Architecture rarely produces exact copies, though parts are standardized across buildings. This is a process that is changing, as architecture in some cases is adopting industrial methods with a goal to increase efficiency and meet client demands of lower cost, less time, and reduced labour as fee pressures increase.

Architectural production currently has a series of tiers defining the progression of assembly which flows from material to fabrication to construction (see Figure 0.1). The fulfillment of architectural uniqueness can be met through a unique approach in any of these tiers. The Material tier covers processing of raw materials into a usable object (e.g. channels, beams, boards, slabs, bars, rods, or cables.) The Fabrication tier pertains to the assembly of objects into components. Construction deals with the final joining of these components into a building. Factors such as labour, time, and cost heavily impact the quality, craft, and value of any object transitioning through the process. Shifts in where labour, time, and cost lie within the tiers affect the outcome of the built form.

Communication is difficult between the tiers of material, fabrication, and construction. Each tier has a specialized knowledge base and, as such, naturally approaches solutions to problems differently. Navigating a balance between the material limits, the processing limits, and the performance limits require tremendous communication between the tiers. Standard details

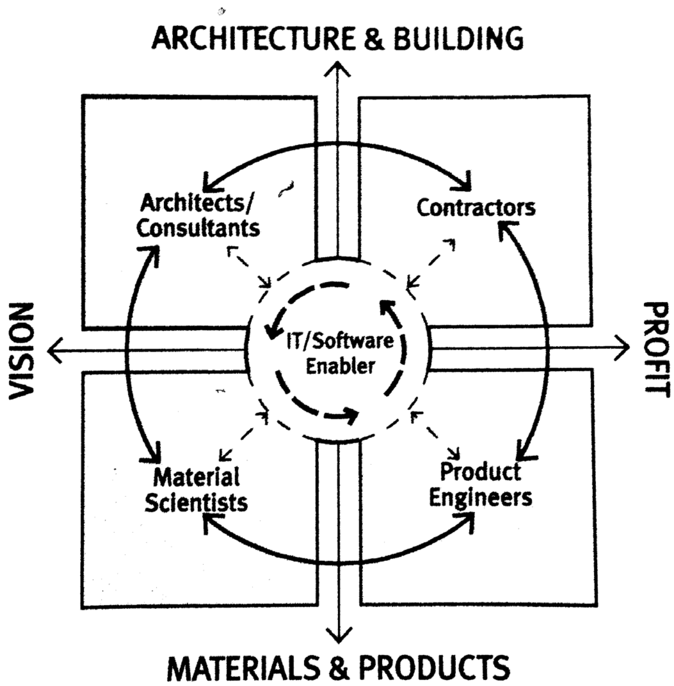


Figure 00.3 • Potential connection of disciplines

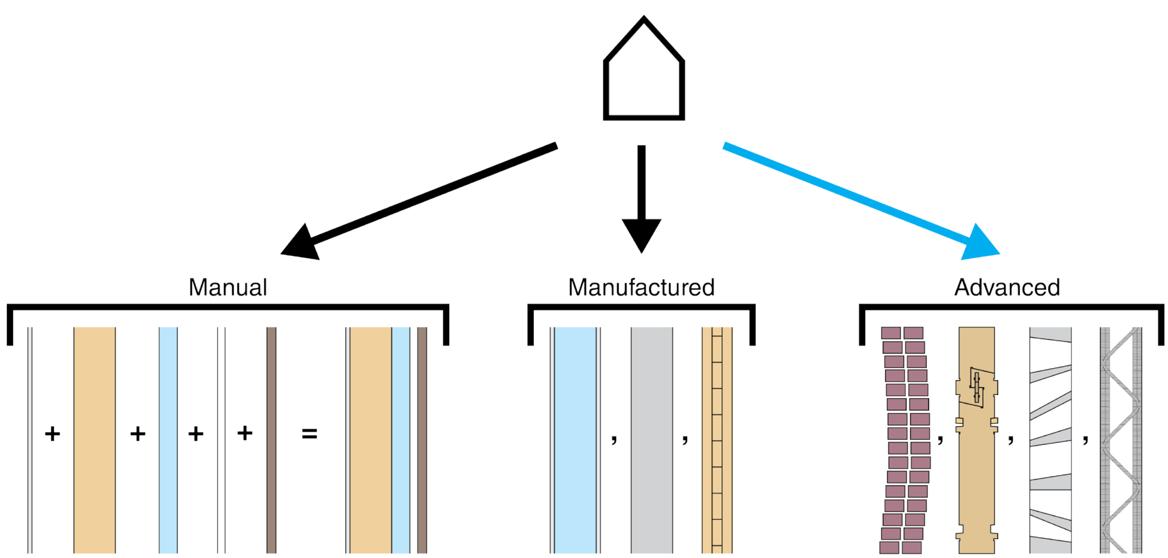


Figure 00.4 • Complex Systems

and approaches allow for knowledge to be embedded in a form which can be shared and discussed across disciplines. The adoption of digital design attempts to tie together these fractured knowledge bases through more precise communication. With knowledge bases become digitally shareable, designing to a given standard will become more effective.

oo.2.2 The potential of Additive Manufacturing

Three-dimensional printing offers potentials to the architectural industry by its ability to:

- translate digital objects into physical objects
- universally produce any shape
- simplify constraints between tiers:

Material = Fabrication = Construction

Direct digital fabrication of design data to physical objects is possible through the implementation of Computer Assisted Manufacturing (CAM). CAM gives digital data the ability to directly command movements, tools, and actions of a machine. Additive manufacturing would not be possible without CAM processing, forging a strong connection to the digital environment. Previously, skill was required to shape or form a material by hand, now descriptive geometry and its derivative code are required. This connection allows digital data to be easily passed from computer to physical without first being broken into physical media, such as 2D drawing or specification manuals. Original design data can be fully utilized as final production data with 3D printing.

Manufacturing processes are typically designed to solve the production of one type of object. In the past a process would have numerous machines each performing a specific task; understanding how the individual process paired with design intent was complicated. Now one machine can produce a final product simplifying the fabrication process. Additive manufacturing creates an object by building it up from nothing, requiring no moulds or forms as it builds. This gives three-dimensional printing the flexibility to accept a variety of designs and produce a variety of objects.

Communication between material knowledge, manufacturing knowledge and construction knowledge can become embedded into three-dimensional printing. One process can produce many objects while retaining the ability to produce with many materials. Material knowledge is limited to the standard materials available for printing which meet performance requirements. Manufacturing knowledge is conveniently contained within the digital mechanization of additive manufacturing. Construction knowledge remains the defining aspect of the purpose for an object to be produced.

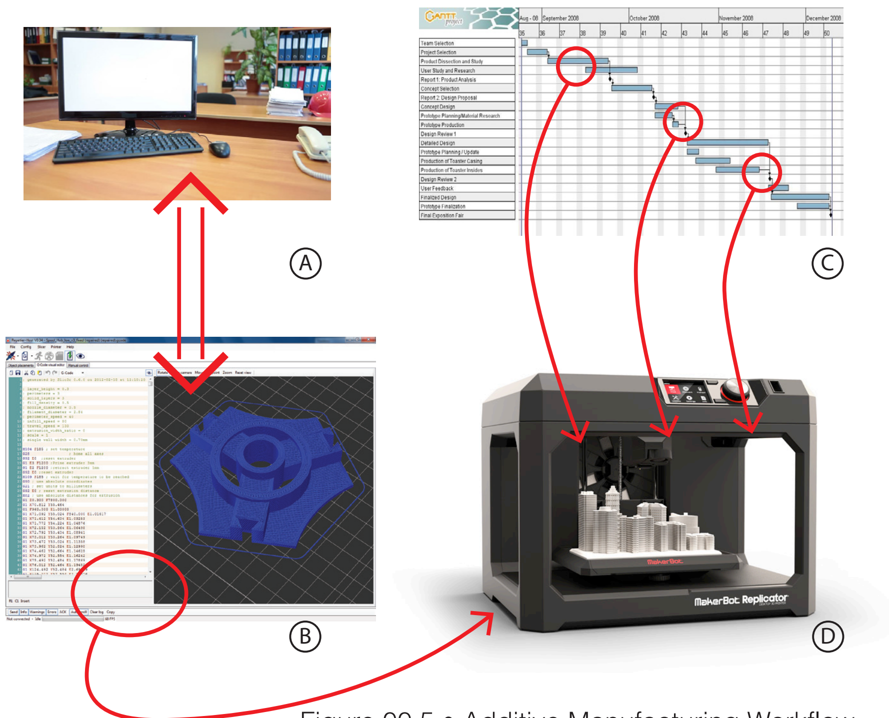


Figure 00.5 • Additive Manufacturing Workflow

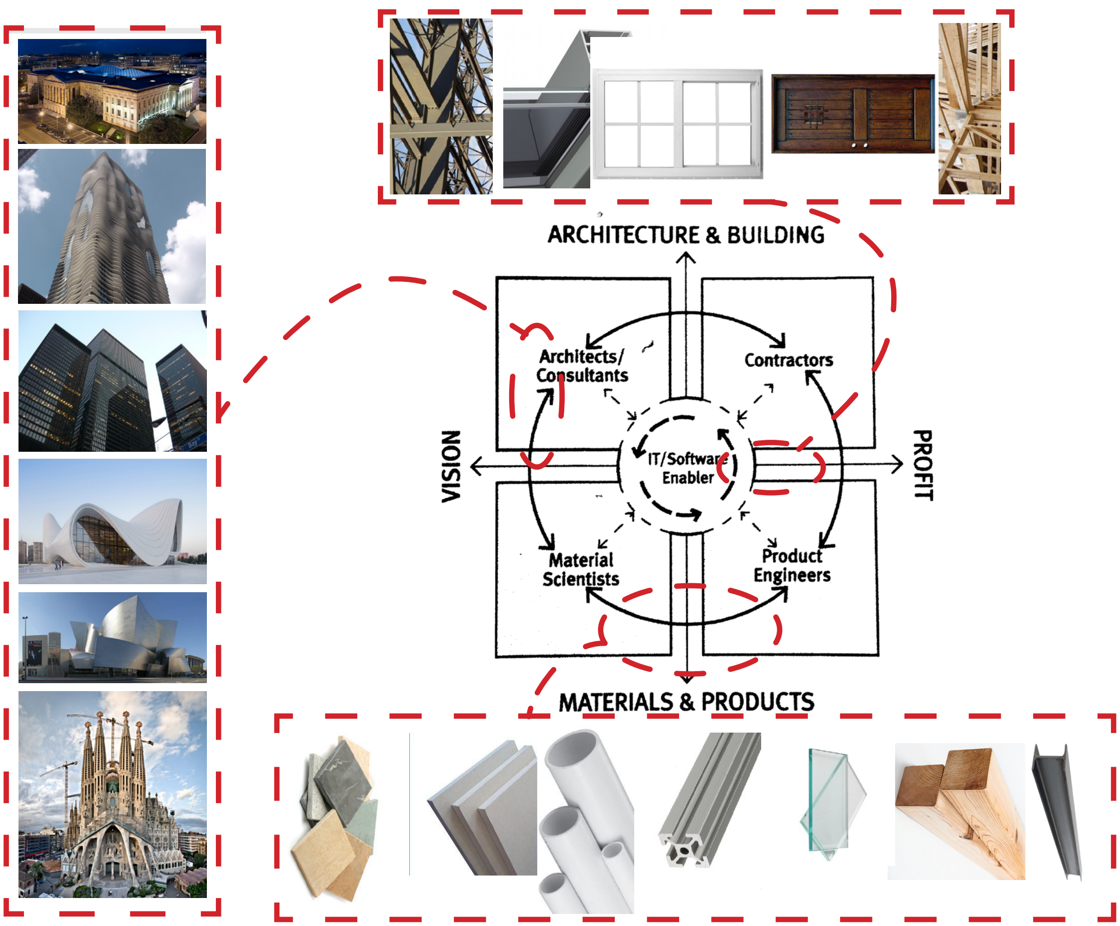


Figure 00.6 • Connection of parts and their knowledge base

oo.2.3 The benefit to the Architect

Architects rely on standard details, specifications, and construction approaches during the process of taking a design from idea to completion. Architects are charged with having a broad spectrum of knowledge which helps them weave together these specialized disciplines. This process involves communication with many different facets of the industry, engineers, contractors, materials specialists and clients. Additive manufacturing will be a useful tool for architects to achieve the unique vision of a project while navigating the tensions of the industry.

oo.3 Approach

This thesis will explore the current state of architectural production through means of manufacturing, and the limits pushed with contemporary emerging technologies. As Mikell Groover states “the history of manufacturing can be separated into two subjects: (1) human’s discovery and invention of materials and processes to makes things and (2) development of the systems of production.” (Groover, pg. 2) Following this logic, manufacturing processes of objects will be analyzed with a critical understanding of three-dimensional printing. Production processes will be evaluated for how emerging technologies (or three-dimensional printing) can transform the flow of production and current methods of manufacturing. We will then follow these changes and their subsequent impact in manufacturing architecture. Concluding with an explanation of what three-dimensional printing brings to architecture, and what cultural aspects could change to allow three-dimensional printing to find a place in the manufacturing of architecture.

ARCHITECTURE | DIGITAL TECHNOLOGIES

01

1000
500 BCE
0
500 CE
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

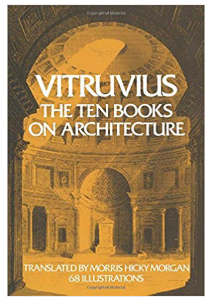
Ancient Greek · Roman · Byzantine · Moorish · Romanesque · Norman · Gothic · Renaissance · Mannerism · Baroque · Palladian · Georgian · Neoclassical · Gothic Revival · Federal · Victorian

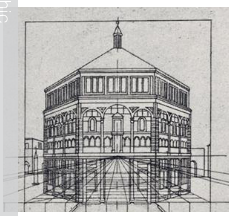
Euclid
c.300 B.C. *Optics*

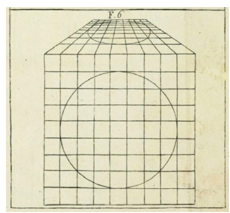
Early text describing the phenomena of sight through mathmatical properties, such as the fourth: "Things seen under a greater angle appear greater, and those under a lesser angle less, while those under equal angles appear equal."

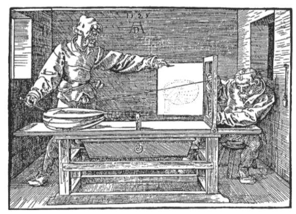
Vitruvius Pollio's
c.27 B.C. *The Ten Books on Architecture*

First text documenting western landscape architecture, architecture, engineering and town planing. Describing form, layout and organization in a set of standards to be adheared to.









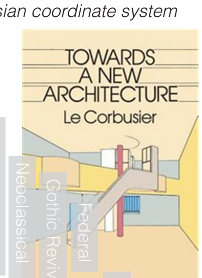
Perspective
c.1410 Filippo Brunelleschi *Perspective Technique*
1435 Leon Battista Alberti *Della pittura*
1525 Albrecht Durer *Perspective Machine*

Artistic application of geometric ideals
The translation of the visual phenomenon of perspective was able to be anaylitically described with a physical tool and explanation. Developed independently by various artists and mathematicians.

Andrea Palladio
1570 *The Four Books on Architecture*

Renaissance text accounting material and techniques to the design of space from home to city.

Rene Descartes
1637 *Cartesian coordinate system*



Le Corbusier
1923 *Towards a New Architecture*

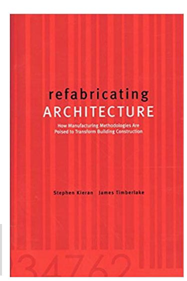
Modernist Text aligning the new world order to a reduced functional aesthetic based on the machine for living

Computer Aided Design
1957 Dr. Patrick J. Hanratty *PRONTO*
1975 CAD *systems grow in popularity*
1989 NURBS *Mathematical representation of freeform surfaces*
T-FLEX *Parametric modeling introduced to CAD*

The development of Computer numerical control allows for the creation of 2D and later 3D drawings with the use of a computer.

Stephen Kieran
2003 *refavricating ARCHITECTURE*

Review of manufacturing methodologies in adjacent industries to architectur and how these workflow's should be addapted



o1 Architecture ≠ Digital ≠ Technologies

o1.1 Introduction

This section will first review a few theories regarding architectural production; we will see what factors led the industry to become isolated from production. Followed by an overview of current explorations using additive manufacturing for the production of architecture. These explorations will set a baseline for the capabilities of current and fringe additive manufacturing technology.

Theories of architectural production have followed manufacturing trends through history in attempts to optimize time, cost, and labour. Le Corbusier saw a reduction of the house into a machine that can be easily reproduced while being brutally efficient with materials. This reduction of the building into components allows for its ease of being numerically classified and controlled. (Corbusier, 1970, pg 10) Kieran|Timberlake build on the idea of a component as the avenue to customize on a large scale but maintain the framework of mass production. (Kieran Timberlake, 2005, pg 133) With digital control, Gregg Pasquarelli (SHoP) has found digital computation allows a hand at creating many unique elements within the same constraint of many repeated elements. They rely on digital computation to create complete uniqueness and deliver a massive output of unique items in a database which with modern computing, is manageable to the contractor. (SHoP, 2002, pg11) An ever-increasing digital framework has developed along these theories, allowing them to utilize differing production methods and processes to create unique and challenging work while adhering to the three constraints of time, cost, and labour.

Additive manufacturing is intrinsically a digital production method, working within the realm of translating three-dimensional data. Many exploratory works are pushing the boundaries of architectural production; these fringe production methods help push forward the commonplace, creating an opportunity for trickle down adaption. With the advent of three-dimensional printing, the concern has been less focused on what it has changed, to where it can make a change; the case studies in this section challenge scale, materiality and volume as it compares to architectural components.

o1.2 Theories of Architectural Production

o1.2.1 Towards a New Architecture

New technology developed in the twentieth century focused on the optimization of construction methods. Le Corbusier theorized in the 1920s, on the construction of an ideal dwelling, one of efficiency and purpose which promptly became idealized as the "machine for living." (Corbusier, 1970, pg 4) Reduced to the function of the machine architecture could become a product of the industrial age. The principles of his theory focus on optimizing and distilling form, break the building into systems and components, and simplifying construction to a role of assembly, not craft.

Section o1

Figure 01.1 • Timeline of architectural theory's and styles

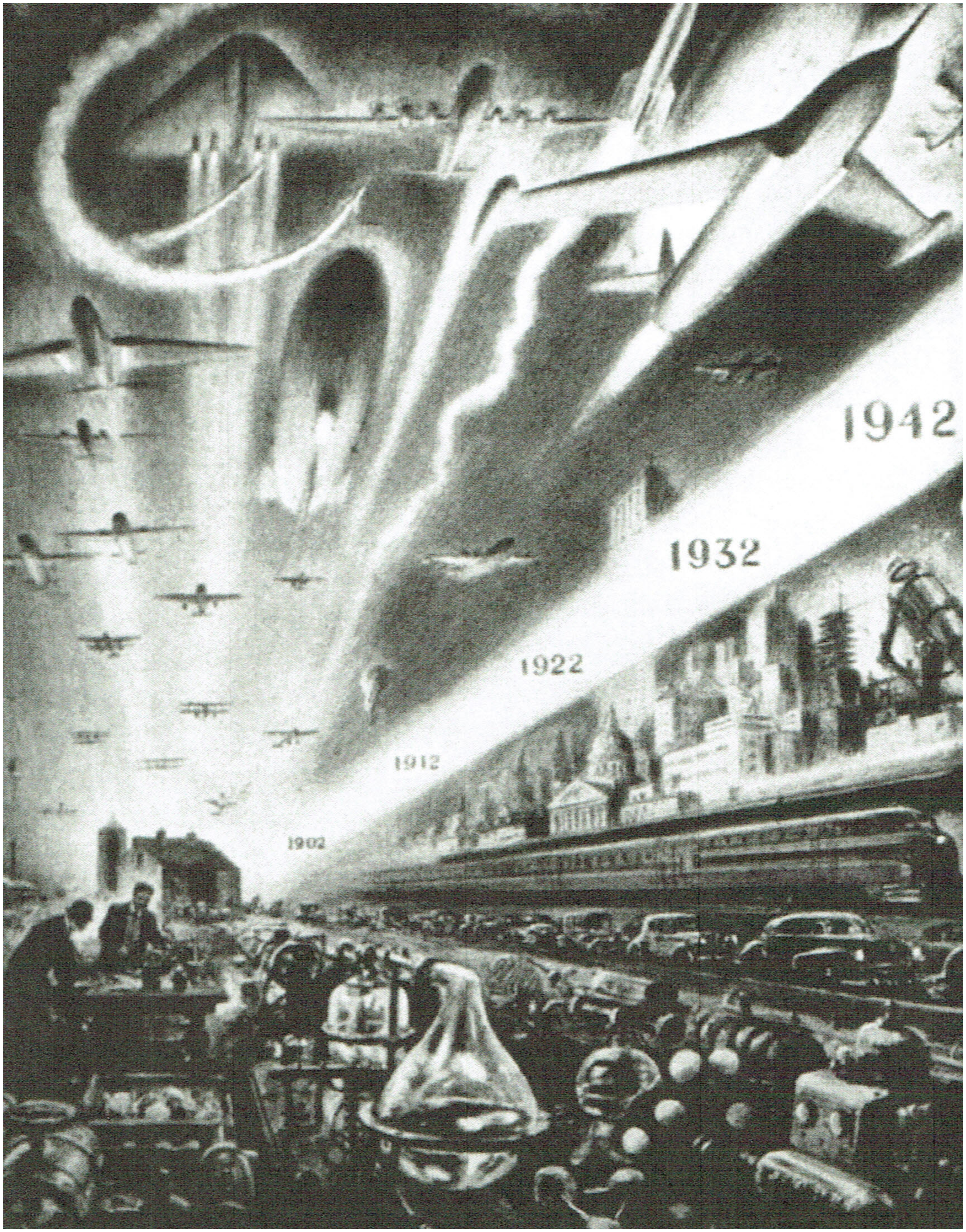


Figure 01.2 • The modern idea of linear technological 'progress'
Source: Smith (1995), from Compton (1952)

Optimizing/Distilling

Le Corbusier idealizes the rigorous approach of an engineer to distil a problem into a solution of function performance. His work paved the way for modernist ideals of function over form to deliver the perfect built environment tailored to suit the program it contains. He likens the built form to a series of tools that can be optimally utilized to make the perfect living environment, from the dwelling to community. The mass produced house offers affordability and accessibility that equalizes the state of living. (Le Corbusier, 1970, pg 245)

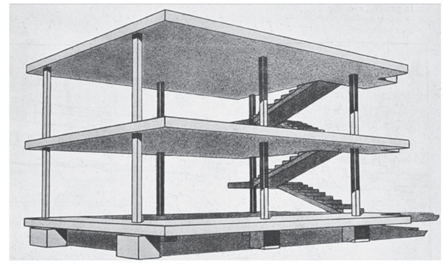


Figure 01.3 • Domino House

Division of building/Introduction of Systems

With the separation of building systems, architecture became composed of distinct functional parts. The structure, façade, and interior environment established themselves as independent parts of a whole. The Domino house [See Figure 01.3] is an example of how the structure could be independently removed from the other systems of a building, freeing the design elements of the space. Construction of a system that has a refined and reduced structural system became more efficient though it has developed into the complex myriad of control layers we have today. We gain the freedom of formal expression but also see a shift to a fractured building system. (Le Corbusier, 1970, pg 263)

Simplifying Construction

With architecture treated as a machine, it allows itself to be viewed as a formal problem composed of distinct elements. Ornamentation was removed and replaced with refined, simple, easily manufactured shapes, distancing architecture from ornamentation, and allowing for the reduction of skill required by labourers. This mirrored the transformations implemented in the automobile industry with assembly lines.

In the post-war era, production of new houses proceeded at an unprecedented rate. This encouraged and demanded a repeatable style of construction; and adaption of manufacturing ideals into the construction industry. With this simplification of production, homes became a target for mass production. Homes could be catalogued, ordered and delivered with ease as a manufactured object; some assembly required. [See Figure 01.4] Sears house catalogue. (Thornton, 2004, pg12)

Figure 01.4 • Sears House

o1.2.2 Refabricating Architecture

Kieran Timberlake, a current-day architectural practice, takes an approach to critically review Architectural production through the lens of other industries, bridging between automobile, aviation, naval, and architectural production. They establish that digital integration can lead to greater efficiency and quality of product. They break down the governing roles of manufacturing and how they relate to architecture.

All products are governed by the three variables Cost/Time/Quality; only two can be met effectively, but Kieran Timberlake propose that digital work-flow allows for better management of all three, creating a better product on all three fronts.

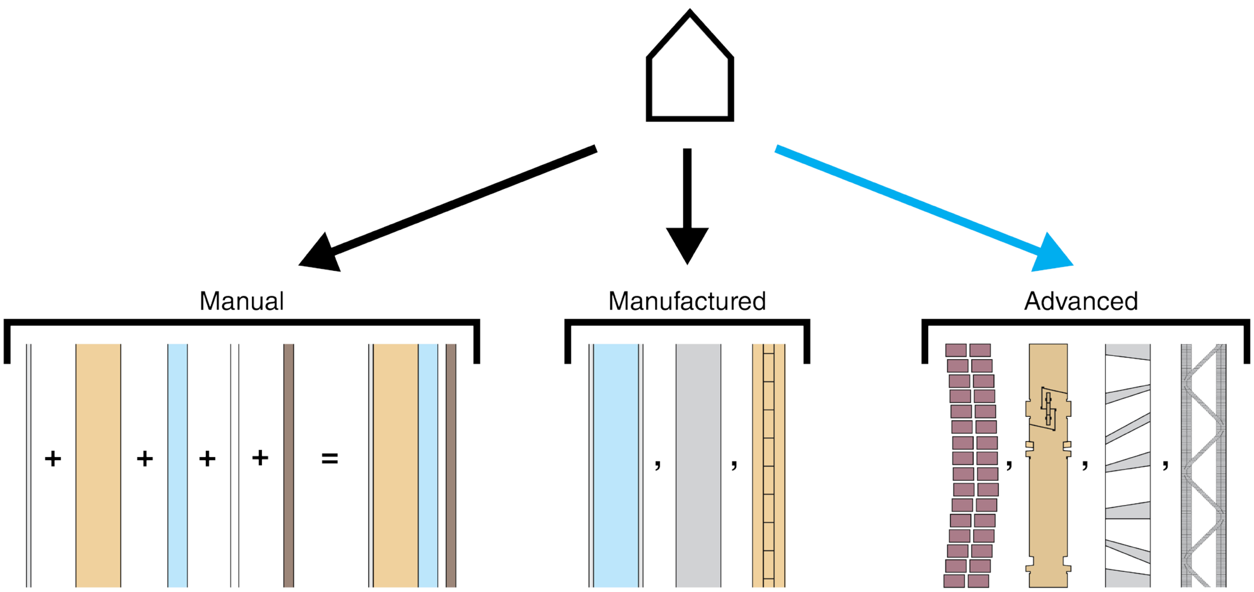


Figure 01.5 • The modern assembly
The modern assembly can be fabricated many ways. Manually describes the basic approach of stick frame construction, using small parts fabricated on site to build up a wall layer by layer. Manufactured entails a prefabricated unit which comes to the site ready to install with the joints being site verified and tweaked to suit. Advanced describes the use of digital fabrication to create the base building structure, with additional control layers still being worked into the solution.

Communication Bridging

[Figure 1.6] Through the implementation of digital systems, it becomes easier to connect specialized consultants. This provides the opportunity for cross-pollination of ideas between disciplines which have become increasingly separated, such as material scientists and architects. Feedback loops are a benefit as communication can travel through open systems using digital model and design files as the basis for communication. (Kieran Timberlake, 2004, pg 23)

Componentization/Assembly

The distillation of architecture into components allows for production to be divided into parallel streams of parts or units. These units are then easily shipped to site for assembly. With little on-site fabrication, architecture can be produced in higher quality. Digital schedules and management tools control the flow of products allowing for just-in-time production and delivery. (Kieran Timberlake, 2004, pg 107)

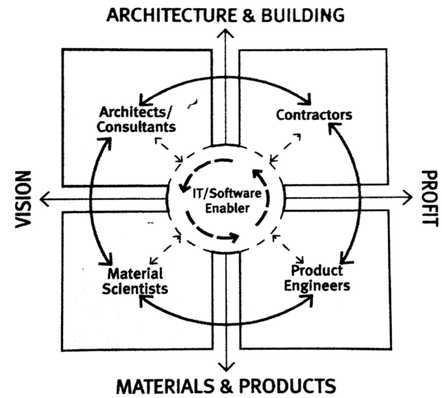


Figure 01.6 • Managing Knowledge

Mass customization

Kieran Timberlake are believers that a digital workflow allows for the customization of unique pieces easily. They include mass customization as an aspect of meeting client demands quickly and easily through changing small parts of prefabricated modules. Borrowing from the automobile industry, components of the whole can be individualized and later assembled. This diverts the need to install a part any differently than the previous part. (Kieran Timberlake, 2004, pg 133)

o1.2.3 Digital Architecture

The adoption of digital architecture has helped to conquer new complexities. Computers have provided a platform to explore formal constraints, flexible communication, push complexity, and ease translation of digital to physical.

Exploring Formal Constraints

Digital design in architecture has not given new ambition to architects, what it has done is given architects a tool to conceive of these complex shapes and be able to communicate to those who will pay for them and who will build them. The translation from drawing to digital has shifted the presence of the designer's hand one step further from the physical entity. This has advanced the exploration of formal constraints through the ability to play through multiple possibilities quickly without being tied to a stack of drawings. (Kolarevic, p.39)

Flexible communication

A digital artifact of this creation allows for multiple iterations to be explored simultaneously, as well as multiple exports. It can be viewed as a photorealistic image, it can be broken down into traditional isometric drawings, it can be exported in sections, or it can be transferred as a three-dimensional object for others to explore. With this availability, the desires of the final object can be adequately portrayed as a digital element. They can also be reduced to whatever format best communicates the intention for

Figure 01.7 • Examples of complex formal architecture
(a) BIG, (b) SOM, (c) Frank Gehry, and (d) Zaha Hadid. Examples facilitate the three points above; Formal complexity – fabrication challenges -Technology allows for more challenging forms Fabricating Architecture

its ability to be fabricated. (Kolarevic, p.45)

Pushing Complexity within Architecture

There are some things which we may not be able to reproduce in our digitally dominated industry due to a loss of skill in trades and movement away from traditional practices. However, many things can now be created much quicker with our digitally oriented design process. Digital design has given us tools to analyze and optimize the forms we have a desire to create. Doubly curved surfaces can be broken down into constructible components, ruled surfaces, contoured surfaces, etc. This can be automated to an extent, allowing freedoms within the analysis of the design and labour of construction. (Kolarevic, p.47)

o1.2.4 Summary

As identified in this section, Architecture is built from the combination and arrangement of many smaller individual pieces. These pieces range in size and material, with many possible solutions to solve a problem. Choices are influenced by factors not necessarily based on performance but aesthetics, culture, and personal ego. Post-modernism transitioned the practice of architecture from one that was primarily built to suit, to one based upon the mass-produced piece. Focusing on optimizing construction to allow for its production to flow in a manner similar to that of manufacturing. Building aesthetic adapted a language that was based upon the regulating line, using repeatable elements in materials that could be efficiently manufactured. This developed an architecture which depends on the component part. Striving for the benefits of reduced construction time and cost through the ability to streamline part assembly on-site. Alternatively this will make design possible so that it no longer has to be simplified to be produced.

Componentized architecture became a tool within architecture to have elements be efficiently produced, yet allowed for an amount of customization. Without CAD implementation, architecture would have a difficult time utilizing and managing the many components and choices put into every project. Digital architecture has allowed for formal freedom in the design model but faces the common difficulty of translating into the physical world. To make this translation possible, elements are simplified, optimized, or even parsed out of a design. New digital tools combined with new manufacturing processes allow architects to utilize the manufacturing power of today's industry.

As new technologies are developed, they slowly find their way into architecture. Ideals were borrowed to reduce architecture to a simple assembly of prefabricated parts; now with additive manufacturing, there is a new technology looking for its ability to fit and transform how we produce architecture. The case studies show the possibility of producing complex forms which are digitally created, in a seamless manner from the digital file. Production of technically complex forms no longer correlates with skilled craftsmen or increased labour, as the part has the potential to be produced as easily as a geometrically simple part-through a machine, with the push of a button.

"We have all these software tools that help us to calculate and design the most amazing things, but we have to simplify the design in order to get it produced in an efficient and effective way," says Galjaard. "So we wondered whether there is a production method that gives us more freedom than the ones we're using at the moment."

- Galjaard (Could you 3D print your building components – Building Design)

o1.3 Case studies of 3D printing

As additive manufacturing has grown over the last 50 years, it has been building roots in the architectural world. With an acceleration of interest over the last decade, such explorations have looked into how the new technology would effect craft, design, and construction within a variety of scale. Additive manufacturing promises ways to accelerate the physical production of items, potentially cutting down lead time. Additive manufacturing has fewer geometric constraints allowing advantages for the ability of digital design to explore fluid and amorphous forms while still being able to flow into digital fabrication. Additionally, digital designs are a fully modelled solution which can be sent straight to production, potentially cutting down on fabrication issues and interferences.

The following case studies portray the many potential avenues where architecture and additive manufacturing intersect. These projects display varying capability in material technology and their consumer/architectural applications. They range in both scale, being small (fixtures, objects or components smaller than a person), medium (modules, components or constructs big enough to occupy match a person), or large (constructs or installations much larger than a person.) Manufacturing processes will be noted upon briefly; refer to section 4 for in-depth explanations of these processes, materials and limitations.

The concluding focus will be given on the freedom of constraints achieved or intended to achieve through choosing production via three-dimensional printing.

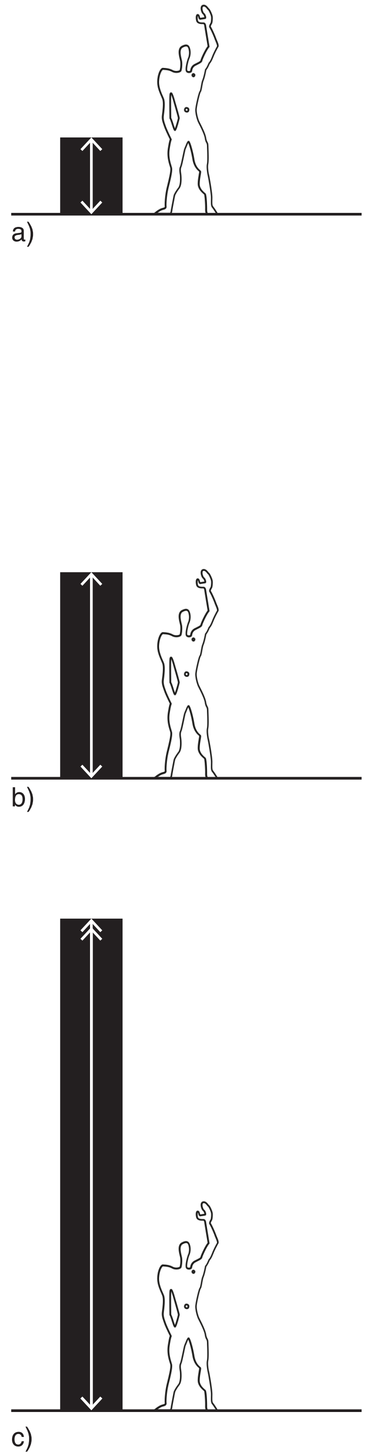


Figure 01.8 • Scale Icon's
A) Small: fixtures, objects or components smaller then a person
b) medium: modules, components or constructs big enough to occupy match a person
c) large: constructs or installations much larger than a person

Figure 01.9 • DVX Trope Faucet
The faucet divides the water into four physically distinct columns, joining again at the neck.

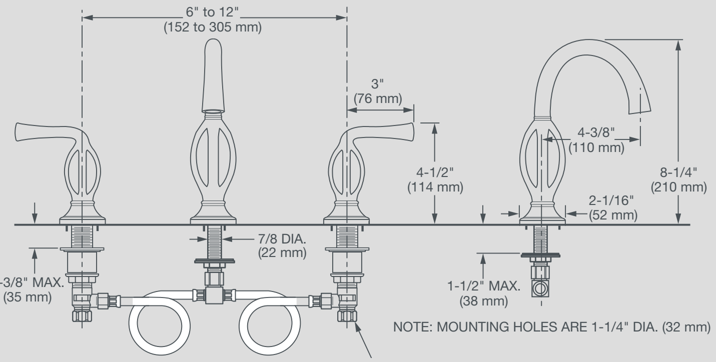


Figure 01.10 • DVX Trope Specifications

Figure 01.11 • DVX Vibrato Faucet
The spiral faucet takes individual streams and merges them slowly through the stem.

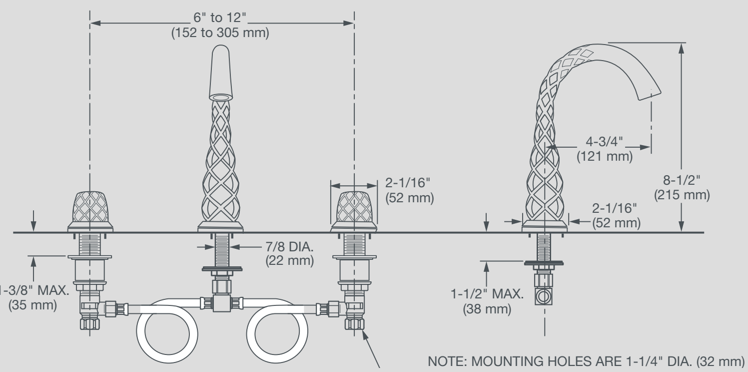


Figure 01.12 • DVX Vibrato Specifications

Figure 01.13 • DVX Shadowbrook Faucet
The faucet divides a common stream into multiple outlets which cascade down in a ever building waterfall.

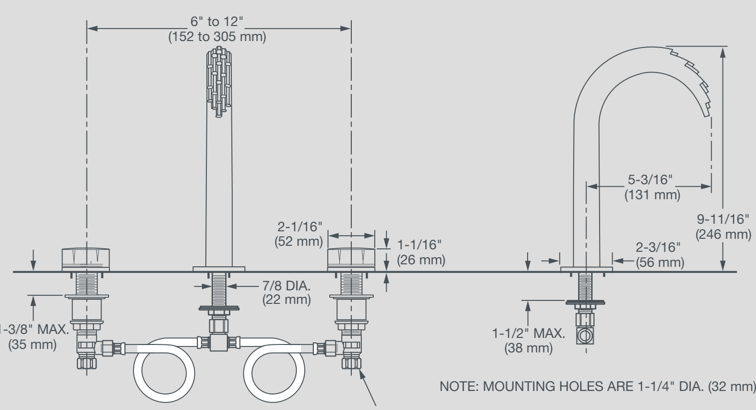
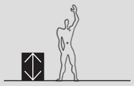


Figure 01.14 • DVX Shadowbrook Specifications

o1.3.1 DXV Faucet



Scale:	Small
Date:	2015
Designer:	American Standard
Sponsor:	N/A
Location:	North America
Market:	Commercially Available
Technology:	Selective Laser Sintering
Material:	Stainless Steel

American Standards DVX line has developed three faucets created by the additive manufacturing technique of selective laser sintering (SLS). The faucets showcase unique aesthetics and explore the possibilities of the technology. These are the first 3D printed consumer products of their type and meet the applicable standards for plumbing and accessories. However, the current price point will likely keep them out of the everyday user's experience.

The design of the faucets strives to introduce wonder to the process of water delivery. In each of the three designs a unique aspect is utilized to transform the experience of each faucet. Two have individual channels crafted within the metal allowing for these channels to be identified visually with the combined stream looking completely normal. The first creates a simple series of columns rising up to support the main neck of the faucet. The second creates a lattice that converges into the spout. The final design utilizes a fragmented delivery of the water to create a unique experience. There are nineteen individually modeled waterways delivering a stream precisely designed to mimic the effect of water bouncing on rocks in a riverbed.

The faucets are constructed of stainless steel using selective laser sintering (SLS), with a build time of about 24 hours. Individual rows of metal powder are melted together and a solid metal block arises from the excess powder. The printed object then requires hand-finishing to clean off extraneous metal and reveal its true form. The piece is further hand-polished giving it the smooth butler finish which mimics the texture and luster of silver pieces after years of being hand buffed and polished.

American standard boasts to be the first company to offer a commercially-available residential faucet. The faucets cement their position as innovators, establishing them as forward thinking, striving towards a future of custom production. They see the process of 3D printing as one that democratizes design and decentralizes manufacturing. They summarize that this will impact their business in two possible ways. First they see a reduction of the inventory pressures that arise from mass production of standardized objects, as bespoke construction of a part will require made to order work flow. Secondly, this made to order process will change the availability and the way product design is managed. The DVX faucets integrate their future vision into todays established system, all having passed applicable standards, and environmental certifications. The largest hold up will be the entrance price point of this new line that has been produced as part of the DXV line from American Standard. These are premium products, curated and designed to be of a high design style typically in the range of $700 USD. In comparison to the three dimensionally printed faucets, which are to be priced at around $12,000-20,000 USD. A price point borne by the prototype being both the first of its kind and utilizing a culturally sensational technology. Hopefully this will change with the development of the technology and the subsequent design work flow of future faucets designs. (DePalma, American Standard, 2015)

Figure 01.15 • Printed Node

Figure 01.16 • Node with rod connections

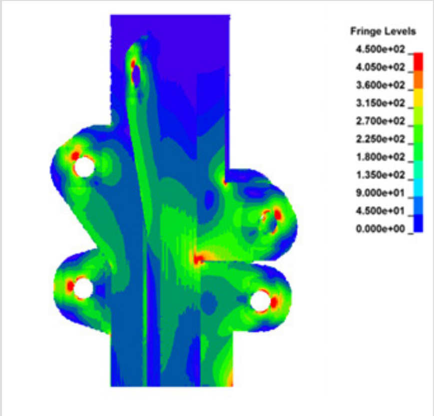


Figure 01.17 • Structural analysis

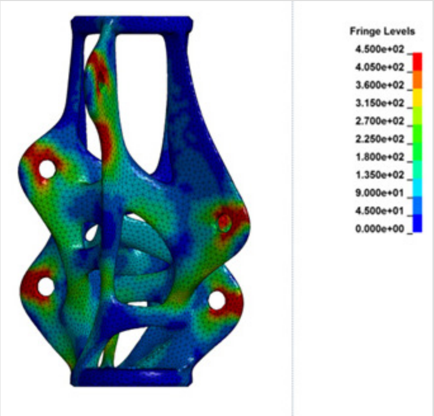


Figure 01.18 • Structural analysis

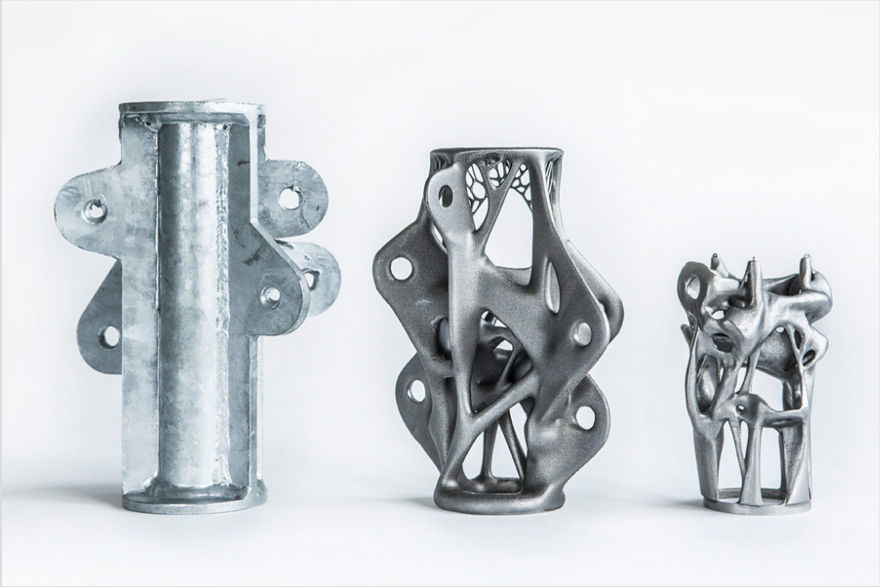
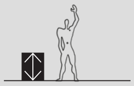


Figure 01.19 • Generation of printed nodes

o1.3.2 ARUP Steel Connection

Scale:	Small 
Date:	2014-2017
Designer:	ARUP
Sponsor:	WithinLab, CRDM/3D Systems, EOS
Location:	EU
Market:	Construction Prototype
Technology:	Selective Laser Sintering
Material:	Maraging Steel

Since 2014 ARUP, a global design and engineering firm, has been investigating the benefits of designing structural nodes with the intent of producing them using additive manufacturing methods. They have been explored this concept through the design of a large tensegrity structure built of cables and rods to create a sculptural lighting canopy, to be a central piece for a market in the Haugue, Netherlands (Birch, 2015). Though the project fell through ARUP's team took the opportunity to study how alternative fabrication processes could ease the complexity of construction for structural nodes with the expectation to reduce waste and cost (Winston, 2014).

The challenge of the node allowed for two unique opportunities for the production of the components. First, the structural design could remain focused on producing individual nodes rather than the traditional method of optimizing the design to utilize repetitive units. Second, the production through additive manufacturing allows for direct translation of the digital design into physical structural elements allowing the material to be placed precisely where it was needed. (Birch, 2015)

Since the initial research and development, the project has evolved showcasing two iterations of the technical design as well as testing different methods of additive manufacturing production. The research aims to show the potential to reduce costs and cut waste of the construction sector with additive manufacturing of building components. (Winston, 2014)

Design/Production

ARUP's research and design team looked at prototyping a structural node required for the tensegrity structure. The material used for the nodes what initially to be stainless steel, but production capabilities were more easily accessible with Maraging steel. Maraging steel is considerably stronger with increased strength of almost four times that of ordinary construction steel (Winston, 2014). The first iteration took the standard hand-welded node and optimized the structure to allow for material only in locations required. In 2015, their preliminary material tests found the 3D printed node was lighter and stronger than its welded counterpart, revealing the potential for lighter more material-efficient components. Initial testing of the node yielded results which exactly match the material specifications of the production machine. Giving the team reliability on the machines capability to produce parts which can optimize material use along structural paths in an efficient manner (Winston, 2014). ARUP critically reviewed the design of the node and concluded it fell reliant on preconceived ideas of traditional production. They found that geometric constraints were coming from their training and experience in dealing with geometry designed for previous production methods, rather than an approach based on the new fabrication process (Winston, 2014). ARUP decided to push their concept further letting the next iteration of the node have a relaxed geometric constraint focusing primarily on material use in structural manners and optimizing the part for production with additive manufacturing (Winston, 2014). In 2015 ARUP announced the second iteration showing the further reduction of the weight of the node through refined object design (Niehe, 2015). As part of the second iteration, they were eager to utilize the added strength of the 3D printed steel and produce nodes which would be slimmer, smaller and lighter (Winston, 2014). The team reevaluated the connection locations and strategy looking holistically at the structure and the node, removing the traditional toggle fork element. (Langenberg, 2015)They were free of material constraints and able to create more efficient structural paths through the node this resulted in a unique node which was more compact, saving on material volume and printing time. Overall the printed nodes allowed for the structure as a whole to be approximately 40% lighter than the current equivalent. (Langenberg, 2015)

As well as a recent update to the production of the nodes with additive manufacturing the firm has teamed up with company 3Dealise to utilize their 3D-printed sand moulds. Printing foundry sand allows for the quick production of sophisticated and unique moulds in which the material can be reused, allowing costs to be kept low. By utilizing 3d printing in the production of the mould, traditional methods of metalworking could be utilized allowing the premium of the costly production to be optimized with a cheaper material/process. When compared to directly 3d printing steel components, ARUP found greater flexibility in the cost of the end part, as well as size constraints. (Thorns, 2017)

Impact

The process took many iterations to fully take advantage of 3D printing, while traditional fabrication creates cheaper parts, even with more waste material. Also, the size of each piece was limited by the size of the printing bed. Material selection was limited for the construction industry; as a result, ARUP paid for higher grade materials then they would typically specify. Strength testing is to be further studied, but it was noted that the material properties of the final product matched the estimated structural ability.

The benefits of 3DP were a lighter piece, material efficiency, stronger materials could be used (as they were the only ones available), and design geometry was not a restriction(but became a user limit as the engineers have been so heavily trained to reduce complexity). Galjaard team lead at ARUP concluded that the availability of printers to produce larger items is still a limiting factor in the implementation of additive manufacturing on a large scale, but recognizes that the development of larger machines is underway. (Winston, 2014) Regardless the research shows that formal complexity is relieved with the additive manufacturing process through its ability to save material and weight within a structure. They hope to implement a 3D printed part in a full-scale application within the year. (Winston, 2014) Through the exploration of manufacturing a sample node, ARUP compared their preliminary studies to the baseline standard fabricated with steel stock welded together as per design requirements. The use of additive manufacturing allows for a completely design-driven manufacturing process (Birch, 2015) When considering the cost of the part, they looked at the holistic value of the structure. Looking at the longevity of the structure, and it's overall lifecycle, how it would arrive at the site, and the labour required to assemble the structure, as well as the impact a lighter weight structure would have on other design items, such as the foundation (Winston, 2014). When looking at only production, the part cost would stay high, especially machining time, but looking at a lifespan cycle could help rationalize the cost. Galjaard found the area of greatest potential success for additive manufacturing of building components were a lighter structure and the ability to reduce parts (Winston, 2014).

Figure 01.20 • XtreeE Column

o1.3.3 XtreeE Column

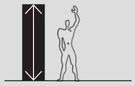
XtreeE is a young France based startup that develops advanced large-scale 3d printing technology. They are making 3D printing a viable option in architectural design, engineering and construction through collaborative design and large-scale prototype manufacturing, as well as rental of their printing systems. They have developed a custom 3d printing robot with help from ABB, Dassault Systemes (of Solidworks) and Lafarge-Holcim (Alec, 2016). Lafarge-Holcim has set up a partnership with XtreeE, and they have worked in collaboration with other parties on two significant projects. A 3D printed pavilion commissioned by the Ile-de-France regional authority and the post supporting a playground roof of a school in Aix-en-Provence, both are architectural firsts in Europe (Alec, 2016).

Architect Marc Dalibard originally designed the Aix-en-Provence project with XtreeE taking over the final design and the prototypes. Topological optimization was used to develop the end geometry that was broken up into four parts for prefabrication. XtreeE workflow allowed for the translation of the designed element to produce the toolpath, and subsequently, 3D printed the envelope. The printing time was 15 hours and 30 mins. Structural engineering office Artelia collaborated with XtreeE in forming the constraints for the columns construction (XtreeE, 2017). The column is made up of a 3D printed envelope with a concrete fill. Lafarge-Holcim developed a special high-end concrete Ductal to be used by the XtreeE 3d printer as well as the concrete fill for the shell (Jakupovic, 2017). The material consists of cement, silica fine, sand, superplasticizer, and water. The post was assembled by concrete pre-caster Fehr Architectural. Once the column was on site, it was coated and polished. The column stands approximately 4 meters tall (13 feet) and is made up of a relatively intricate design.

XtreeE uses a form of layered Material Extrusion, very similar to the large-scale implementation of Fused Deposition Modeling, a common household program. XtreeE uses three methods of layering effectively: aligning a layer directly on top of the previous layer, offsetting a layer slightly to one side or the other, and building a sacrificial support system that is to be removed for the end product. AAB collaborated with XtreeE to make their printers' six-axis robotic arm that allows it to move in any direction, bringing a wide range of articulation for the printing nozzle (Jakupovic, 2017). The printer currently fixes to a base and is suited for the indoors, but they hope to make it mobile and suited to outside work.

At this point XtreeE has made an impact in the industry, through the partnership with major companies, to show the possibilities of using large-scale layered Material Extrusion. They lay claim to having the first structural three-D printed component in a public building (Jakupovic, 2017). Part of their business collaborating with companies to find 3D print methods to make their vision a reality. Lafarge-Holcim has more recently united with XtreeE to build a concept house in France (XtreeE, 2017). Four columns and the mould for a perforated wall were co-designed

Scale:	Medium
Date:	2017
Designer:	Marc Dalibard
Sponsor:	LafargeHolcim
Location:	France
Market:	Const. (Struct. Formwork)
Technology:	Fused Deposition Modeling
Material:	LafargeHolcim (Special Concrete Mixture)



and printed by XtreeE, and placed on site July 2017. The YRYS concept house is supported by Maisons France Confort and involved 18 partners (XtreeE, 2017). They are continually working on making progress with their printing machines that they make available for rental and use in helping to further the 3D printing progress.

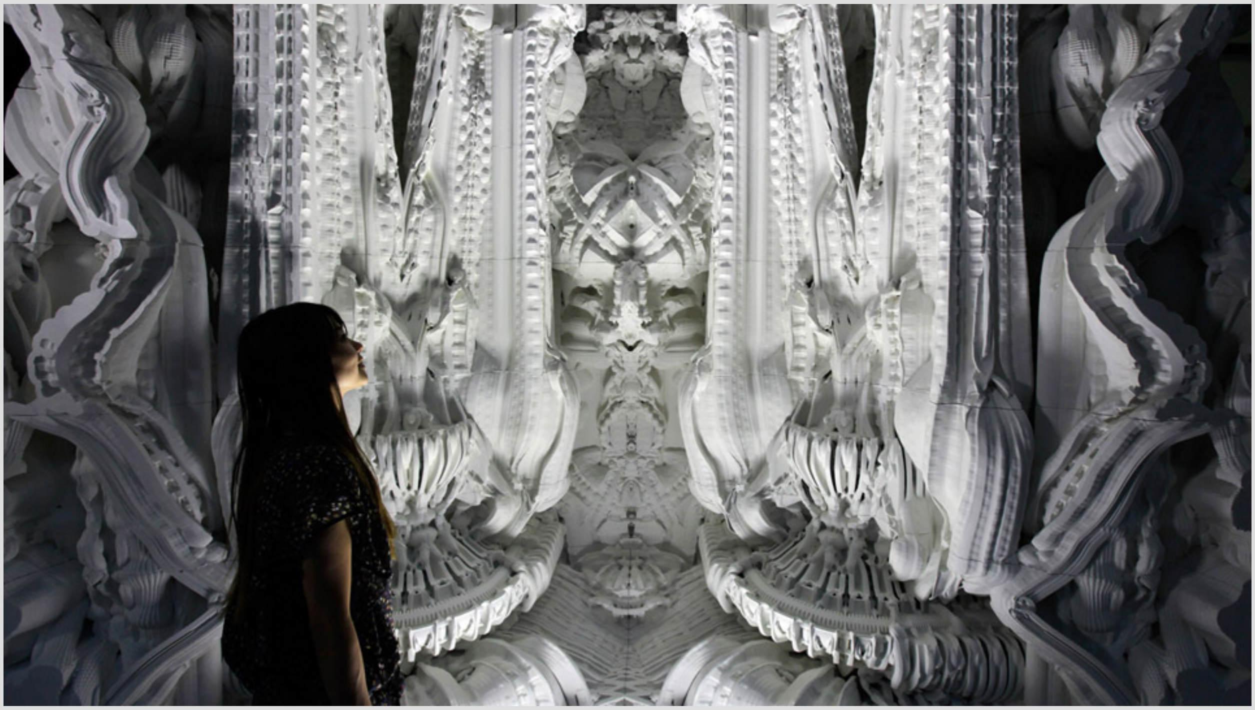


Figure 01.21 • Digital Groto

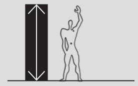
o1.3.4 Digital Grotesque

Architects and programmers, Hansmeyer and Dillenburger, collaborated in the creation of Digital Grotesque, a modern take on the grotto. The project aims to use solely digital methods to generate a form of minutely intricate detail to explore the limits of digital design and production. Computational design replaces the process of an Architect developing form with a mouse in a CAD program with the production of surfaces and facets driven by code based procedures. Procedures which are executed at a whim to generate forms within the desired parameters. The team argues the design has a complexity and richness which is “impossible” to draw by hand let alone translated from a two-dimensional sketch into a three-dimensional object. Building forms pixel by pixel is where additive manufacturing is an applicable solution to the problem of translating these computationally complex forms into reality. Thus demonstrating, the extreme complexity achievable by 3DP through the production of a modern grotto void of the dependence on craftsmanship.

The team used parametric equations to generate extremely complex forms, such that they would “appear at once synthetic and organic.” (Digital Grotesque, 2018) The effect was the creation of a surface that appears as a continually divided surface, similar to a fractal pattern. (Sharma, 2013.) Twisting surfaces give way to folding planes and swooping gestures, these remaining shapes then give way to a further division and articulation, in the end, no surface reads as a simple object, but much rather as a collection of terrible dreams superimposed upon each other. The level of articulation can even create detail that exceeds the threshold of physical or visual perceptions, creating an architecture able to range the full scale of human perception. The digital canvas that holds the object, unfortunately, allows for a level of detail not easily communicated let alone achievable through standard production methods. The complexity of the final geometry consisted of millions of individual facets; the designers would not settle to allow their vision to be reduced (or geometrically optimised) therefore they settled on additive manufacturing.

Additive manufacturing allowed a replication of their code generated design at a resolution of a tenth of a millimetre, for an installation which stands at 3.2 meters high covering 16 square meters of floor space. They created an immersive, highly articulated room which allows for three-dimension printing to be experienced immersively. (Digital Grotesque, 2018) With the application of three-dimensional technologies typically being limited to prototyping small-scale models, the team hoped to find traction with their implementation. Some of the major holdups being the limited volume for build area, high cost of machines, and varied selection of materials and their strengths. (Digital Grotesque, 2018) This project utilized sand-printing technology, which applies a resin jetted onto the particles in specific patterns to produce forms. The technology was primarily developed to create casting forms for industrial applications. (Sharma, 2013.) This allows for a high degree of detail with a reasonably large print volume (up to 8 cubic meters) and produces relatively solid and

Scale:	Medium
Date:	2014
Designer:	Michael Hansmeyer, Benjamin Dillenburger
Sponsor:	N/A
Location:	EU
Market:	Research & Development
Technology:	Binder Jetting
Material:	Sand and Polymer



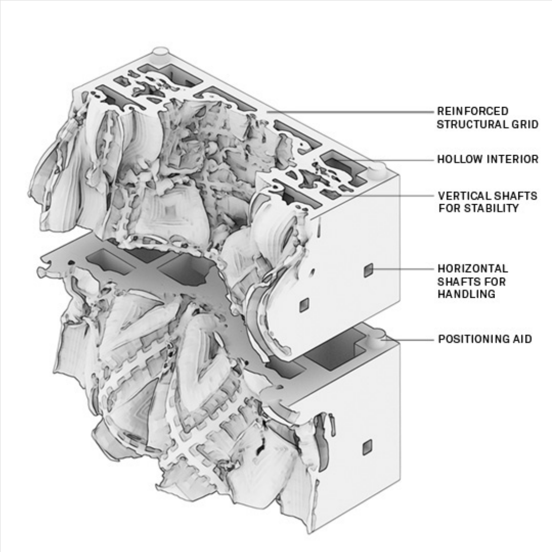


Figure 01.22 • Diagram of Component

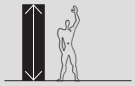
Figure 01.23 • Post Processing

robust objects. The final objects are compared to sandstone, and can be similarly applied in the architectural world, while the grotto was designed to be fully self-supporting other installations have implemented a facade system installed over hidden structural supports.

Overall Digital grotesque achieves the result of creating a highly detailed three-dimensionally printed environment, one which also goes as far to create an immersive environment. The effects of such a complex element becoming physical are a true feat – and an example of a product which correctly calls to be produced with additive manufacturing. Though they approach the cost of a printing as an afterthought, if one is to print a surface of this volume, then printing the highly articulated version will not change the cost. This unilateral approach denies the fact that these comparative surfaces may be produced through a multitude of other methods. The team did capitalize on a form of 3D printing which is easily translatable to architecture. The printing of sandstone like elements allows for structural capacity to make a self-supporting screen. Achievable through the use of a Voxeljet printer, having the largest build volume amongst sand printing 3d printers and further engineered to produce the finer details produced through the computational design. (Sharma, 2013.) With the success of the first iteration, the team has followed up with further iterations, the Arabesque Wall (2015) and most recently the Grotto II (2017).

Figure 01.24 • Prototype Bridge

o1.3.5 MX3D Bridge

Scale: Medium 
Date: 2015
Designer: Joris Laarman
Sponsor: IaaC, Heijmans, Autodesk, ARUP, ABB Robitics, Air Liquide, Arcelor Mittal, Lenova, STV, delcam, Within, TU Delft, AMS, Amsterdam City Council
Location: Netherlands
Market: Construction Prototype
Technology: Modified Welding Technique
Material: Steel Alloy

The Joris Laarman lab created the multiaxis 3D printer (MX3D) to meet the need for a machine with the capability to print large scale projects. As more projects were completed, it became apparent that an independent company needed to be created and MX3D was started. This split happened not long after the dragon bench project, another of Joris Laarmans' innovative projects. As an independent company, MX3D continued to advance and refine their systems capabilities. The MX3D system is designed to 3D print freeform metal structures while travelling along the recently deposited material it has just finished printing. In 2015, MX3D revealed the small weight bearing structure they had printed and announced that they would be printing a 3d metal bridge across the canal in Amsterdam. It is anticipated that the bridge will be on site and completed by October of 2018 in time for Dutch Design Week.

This is the first project of this type in Amsterdam. In taking on this project, MX3D has had many opportunities to learn, grow and establish many of the standards for future projects. Entirely printing a large structure over an expanse using the material just printed as the ground on which the machine stands in order to cross the gap is groundbreaking. In 2016, MX3D collaborated with ARUP to overcome some of the variables that affected construction. Variables such as the bridgeheads not aligning, between the tolerance in the construction of the original wall and material used for the bridge. Other variables came into play as well before the project even begin to print including the weather and a lack of control over pedestrians. Because of these variables, it was decided that the bridge would be printed in a warehouse and later moved on site. Removing the aspect of built in-situ for the project, but increasing confidence in its ability to maintain consistent quality.

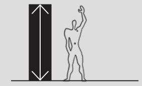
MX3D has taken the bridge through many stages since 2015 to get to the point it will be at by the end of 2018. Problems such as the integrity of the supporting walls and the policies of the government in Amsterdam. MX3D has had to work with officials to establish new building permit parameters since this new technology is not covered in any of the previously established parameters. New companies were brought onto the project to meet these challenges, leading to a multitude of iterations essentially changing the whole design in order to print a successful bridge. Live sensors are helping with this process as they show the strengths and weakness of the bridge and there is much hope that with this amount of evaluation and monitoring it may prove over time to be one of the strongest bridges in Amsterdam.

The bridge is 12.5 m long, 6.3 m wide, spans a gap of 12 m, took four robots to print, 4.500 kg of stainless steel and 1100 km of wire. A new steel composite was put together for this project. The system is built to print in the air while it moves along the structure it has just printed. As the name MultiaXis 3D suggests, it consists of a 6-axis arm with the capabilities of printing metal.

MX3D collaborated with quite a few companies for the printing of this project. They partnered with engineers from Arup, researchers from the Imperial College of London, mathematicians from the Alan Turing Institute, specialists from the internet of things, and officials from the city of Amsterdam they developed performance load tests and a smart sensor network in order to evaluate the safety of the bridge and to collect information to use to continue to refine the 3D system developed by Joris Laarman Lab. The sensors will record such things as the physical elements, strain, displacement, traffic and the response of the bridge and how it is holding up. A digital copy is being created that will mimic recordings from the sensors on the real bridge. Feedback from the sensors will serve to help improve and safety the current bridge as well as to improve all future work done by MX3D. There is the possibility with this kind of monitoring and technology that this bridge will be the safest bridge. (Estes, 2018) Other responsibilities of the participants are summarized on the project website. "Joris Laarman Lab designs the Bridge, Arup is the lead structural engineer, ArcelorMittal provides the metallurgical expertise, Autodesk assists with their knowledge on digital production tools, Heijmans is our construction expert, Lenovo supports us with computational hardware, ABB is the robotics specialist, Air Liquide & Oerlikon know everything about welding and lastly, Plymovent protects the air our employees breath whilst AMS and TU Delft do invaluable research. Gemeente Amsterdam is the first customer of our collaborative bridge building department." (MX3D Bridge. 2018)

Figure 01.25 • Freestanding Construction

o1.3.6 Minibuilders

Scale:	Medium 
Date:	2013
Designer:	IaaC
Sponsor:	IaaC, SD Ventures
Location:	Barcelona
Market:	Research and Development
Technology:	Extrusion
Material:	Marble Polymer

Minibuilders approaches the construction of a structure utilizing a team of additive robots specialized in different tasks. The Minibuilders team is based out of the Institute for Advanced Architecture of Catalonia and is led by Petr Novikov and Sasa Jokic. The unique three-robot system approach parallels a division of labour to streamline production and build human-scale structures out of a marble and polymer composite. (Mortice, 2018) The strategy of dividing the tasks of production among a series of robots allows for swarm production (or simultaneous labour) it also allows for production volume to be permanently severed from machine size. (Rory, 2014) No longer are industrial machines highjacked to print large pieces in isolation, as the small machines can be sent out in teams tackling a project in-situ. (Hall, 2014)

The design of the structure is intended to showcase the action of the three robots. The first robot is the “base robot” and lays the bottom ten layers. It is built like an upside down U which allows the gantry to rise as more layers are printed in a spiraling path roughly tracing the previously applied layer. (Rory, 2014) The “grip robot” follows, attaching to the previously built layers and continues application of the build material. The unit consists of pressurized horizontal wheels allowing it to cling to the previously installed layers as it further applies layers to build up the structure. Heaters are incorporated to accelerate the curing of the printed layers allowing the printing of cantilever layers as well as having the strength to support the robot. (Rory, 2014) The Vacuum Robot allows for bi-directional printing, as it adheres itself to the vertical plane it can now print reinforcing bands on the structure. This improves upon the previous weakness of unidirectional prints by creating structural reinforcement in various directions. The robots are all connected to a central supply unit, which feeds materials through tubes and can follow them around the build area as required. Other features of the system include linking sensors and local positioning systems allowing for feedback loops through the fabrication process. Live data from the machines connects back to custom software which allows an operator to control the robots.

The twofold nature of the project was not only the development of the printing technology but the structures it produced. The 15-meter high prototype was printed as an installation at the Design Museum of Barcelona (Dhub). It displays the ability of their machines to establish curved structures and leads to the further development of structures incorporating higher complexity. The promise of a complete building is still in the works, having issues such as openings and climate endurance yet to be proven. (Minibuilders. 2016)

To Novikov, the project has not created a solve-all building solution but rather respects the ability of their robots to address construction within irregular environments. A large drawback is the lack of printing materials, which is an area of continuous development for this industry. (Mortice, 2018) The hope is that these adaptable 3D printing robots can conquer difficulties in remote or inhospitable locations. This fails to address a requirement of foundations which modern buildings are typically tied to, suggesting that 3D printing is stuck in a transient state. The potentials include working at heights or within dangerous areas, removing people from working in hazardous situations. (Hall, 2016)

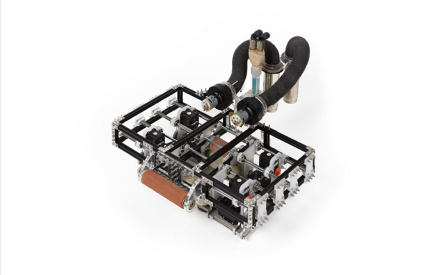


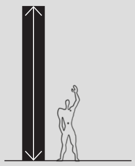
Figure 01.26 • Mini Bot - A

Figure 01.27 • Mini Bot - B

Figure 01.28 • Mini Bot - C

Figure 01.29 • Fabrication of the Module

o1.3.7 AMIE 1.0



Scale:	Large
Date:	2016
Designer:	SOM
Sponsor:	US DOE, Clayton Home Builders
Location:	USA
Market:	Research and Development
Technology:	Fused Deposition Modeling
Material:	ABS with Carbon Fibre

AMIE is an acronym for Additive Manufacturing Integrated Energy and a joint venture backed by the US Department of Energy. The project was completed in 2015 and is located in Oak Ridge, Tennessee. (SOM, 2015) Many people collaborated to bring this project about. The University of Tennesee (UT), Clayton Homes, General Electric (GE), Alcoa, NanoPore, Tru-Design, SOM, UT-ORNL Governor's Chair for Energy and Urbanism collaboration, ORNL, and the University of Architecture and Design were all involved in making this project possible. (SOM, 2015) AMIE 1.0 is geared toward energy conservation and decreasing environmental impact through transforming the construction and operation of a house and vehicle. They found Additive manufacturing as an emerging technology which complements the goal for manufacturing with environmental consciousness. (SOM, 2015) The project not only looks at the impact that is made during manufacturing but at the long-term impact of operating. The 3D printed pavilion and the 3D printed car are designed to share energy through a Wireless bi-directional energy system. (Rhodes, 2016) This allows the PV array integrated into the house to supplement power for the car if required, or the car to supplement power to the house if the batteries are drained.

The structure of the pavilion is made up of C-shaped curves printed two-feet wide; the shape flares out at 45-degree angle along the z-axis, and bends along the 90-degree angles at both the top and bottom of the frame. Each 'C' shaped curve was designed to connect at the middle of the floor and ceiling creating ring-shaped segments. (SOM, 2015) These ring-shaped segments were then assembled to create the final structure, with the building made up of 10 rings and the canopy eight rings. (Stoughton, 2016) The pavilion is made up of 79% insulated solid surfaces and 21% glazed areas. (SOM, 2015) With a final built area of 210 square feet, measuring approximately 38x12x13 feet. (McCorkle, 2015)

For the main building, ABS plastic was used, with about 20% reinforced with carbon fibre. When this material is 3D printed it has a grain; when loads run parallel to the grain the material is five times stronger and more ductile. The design encountered structural challenges with the 3D printed material but pooled the combined knowledge of ORNL, Clayton Homes, and SOM. The team overcame these material weaknesses and printing limits by: following the grain of the printer for walls, ceilings, and floors, printing the rings in pieces and splicing them together, installing four post-tensioning rods through the assembled building sections, printing buttresses and trusses into the frames, and the use of sliding connections between AMIE and the steel support chassis. As there has not been an established proof of how these materials work when 3d printed, it was essential to run full-scale destructive testing. The test yielded excellent results showing that the building more than exceeded the requirements. (SOM, 2015)

The project successfully delivered a co-dependent but off-grid building and vehicle within the short 12-month timeline. Challenged with 25,000 lbs of printed parts the project pushed

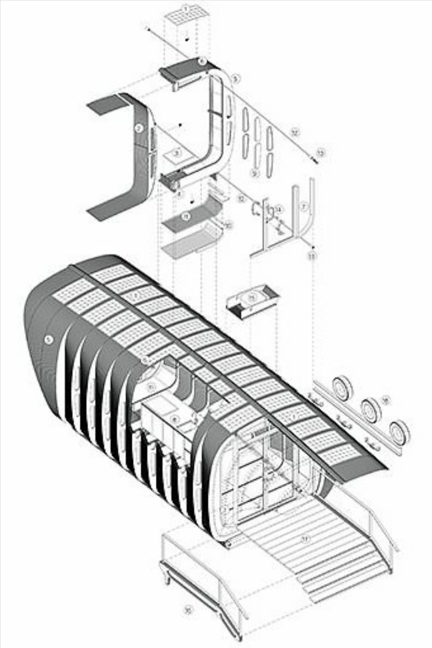


Figure 01.30 • Exploded Axo

the standard scale of additive manufacturing in both size and structural capacity for ABS. The conjunction with Clayton Homes displays the compatibility of the new technology within the established workflow of the industry. The structural design of the house was tested, but specific capabilities are left unanswered about the life safety for situations with fire, or the long-term durability when exposed to UV and other elements.

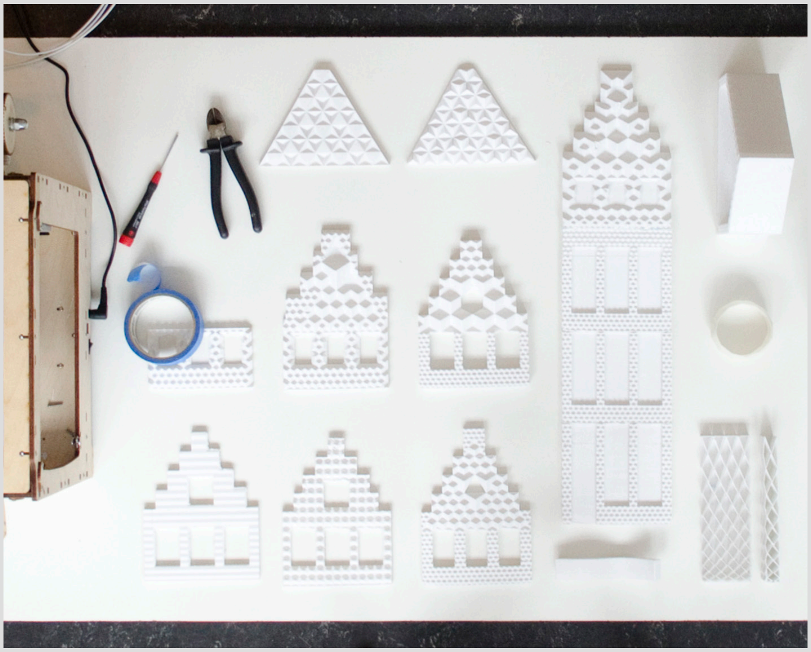
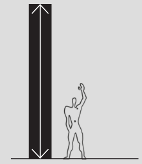


Figure 01.31 • Scale Facade Prototypes

Figure 01.32 • Render of the House

o1.3.8 DUS Canal House



Scale: Large
Date: 2013-present
Designer: DUS Architects
Sponsor: Henkel, Demeeuw, Heijmans, Arup, Ultimaker, Europese Unie, Kansen Voor West 2, Provincie Noord-Holland, PNO, Rijksdienst Voor Ondernemend Nederland, Stichting Doen, Igus, Elcee, Emerson, Xtrution, Lenovo, Amsterdam smart city, Alliander, Fiction factory, Tentech, Bestcon, Protospace, Rooie Joris, AON, RSA, Buko, Bouwatch, De Alliantie
Location: Netherlands
Market: Arcdhitectural Prototype
Technology: Fused Deposition Modeling
Material: Various Plastics

DUS Architects is a Dutch firm that has worked in collaboration with Ultimaker Ltd, Fablab Protospace and Open Coop to bring together the Kamermaker that was unveiled at the OFF PICNIC. (Vinnitskaya, 2012) A big focus for DUS is to try to find a way to reduce their environmental footprint. Their plan to use locally recycled materials, including biodegradable plastic would help reduce landfills and transport. DUS and German-based company Henkel are working together to create a bio-based material adhesive called “hotmelt”. The long-term goal is for this material to be torn down and used again, and again…to make new buildings. (Scott, 2014) The Kamermaker will be used to print the materials they are experimenting with.

The Kamermaker is built as a mobile pavilion. The name translates to ‘room builder’ and occupies an existing shipping container stood on end coming in at 20 feet tall (6m) with an 8 foot (2.2m) square base. (Grieco, 2013) It is capable of printing up to 11 feet high and 7 feet wide, with the original printing speed maxing out at 240 mm/s. (DUS Architects, 2013) The exterior is made of stainless steel that has a pattern of puncture holes. In the future, the holes will be used for the miniature windmills to produce energy for running the printer. The Kamermaker will be used to print these windmills out of glow-in-the-dark PLA plastic filament. (Grieco, 2013)

The Kamer Maker will be on location for the printing of the Canal house. (Scott, 2014) The Canal house provides an opportunity to advance the technology and mechanics of the Kamermaker. Through this research, project knowledge will be collected about: parametric design, XL printing, printing material, construction, smart technology, and housing. (DUS Architects, 2015) The house will be put together one room at a time. Each room is assembled from pieces printed by the Kamermaker. These rooms will be safety tested before being added to the main house. DUS will be working on improving the printing material they use and will be testing in the building of the Canal House. (Scott, 2014) This will be visible as each of the 13 rooms will be printed with the intention of using new updates that reflect what has been learned from research. (DUS Architects, 2015) With the capabilities of the Kamermaker, there may be a future where people can go online and design each room of their dream house and have it printed. There is the hope that this can improve the communication between designer, client and builder. (Scott, 2014) Questions are brought up with this kind of project about the impact it will have on employment. (Vinnitskaya, 2012)

Some of the changes that have been made to the Kamermaker since starting the canal house; two fans have been added to bring down the hardening time of the printed material, and the container holding the ready to print material has been enlarged(they 3D printed a larger container). The changes made to the printer have increased the speed by three times. (DUS Architects, 2013)

Recently DUS and partners have created the XL 3D Printer 2.0; an upgraded version of the original. Some of the improvements

Figure 01.33 • The Kamermaker

Figure 01.34 • Full Scale Prototype

Figure 01.35 • Full Scale Prototype

added to this printer are automated material input, integrated drying system (allows for 24/7 printing), and remote control. XL 3D 2.0 is remotely controlled through its website. Some of the advantages to adding remote control are the increased print volume (due to the space opened up by not installing a control room), and having access to the printer from many locations near and far. (DUS Architects, 2013)

Figure 01.36 • Scale Model

Figure 01.37 • Prints in Progress

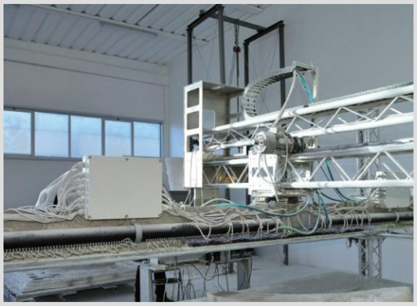
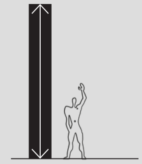


Figure 01.38 • D-Shape machine

Figure 01.39 • Workshop with Prototypes

o1.3.9 D-Shape



Scale:	Large
Date:	2006
Designer:	Andrea Morgante / Enrico Dini
Sponsor:	Monolite
Location:	Great Britain
Market:	Research and Development
Technology:	Binder Jetting
Material:	Sandstone and Polymer

In 2006 Enrico Dini unveiled the Radiolaria Pavilion, a free-form structure that was the result of collaboration with Andrea Morgante and the D-Shape 3D printer. (Turner, 2013) The liquid-jet printer allows for large-scale prints of up to 10 meters tall. D-Shape signifies one of the first forays into 3D printing for the architectural world and creates a lasting impression with the massive sandstone structures produced. (Blagdon, 2012) After the success of the pavilion, Dini developed the D-Shape process to create reefs out of reclaimed ocean sand, rehabilitating fish cultures in areas of coastal damage. (Liat, 2013) The latest news on Dini is the creation of Desamanera an Italian 3DP company specializing in the creation of large-scale stone artefacts. (Molitch-Hou, 2016) There are also developments with the European Space Agency with the research of 3d printing lunar structures utilizing the lightweight printer and resin technology. (Hsu, 2010)

Paired with the latest modelling software freeform architecture has been pushing the boundaries, utilizing parametric and scripting tools to generate ever complex forms. The team was inspired by Ernst Haeckel's studies on radiolarians and mineral and siliceous skeletons. Drawing on the similarities in creation, the mineral and siliceous skeletons form over years of slow deposition of material layer by layer. Mirroring the compositional deposition of the 3D printed resin to build complex geometry without the use of provisional, temporary formwork or disposable, expensive moulds. (Turner, 2013)

The ductility of concrete is dependent upon expensive and time-consuming formwork. D-Shape allows the production of curved surfaces, such as domes, without the use of complicated formwork. Allowing for a reduction in labour, errors, and mess through the printers ability to transform the CAD model into a physical structure layer by layer. (Blagdon, 2012) The printer uses an inorganic binder deposited to a sand mixture containing a solid catalyst. When combined the liquid agent reacts to the catalyst and cures into a hard sandstone-like material. (Blagdon, 2012) The designers indicate that the material has been subjected to traction, compression and bending tests. The results indicate excellent strength properties, exceeding Portland cement while maintaining environmentally friendly aspects. Printing happens onto a bed of the material, building each layer 5-10 mm's at a time. (Turner, 2013) This allows the built object to be fully supported by the excess material until removed at the completion of the process. The material cures fully within 24 hours at which time surplus sand can then be removed and used for future prints. (Blagdon, 2012) The printer head spans the width of the print bed and is supported on a lattice structure. The light structure allows for mobilization of the unit, presenting a possibility of production onsite, though currently, the machine capitalizes on enclosed space in an industrial warehouse. (Turner, 2013) One of the major drawbacks of the technology is the immense weight of the final artefacts, requiring the componentization of structures, or removal of barriers to in-situ printing.

Figure 01.40 • Prototype with two storey frame

Figure 01.41 • Printed Structure

Figure 01.42 • Printed Model Homes

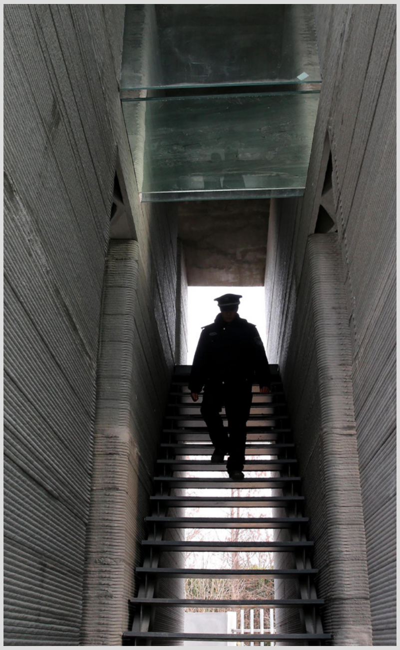
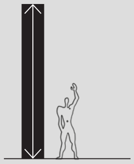


Figure 01.43 • Interior of Printed House



o1.3.10 WinSun - 3D Printed Architecture

Scale:	Large
Date:	2014
Designer:	WinSun
Sponsor:	N/A
Location:	China
Market:	Commercially Available
Technology:	FDM
Material:	Magic Stone

WinSun is a Chinese corporation, based in Suzhou China, which specializes in construction and materials. The company has roots in the fabrication of non-standard interior or exterior surfaces as well as the development of new materials. (Future of Construction, 2016) They first hit the 3D printing market with their display of 10 small 200 square-meter houses in the beginning of 2014. The homes were printed with a large format 3D printer which took 12 years to develop and over 20 million yuan (3.2 million USD). WinSun estimates the cost of printing these homes is about half that of the traditional method, but the technology still faces regulatory hurdles. (Fung, 2014) Ten months later, in 2015, the company revealed its significant progress with the production of two large-scale buildings put on display at Suzhou Industrial Park. The latest landmark feature is a fully functioning office fabricated in Suzhou and constructed in Dubai. It marks the beginning of a dedicated focus on 3D printing within the UAE, and the collaboration of high profile companies to produce highly refined projects utilizing 3D printed structures.

Ten single-story structures were built from prefabricated panels, each being uniquely printed. In total the houses cost just $5,000 to build, The structural frame is designed to accommodate services such as plumbing, electrical, and insulation after the assembly of the structure – similar to traditional construction methods. Winsun went on to showcase larger structures, a villa approximately 1,100 square meters as well a 5-storey residential building; the world’s tallest 3D printed building. The villa was specially designed for the Tomson group, a large realty company based in Taiwan, with 10 pre-ordered units coming in at around 161,000 USD each. (Li, 2015) They componentized the construction into a panelized system, allowing for the printing of multiple pieces to then be shipped and assembled on site. (Sevenson, 2015) The ability to high-jack the existing prefabrication market allows WinSun to integrate 3D printing technology into an existing skill-based trade. With successful integration, the freedom of 3D printing can be realized with the individualization of building design per client and application – which to date requires costly labour. (Future of Construction, 2016) The Offices of the Future revealed in Dubai in 2016 utilized the 3D printed structural components. It was then finished and detailed with endless technological features and a clean reduced aesthetic to match. The end product leaving one to question if it was indeed built layer by layer. Compared to traditional onsite construction the company estimates they saved 80% of the construction costs, 60% coming from labour. (Future of Construction, 2016)

The 3D printer is 6.6 meters (22 feet) tall, 10 meters (32 feet) and 150 meters (492 feet). Taking 3D designs from a CAD drawing, the large 3D printer is able to fabricate the individual components of the structure. (Sevenson, 2015) The patented ‘ink’ is composed of cement, fibreglass, sand, and a special hardening agent, with the intent to incorporate scrap construction and mining material to reach towards a green agenda. The nozzle

Figure 01.44 • 3D Printed Residence in Asia

Figure 01.45 • 3D Printed Office in UAE

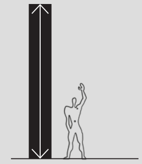
produces material layer by layer, between 0.6 to 3 centimetres thick in the desired shape and size. The printed components are produced with a diagonal reinforced pattern running between the shell walls. These are then reinforced with steel rebar and concrete as required for added structural capacity and shipped to site. When onsite, additional rebar is used to tie the panels together, mechanical and electrical services are run through the walls before the finishing touches, windows, doors, as well as interior and exterior finishes are applied in a traditional manner. (Sevenson, 2015)

The company estimates that with their new construction method they can save 60 per cent of materials in the production of a home. It can also be printed in a third of the time of that traditional construction while reducing manual labour. (Sevenson, 2015) The benefits being a reduction of labour, more affordable material costs, and less risk or injury for contractors. (Li, 2015) The company is also making headway with the standardization of 3D-printing materials for the construction industry. The Chief Engineer of China Construction no.8 Engineering Bureau explained that the two houses [The 5-storey tower and Villa] were in full compliance with the relevant national standards. “It is safe, reliable, and features a good integration of architecture and decoration. But there is no specific national standard for 3D printing architecture, we need to revise and improve such as standard for the future.” (Li, 2015) With the advancement of their printing technology, WinSun has intentions to expand to more than 20 countries to spread the popularity of 3D printing architecture. (Li, 2015)

Figure 01.46 • Apis Cor Finished House

Figure 01.47 • Apis Cor Construction Image

o1.3.11 Apis Cor - 3d Printed House



Scale:	Large
Date:	2017
Designer:	Apis Cor
Sponsor:	PIK, Samsung
Location:	Russia
Market:	Architectural Prototype
Technology:	Fused Deposition Modeling
Material:	Concrete Based Material

Apis Cor printed the world's first livable house in Stupino, Russia. Real Estate developer PIK and Samsung are two of five partners, who collaborated on this project. One of Apis Cor's 3D printers and automatic mix and supply units was used to print this house. The house was printed in 24hrs, with "both the inside and outside, … the entirety of the loadbearing walls, partitions and building envelope…", being printed in that time period. Completed, the house is 38 square metres, and contains a hall, bathroom, living room and kitchen. The construction cost of one house is $10,134, approximately $275 per square meter ($25 a sq.ft.). This amount includes, "the entire scope of work and materials required to erect a house, including the foundation, roof, exterior and interior finishes and insulation". (Bari, 2017) Apis Cor's research shows that they should be able to print cottages 19% cheaper than foam concrete houses by 2018 with the possibility of reducing the expenses another 20-30%. Hopefully this is a workable price for the state program budgets of the countries that Apis Cor is looking at as a market for their homes. Some of these countries include Russia, Asia and the Middle East where there are specifically "state programs for the construction of social low-rise housing and infrastructure" (Scott, 2017)

The printer developed by Apis Cor has the construct of a mobile crane. (Scott, 2017) This 3d printer/mobile crane weighs two tons and has folded dimensions of 4x1m and 6x1.5m. (Apis Cor, 2018) This compact state makes it possible for the printer to be more easily transported to site and in one piece. (Scott, 2017) The printer has a 30 min installation and set-up time. It takes two people for operations and material supply. The crane is able to print houses up to three stories high, with each printer being able to print to a height of 3300mm before it needs to be moved. One 3d printer can print to an area of 132 square meters; Printers can be coordinated to cover a bigger area. The printer is capable of printing at speeds up to 10mm/min. (Apis Cor, 2018) The printer is made to extrude fibre concrete or geopolymer. Apis Cor uses a geopolymer concrete called Geobeton which has high efficiency, a higher thixotropy, fluidity and an ability to adjust the setting time, with a consistently high mechanical strength (compressive strength reaches 100 MPa and more)". (Apis Cor, 2018)

Apis Cor has offices in Russia and San Francisco. (Scott, 2017) Their partners are Sunconomy, PIK Company, Samsung Electonics, BITEX – German technology, Siemens Finance Ltd. Gerbeton LLC, MARCH architectural school, NRU MGSU National Research University, EXPO Leasing Ltd, 3D PULSE, Window Factory, MKB-Leasing, and TechnoNICOLConstruction Systems. (Apis Cor, 2018) Rusnano Sistema Sicar is a private equity fund established by Sistema and RUSNANO that has decided to invest USD 6 million in Apis Cor. They see Apis Cor as pioneers in the future of 3d printing. (Rusnano, 2018)

o1.3.12 Summary

These examples show the range of application in which 3D printing technologies can be implemented in architecture. Some of them are hopeful explorations of a unique structural system not currently possible, while others are logical approaches to making small changes in the current industry. The approach to scale separates many of the projects and the goals that they were hoping to achieve. Each case study also approaches the use of adopting additive manufacturing to solve problems differently; some look at material optimization, others look at freedom of constraints, and others flexibility of schedule.

The ability to tackle the scalar factor is shown in the differing approaches from ARUP, DUSHouse, and WinSun Cor. The structural nodes produced by ARUP confronts the dynamic relationship of time spent trying to optimize the system by removing unique elements to be produced repetitively at a lower cost versus the ability to be able to move straight to production and produce each node uniquely. This small-scale application highlights the struggle between the mass production of objects and the design of objects. The DUS Canal House focuses on the designer/client relationship where manufactured elements can be picked from a catalogue of parts, but simultaneously arranged, changed and formed to suit individual needs. The Application builds upon the idea that components can be added together, but through 3D Printing individually selected and added to make a whole. Customization is accessible through the flexible integration of digital design into fabrication, where the model also contains the physical restraints required to build. WinSun has displayed on a larger scale, the integration of 3D printing into the existing framework of construction. The prefabricated elements can be unique and easily produced, shipped and assembled. Many copies can be printed as well, but complete customization is the goal. They have begun the challenge of adapting building codes to the production of 3D printed elements, beginning to answer the unease about the adaption of this new technology.

To gain an understanding of how these new approaches to manufacturing can fully transform the industry we need to gain an understanding of current manufacturing processes and the controls which guide them.

o1.4 Conclusion

As identified in the first section of this thesis, architecture is built from the combination and arrangement of many smaller individual pieces. These pieces range in size and material, with many possible solutions to solve a problem. Choices are influenced by factors not necessarily based on performance but aesthetics, culture, and personal ego. Through the years, movements have focused on optimizing construction to allow for its production to flow in a manner similar to that of manufacturing. Striving for the benefits of reduced construction time and cost through the ability to streamline part assembly on-site. As new technologies are developed, they slowly find their way into architecture. Ideals were borrowed to reduce architecture to a simple assembly of prefabricated parts; now with additive manufacturing, there is a new technology looking for its ability to fit and transform how we produce architecture. The case studies show the possibility of producing complex forms which are digitally created, in a seamless manner from the digital file. Production of technically complex forms no longer correlates with skilled craftsmen or increased labour, as the part has the potential to be produced as easily as a geometrically simple part - through a machine, with the push of a button.

Materials and Processing

02

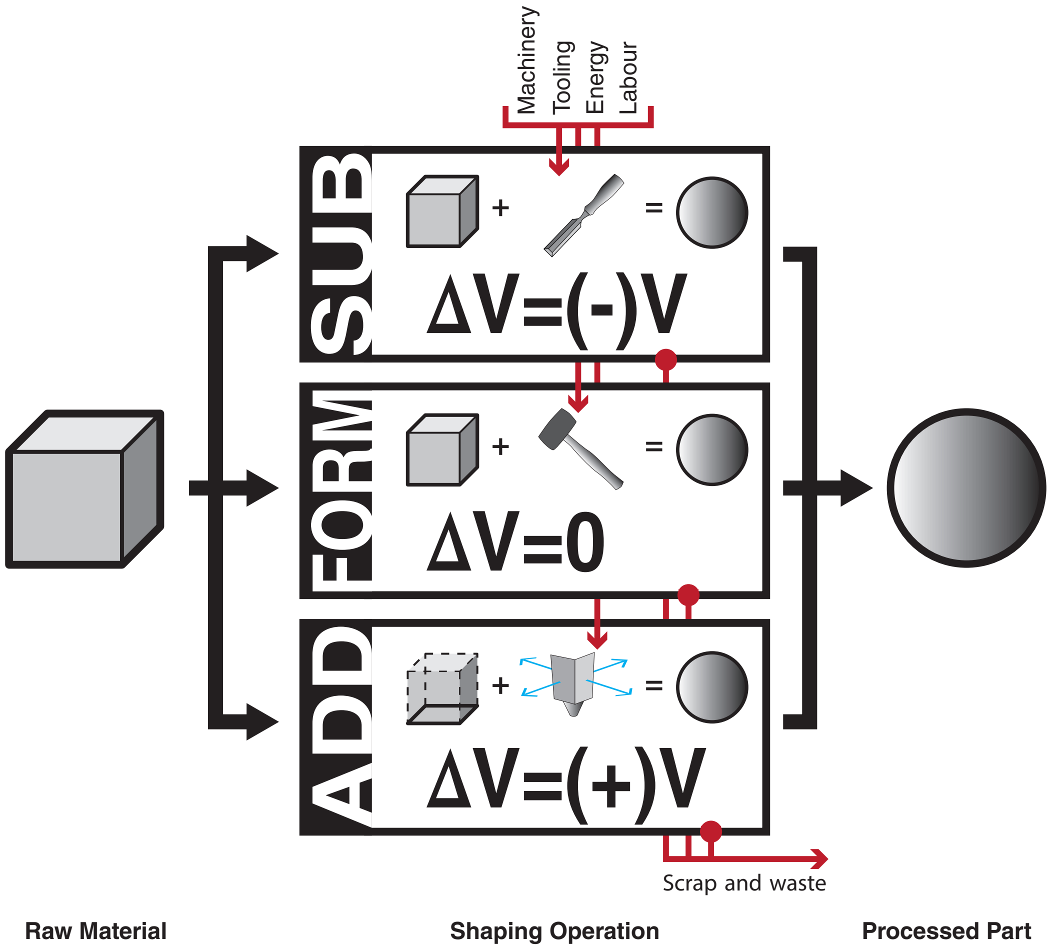


Figure 02.1 • Technical Definition of Manufacturing
(ADDitive, FORMative, SUBtraction. V represents the volume of an object.)
Manufacturing as the transformation of raw material into a processed part through the addition of machinery, tooling, energy, and labour via a shaping operation.

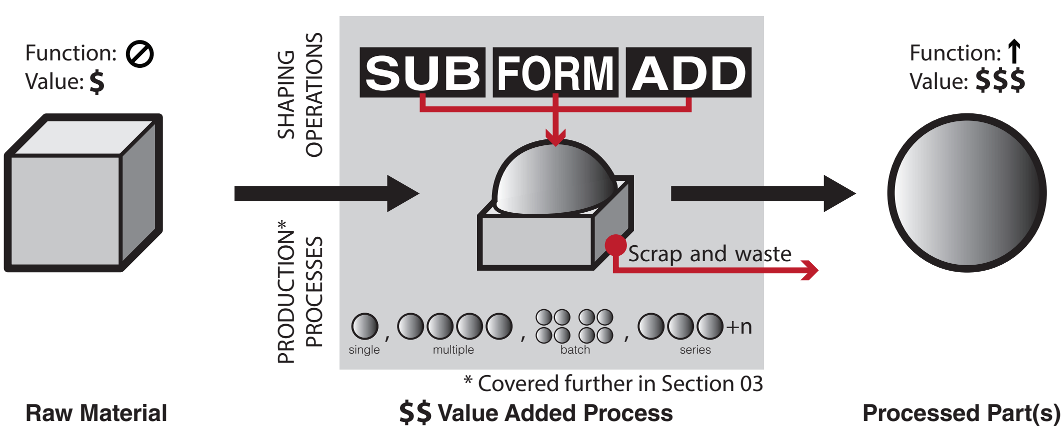


Figure 02.2 • Economic Formula of Manufacturing
An alternate method of looking at manufacturing is through the addition of value to a material through both the shaping and production processes. Value is added due to the increased function of the material, but also due to the cost of operations.

o2: Materials and Processing

o2.1 Introduction

Manufacturing is the term used to describe the process with which humans create objects. Technically defined as, the conversion of a material into a product through the application of physical and chemical processes by way of machinery, tooling, energy and labour. Figure o2.1 diagrams the technical definition of manufacturing with the three categories of shaping operations identified. (Groover, 2013. pg. 3) The word manufacturing derives its meaning from the Latin words ***manus***, meaning “hand” and ***factus***, meaning “make” combined to form the meaning “made by hand.” (Groover, 2013. pg. 2-3) However, manufacturing is commonly used to mean mass-production, implying series production rather than more accurately the creation of single unique items. It is essential to establish that a distinction exists between the *shaping operations* we use to make an object and the *process of production* (covered in section 03) used to increase profit and value. The economic formula shown in Figure o2.2 views these processes as a value-adding process, with production as a second variable. (Groover, 2013. pg. 3) The term manufacturing applies to the production of any item; this section aims to bring an understanding of the use of specific materials.

The shaping operations of manufacturing can be divided into three fundamental categories: formative, subtractive, and additive. Secondary Operations are categorized as post-processing and divided into three categories: assembly, heat-treating, and surface treatment. Formative manufacturing operations refer to methods such as casting or forging, well established in the history of manufacturing with some of the oldest known examples. Subtractive manufacturing operations include methods such as milling, turning, or carving. Additive manufacturing operations are the most recently mechanized category with examples such as additive processes (covered in section 04), three-dimensional printing (3DP), as well as composite methods. (Gebhardt, 2012. pg. 2) Assembly operations take the finished manufactured parts and assemble them into larger component/objects. Heat-treating operations establish physical characteristics within materials, such as annealed steel. Surface treatment operations are typically the final step on the way to consumers and produce the final texture, colour, hardness, etc. for the object. Figure o2.3 organizes these elements of manufacturing into a loose hierarchy from material to

Section 02

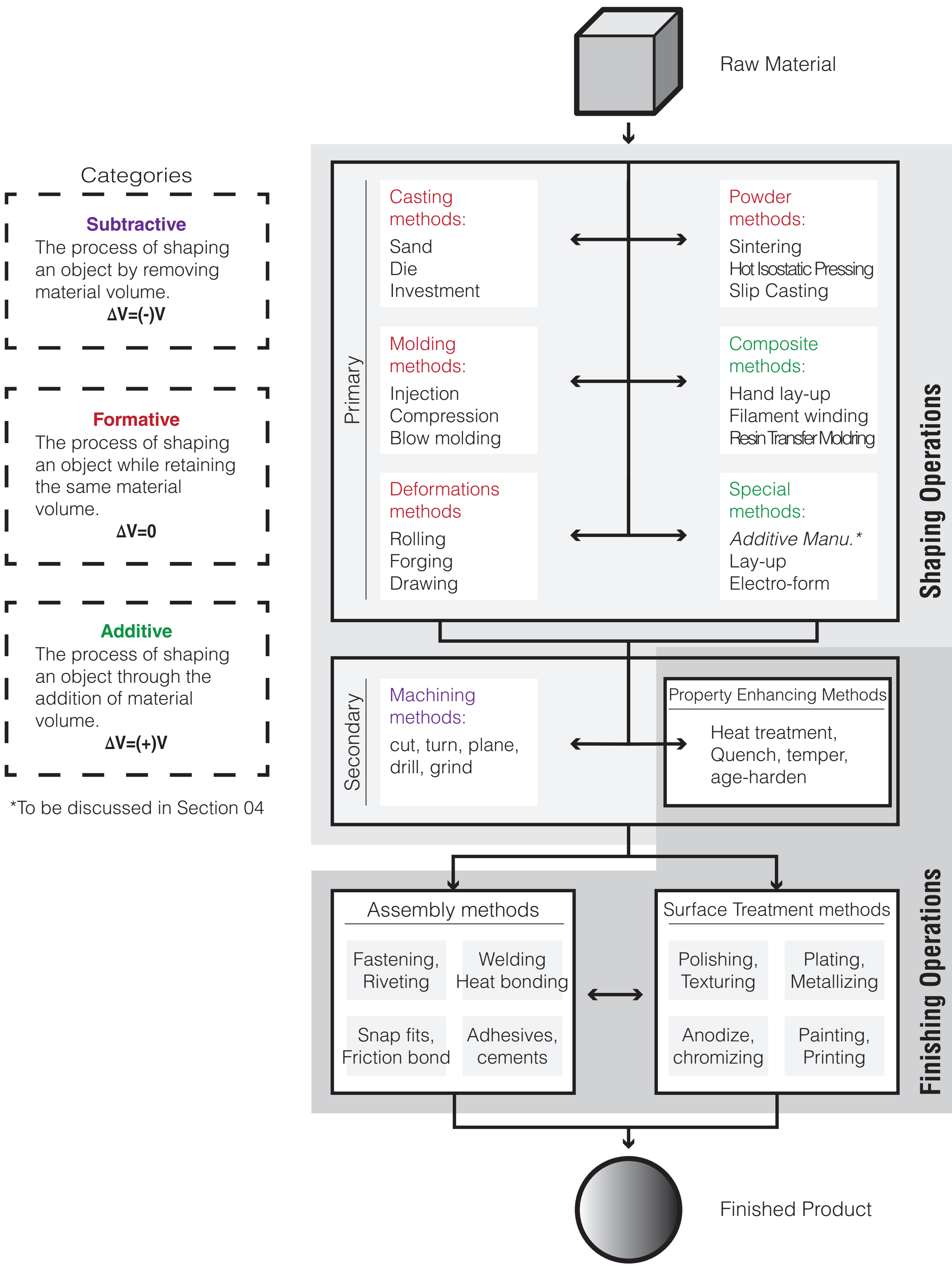


Figure 02.3 • Overview of Manufacturing
This diagram shows the general subdivision of manufacturing operations into primary shaping, secondary shaping, and post processing operations. These operations may happen in a number of different sequences depending on the product requirements. (Adapted from Groover.)

finished product. All consumer items are created through these methods individually or in some combination, having to navigate the complex chain of steps which transform simple materials into everyday objects.

Section o2.2 will provide an overview of materials, establishing the specific qualities that materials have which make them the best choice for particular applications or products we use. Following that section o2.3 will be an in-depth review of current shaping operations and their significance. Section o2.4 will provide an in-depth review of current finishing operations and their significance. Section o2.5 provides a survey of many common architectural products and the shaping processes used to produce them. Section o3 will build off of this groundwork to expand on how historical transformations to the *process of production* have increased the value of manufacturing production and will look at how architecture is currently piggybacking off of these developments.

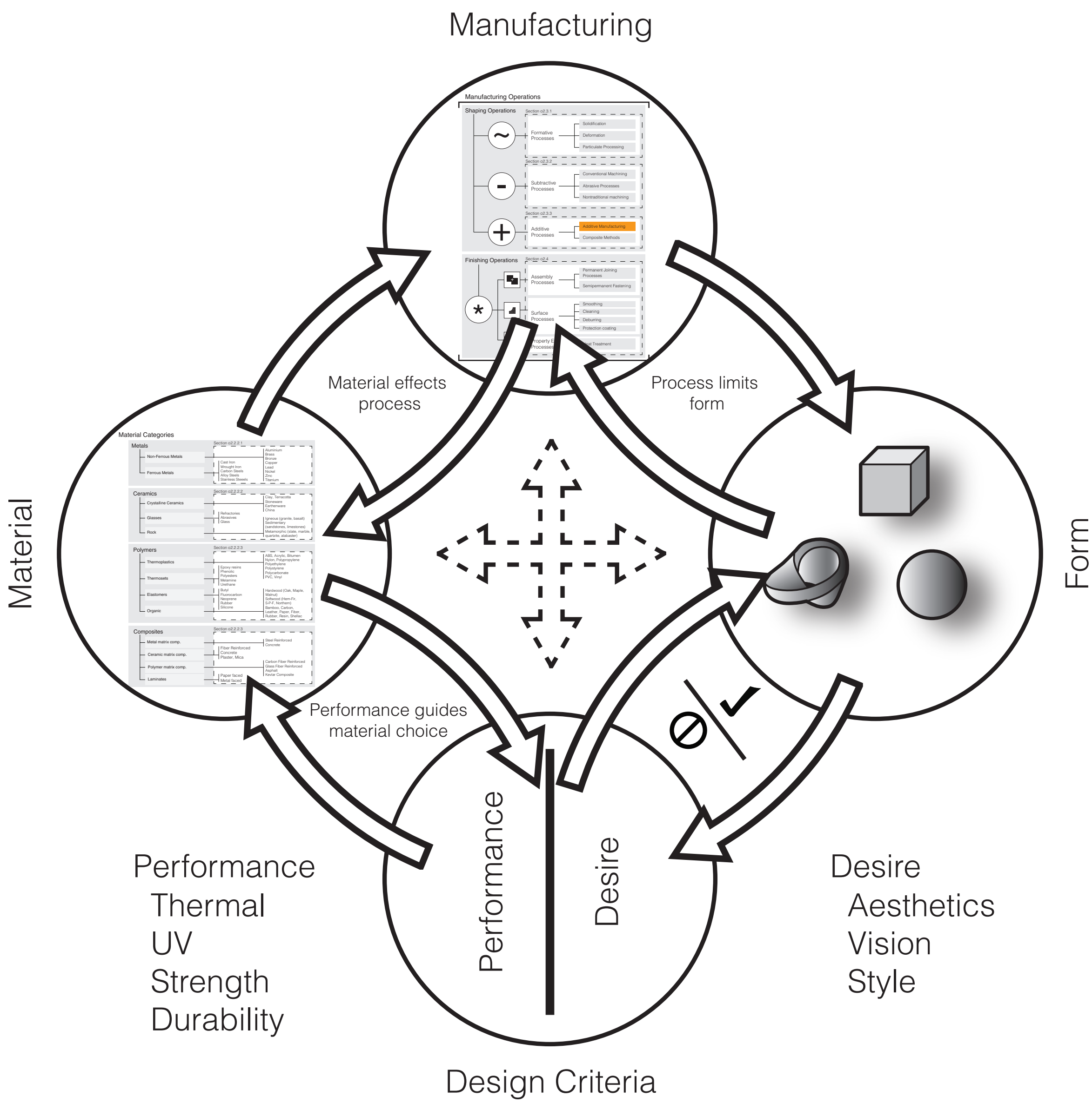


Figure 02.4 • Design Process Loop
The design of a product requires the navigation of the design loop process. On one side the manufacturing and material requirements must be able to meet those of the aesthetic and performance demands.

02.2 Materials

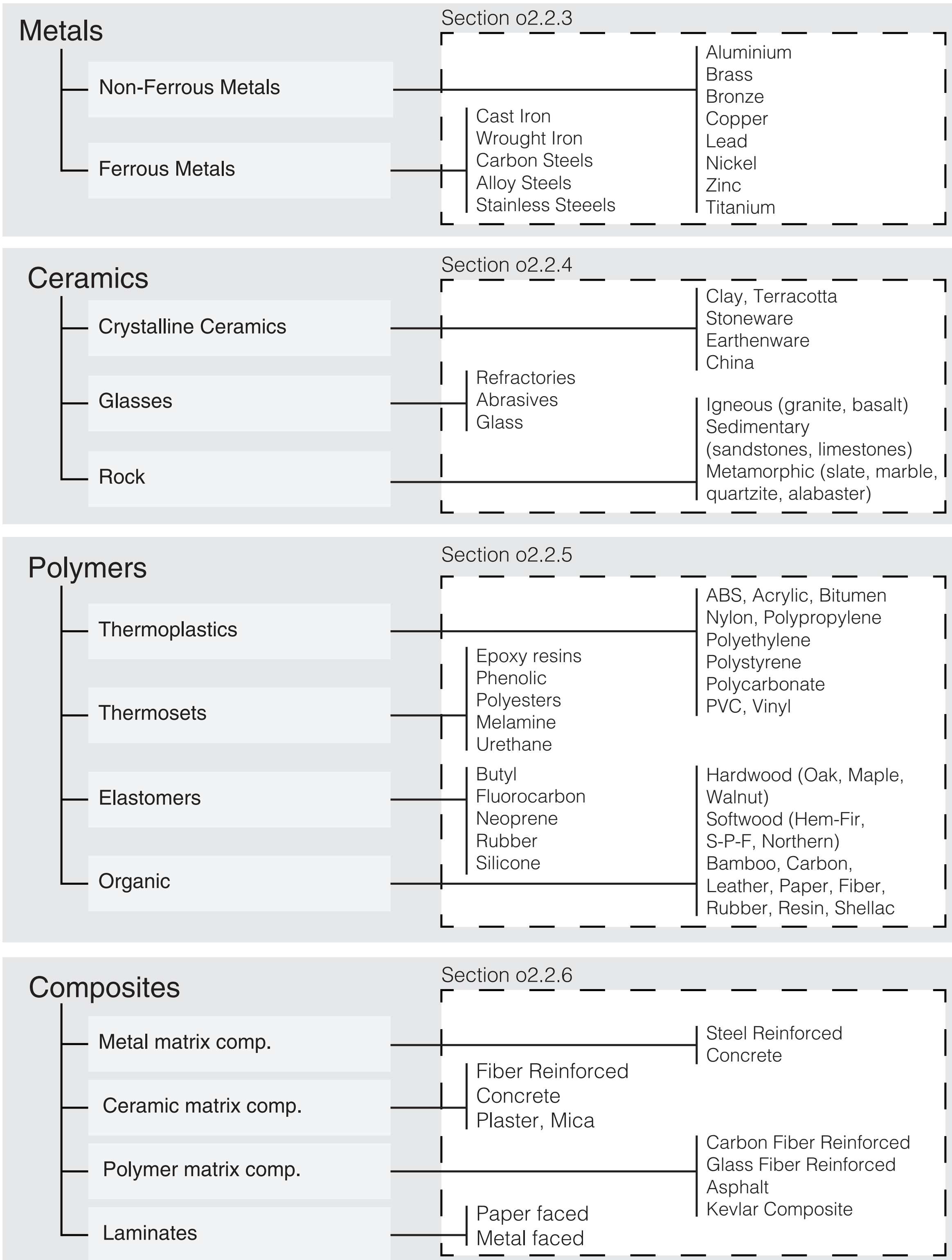
02.2.1 Materials and the Manufacturing Process

The manufacturing process is closely tied to the materials in use. Understanding of material properties is a prerequisite to understanding the method of shaping these materials. Due to varied physical properties of materials, the application of an operation may change in technical nuances, but the general principles are the same, e.g. casting iron and forming ice cubes are in essence the same method, both materials require a mould to take shape, starting in a liquid state with the removal of heat required to solidify, the difference being in the working temperature per material. There is a vast range of materials each with individual properties and requiring an adaptation of a manufacturing process to be effectively shaped.

The best choice of material is paramount for successful manufacturing, adherence to formal constraints, and performance as a product. The design process aims to meet the design objectives by navigating the material properties and applicable manufacturing methods to achieve the final object. This process is cyclical; therefore a design can be started at any point in the cycle but must take into consideration the other three components to create an object. [See figure o2.4] Material properties have a direct impact on the applicable manufacturing processes available. For example, stone can be shaped by cutting while metal can be shaped by cutting and forging. The material of an object dictates the processes available to shape it. Since the performance of an object is related to specific material properties, constraints are placed on the processes and forms available. For example sheet metal and 6-mil plastic sheets both work as effective waterproofing barriers, but one meets the performance constraints of being waterproof, lightweight, economic, and easy to install and transport (6mil).

Materials used in manufacturing must be processed with dependable physical properties and are otherwise known as functional materials. Functional materials are placed into four classifications: metals, ceramics, polymers, and composites. (Groover, 2013. pg. 8) These classifications are based on physical properties, structural makeup, and material behaviour.

Material Categories



02.2.2 Properties of Materials

The classification of materials is based on their atomic physical structure and the properties they exhibit, in general, this gives four categories. The four categories used within manufacturing are metals, ceramics, polymers, and composites. Some industries split these categories up depending on specific material properties, but for the extent of this thesis, these four categories are sufficient. Figure 02.5 gives an overview of the categories and examples of materials.

Material properties are often divided into two categories; mechanical and physical. Mechanical properties determine how it can be shaped and its structural performance under stress or load. These properties include the elastic modulus, ductility, hardness, and various measures of strength. (Groover, 2013. pg. 40) Figure 02.6 shows a compiled graph of strength vs. toughness of various material categories. The function and performance of an object are dependent on its ability to withstand or accept the stresses encountered in service.

Physical properties are the behaviour of materials in response to physical forces other than mechanical. They include properties of thermal, electrical, electrochemical, and volumetric behaviours. As Groover summarizes materials “must conduct electricity (or prevent its conduction), allow heat to be transferred (or allow it to escape), transmit light (or block its transmission), and satisfy a myriad of other functions.” (Groover, 2013. pg. 67) Physical properties can affect the performance of a shaping operation and are essential factors for manufacturers to understand.

Within architecture mechanical properties are considered to the extent of the structural performance of an object. Outside of structural performance, there are other demands of equal importance as materials must control or conduct electricity, heat, light, endure UV, and be resistant or safe through a fire. (Groover, 2013. pg. 4) Architecture relies upon physical properties much more heavily as they provide controls for our enclosures. Following is a review of material and their properties.

Figure 02.5 • Material Classification
All materials can be categorized under one of the above classifications allowing for materials with similar chemical makeup and material properties to be quickly identified.

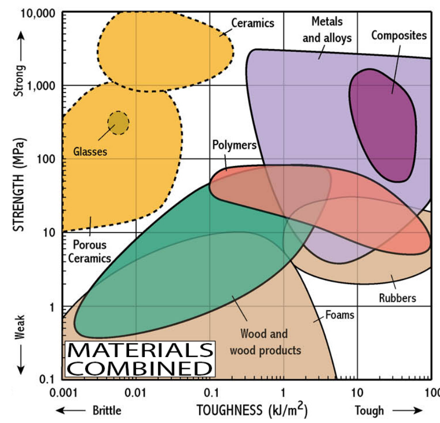


Figure 02.6 • Strength vs toughness
This graph shows the groupings of materials based on their combined performance in regards to specific properties. Other graphs can be found in Ashby.

Common material and architectural use

Example images of use

COPPER

Copper is a metal with non-destructive oxidation that is an excellent choice for exterior finishes. It can resist the elements well, is UV resistant, waterproof, and develops a patina over time. In the case of copper it can be used effectively as a new or aged finish, worked in sheets, cast, or wrought to produce complex details. It allows the transference of electrons well and as such is used in wiring situations often. It's ability to resist corrosion from water makes it popular for domestic piping.

Figure 02.7 • Applications of Copper
a) copper sheets in a roofing application, b) forged copper used as a sink basin with a hammered finish, c) copper fittings for plumbing applications.

ALUMINUM

Aluminum is able to be extruded extremely well and is manufactured with high precision. Lending itself mainly to straight strong sections of various profiles. It has good strength, it is resistant to UV, oxidation is not structurally damaging, and is waterproof. It conducts thermal energy and must be used with thermal breaks in window applications.

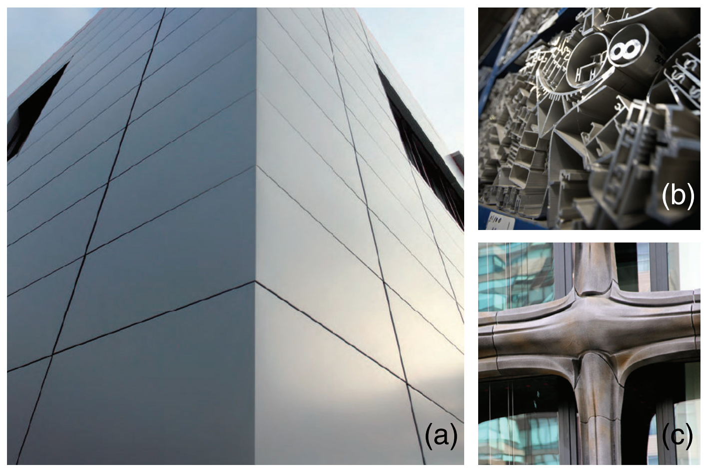


Figure 02.8 • Applications of Aluminum
a) sheet metal with a plastic core in an facade application, b) various extrusions adaptable to numerous applications, c) decorative cast aluminum structural elements.

STEEL

Steel can be worked into many forms through different processes. Steel sections are typically hot rolled and tempered to achieve specific properties of strength. Steel is known for its high yield strength, ductility, toughness, and modulus of elasticity. It will expand with temperature changes, will conduct thermal energy, and needs to be protected from the environment for corrosion control.

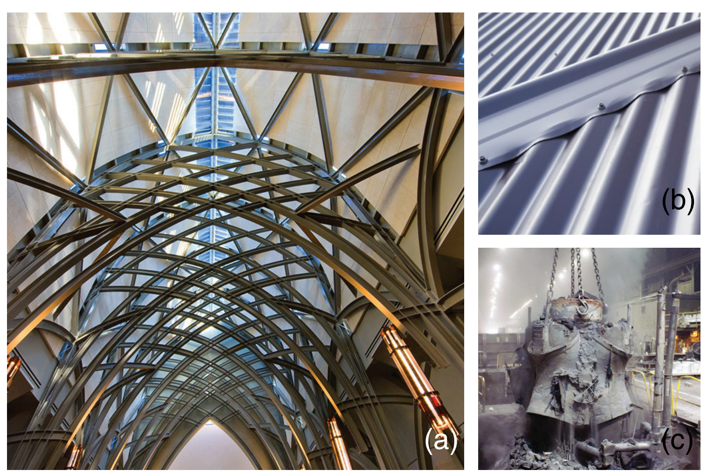


Figure 02.9 • Applications of Steel
a) curved steel beams for structural roof frame, b) profiled sheet metal in roof/siding application, b) cast steel connection for structural column.

02.2.3 Properties of Metals

Typical metals used in manufacturing are alloys, being a combination of two or more elements one of which is a metallic element. (Groover, 2013. pg. 9) Metals are categorized as ferrous and non-ferrous. Ferrous metals are those which include iron, such as cast iron, steel, or weathering steel. Non-ferrous metals are pure metals which do not contain iron and are non-magnetic, such as aluminium and copper.

Metals, in general, are known for their strength, elastic behaviour, plastic deformation (ductility). In terms of strength, metals handle tensile forces well and can withstand high compressive forces, and they can resist creep (deformation under long-term loads) and deform under failure (plasticity). Ductility is a benefit to structures as this typically avoids catastrophic failures (quick unexpected collapse). It also is advantageous to shaping as this allows for metals to be shaped via compressive forces (malleable) and shaped via tensile forces (ductile) at templates below their melting point. (Illston, 2010, pg. 55) Metals are also able to be heated to a melting point and cast into shape this may produce a weaker crystalline structure in some metals but can be forced to re-structure via heat treating. Metals can be joined via mechanical fasteners or can be fused, melted, or welded together. Metals are prone to corrosion; they are typically found in nature as oxides and continuously try to revert to that state. These oxides can form a protective coating (as with copper) or degrade the structural performance (as with steel). The elemental structure of metals allows for a high degree of electrical and thermal conductivity, as well as a relatively high degree of reactivity (e.g. with oxygen).

Metals typically are used for their strength, finish, and manufacturability. Metal is used for structural applications such as resisting high loads and being used in combination with various materials to produce high-performance hybrids. They produce and easily maintain high-quality surface finishes, weather well, and can be textured in an extensive range of styles. Metals also tend to be consistently produced to precise manufacturing tolerances and can be shaped through a wide variety of methods. Figures 02.7 to 02.16 gives examples of materials and typical uses.

METAL

Contemporary examples of common materials used with image and quality highlights

Figure 02.10 • Copper
unique Patina
high strength
high durability
natural finish can be exposed (oxidation does not degrade performance)

Figure 02.11 • Aluminum
Maintains tight tolerances
Extrudes well
Natural finish can be exposed (oxidation does not degrade performance)
Natural colour is desirable

Figure 02.12 • Zinc
High strength to weight, malleable
Finishes well
Natural finish can be exposed with little lifetime maintenance required

Figure 02.13 • Iron
Can be cast or wrought
Industrial aesthetic
Has a good strength to weight ratio, can be used in compression well, but not tension.
Protect from the elements.

Figure 02.14 • Steel
Has a high strength to weight ration making it appropriate for long spans, in condtions of compression and tension.
Protect from the environment to prevent oxidation/degradation.

Figure 02.15 • Stainless Steel
Steel alloy which performs better in exposed situations.
Maintains a high strength to weight ratio similar to steel.

Figure 02.16 • Weathering Steel
All the benefits of steel with the added benefit of finishing with the red/brown oxidation specifically engineered to not degrade performance.

Common material and architectural use

Example images of use

STONE

Stone products such as granite, marble, limestone or sandstone are the backbone of ancient structures preserved to this day. This material can be found in abundance, with a variety of compositions, finishes, colours, and performs in a consistant manner.

Figure 02.17 • Applications of Stone
a) stone facade, b) cultured stone wall, c) interior wall finish.

GLASS

Glass is a clear, transparent solid that is used in a variety of applications. It is widely used as a facade to buildings, and is able to effectively resist the environment, be formed in long straight panels, and be installed fairly easily. Due to the brittle properties of glass special coatings can be applied to help when there is a risk of high impact. A typical glass product is float glass, formed by floating molten glass on molten lava, however there are other methods to preparing glass such as casting and blowing. The translucent qualities will vary by production method.

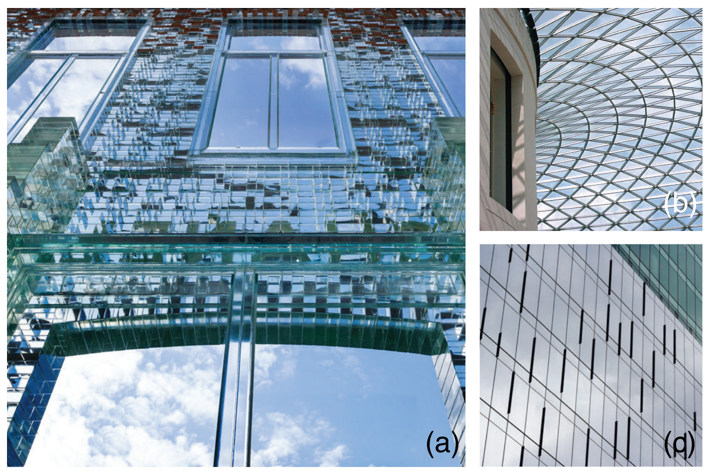


Figure 02.18 • Applications of Glass
a) structural glass block facade, b)glass roof, c)curtain wall facade.

CERAMIC

In general ceramic products come as sheets, tiles, bricks, and cast objects; being composed of porcelain, clay, or terracotta. Due to the hard, tough, UV, and water resistant nature of the material they are used in areas of high traffic, moist or harsh environments. They perform well in compression and have a long standing tradition of being used structurally. Modern use leans towards internal or external finishes where high quality, long lasting products are desired.

Figure 02.19 • Applications of Ceramic
a)extruded terracotta panels, b)ceramic roof tiles, c) ceramic tub.

o2.2.4 Properties of Ceramics

A ceramic consists of a compound of metallic and non-metallic elements, falling into two types, crystalline and glass. Manufacturing processes vary between the two. Crystalline ceramics are formed in various ways from powders, and then fired to fuse the particles together. Glass ceramics can be melted, cast, or formed (such as in traditional glass blowing). (Groover, 2013. pg. 9)

Ceramics, in general, are hard, non-reactive, moderately to very strong in compression, stiff and brittle. A low level of ductility means that ceramics lack plastic deformation and as such are brittle. They cannot withstand point loads or concentrated stresses as their strength is relative to the material volume under load. (Ashby, 2005 pg. 28) The benefits of ceramics are their hard surface, which can maintain a finish with little maintenance. They are able to maintain strength at high temperatures and can withstand corrosion well. Ceramics resist UV well and thermal conductivity and depending on structure (glassy or crystalline) may be susceptible to water damage (Illston 2010, pg. 294).

Ceramics are used in highly abusive environments as floor covering in areas with heavy traffic, and humidity concerns. Ceramics have long established uses such as clay, (pottery) silica (glass) and silicon carbide (grinding). Ceramics such as glass are used for its transparent qualities as well as being resistant to weathering and its strength. Cement is a product manufactured by firing limestone and clay to create complex alumina-silicate minerals. They react with water and when combined with sand and aggregate form the ubiquitous construction material concrete. Other uses, such as bricks, are fired to provide a close pored surface resistant to water penetration. Natural ceramics such as stone provide colorful palates as well as the benefits of stiff, hard, strong, and easily maintained surfaces. Figures 02.17 to 02.26 gives examples of materials and typical uses.

CERAMIC

Contemporary examples of common materials used with image and quality highlights

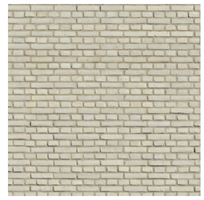


Figure 02.20 • Clay Brick
Durable and Strong - load bearing walls, screens, structure, finishing int./ext., floors, roadways, modular, comes in many shapes/sizes/textures/colours.

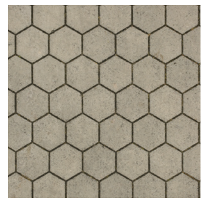


Figure 02.21 • Porcelain Tile
Maintains a tough durable finish. Withstand's high traffic and harsh environments.
Comes in a variety of colours and finishes.

Figure 02.22 • Terra Cotta
Ext. finish, roof or siding, can be used structurally as well.
Has a telltale colour and finish.

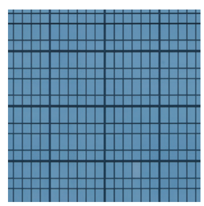


Figure 02.23 • Glass
Int./ext. finishings on floors, walls, ceilings, doors, furniture comes in many shapes/sizes/textures/colours, clear glass used for windows.

Figure 02.24 • Portland Cement
See Composites for Concrete.
Cement is a product made from the deconstitution of lime into calcium oxide combined with clay and iron oxide.

Figure 02.25 • Granites
An igneous rock, formed by solidification of the earth's magma. Hard and dense, thus durable, water impenetrable, impact resistant, and stable in tough environments. It comes in many finishes such as polished, flamed, honed.

Figure 02.26 • Sandstones
as a sedimentary rock these rocks are formed through the deposition of material overtime. Depending on the composition, they take on various properties and colours. It can be finished being sawn, split faced, and clean rubbed.

PolyVinylChloride

PVC is a thermoplastic that is widely used for its ability to be economicall It can be extruded into many shapes and as such is used as tubes, sheets or frames. With a combination of rigid outer shells and foamed interior, PVC sheet goods can attain a high stiffness-to-weight ratio. When used in exterior applications metallic additives are used to stabilize the material and help prevent degradation and discolouration. Direct UV light will eventually discolour and craze the material.

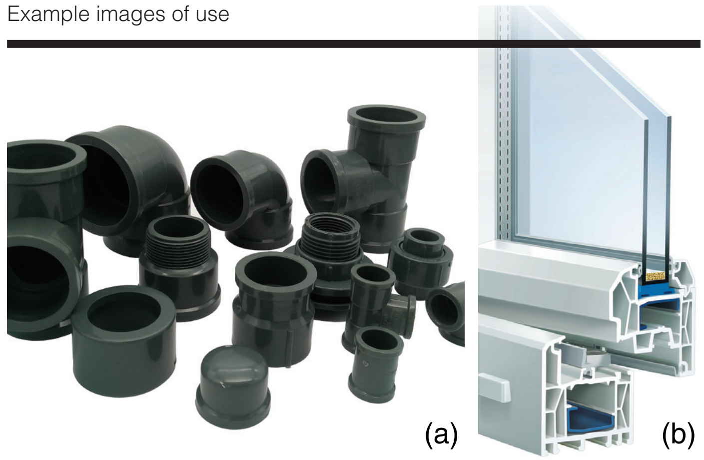


Figure 02.27 • Applications of PVC
a) injection molded plumbing fittings, b)extruded profiles used in window frames.

eXtrudedPolyStyrene

XPS is a dense foam product produced by a vacuum process. It has a closed cell structure with very low water-absorption, vapour and thermal transmission properties. Its dense rigid form allows it to be used as a wall sheathing application and inverted roof assembly, here the rigid form gives it additional desirable properties.

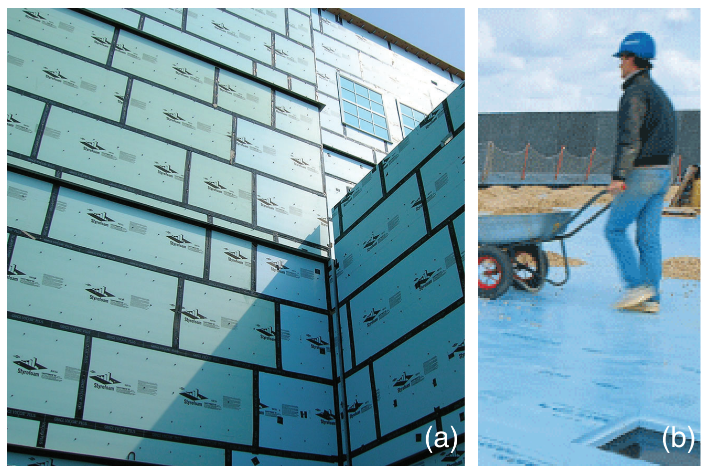


Figure 02.28 • Application of XPS
a)used as exterior sheathing and insulation, b)used for insulation in an inverted roof system.

SILICONE

Silicone is an elastomer which is utilized as a one-component sealant and cures quickly in-situ. Silicone will typically adhere well to metal and glass, but has difficulty on porous surfaces. It is typically used to seal joints between building components such as around a window frame to the supporting structure. Silicone is quite durable and can be expected to last in the range of 25-30 years. Certain types are adapted for use in structural applications; such as cap-less curtain walls. Other applications include flexible moudles for casting.

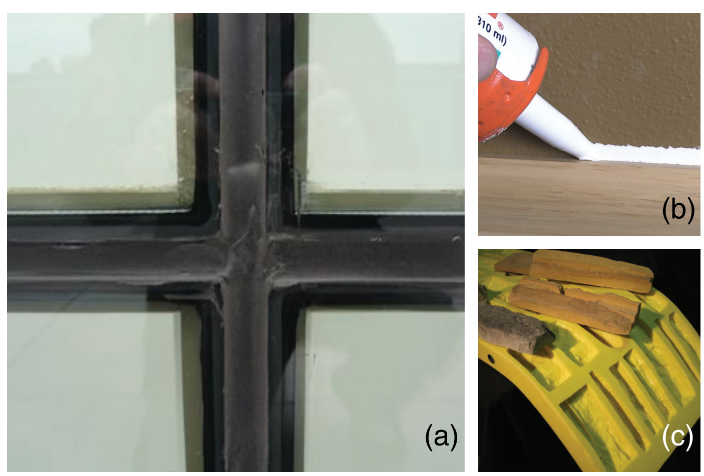


Figure 02.29 • Applications of Silicone
a)structural curtain wall joint, b)sealant between materials, c)flexible molds for products.

o2.2.5 Properties of Polymers

A polymer is a compound based on repeating structural units called *mers*, whose atoms are composed of carbon, silicon, or fluorine plus one or more elements, such as hydrogen, nitrogen, oxygen, and chlorine. The repeated mer unit may form molecular chains thousands of units long when processed but can also form amorphous structures similar to a ceramic material. There are three categories of polymers: thermoplastic polymers, thermosetting polymers, and elastomers. (Groover, 2013. pg. 9)

Properties of polymers vary by category. In general, polymers give characteristic properties of being low density, low stiffness and strength, and high sensitivity to temperature. Specifically, thermoplastic polymers can endure the cycle of heating and cooling with little changes to the molecular structure. Thermosetting polymers chemically transform into a rigid structure upon cooling from a heated plastic state, or through other catalytic processes. Elastomers are polymers with elastic behaviour, a property unique to this material group. Plastics come in many forms; solids, rigid or flexible foams, sheet or film, as well as sealants and adhesives. Although relatively strong, easy to form and work, the downside of plastic is the stiff and brittle nature. Plastics need to be protected from exposure to heat, ultraviolet light or ozone, as they can damage the mer chains thus weakening their strength. (Illston, 2010. pg. 304)

Thermoplastics such as polyethylene, polystyrene, polyvinyl chloride, and nylon, are commonly utilized to mitigate water effectively as vapour barriers to pipes or mitigate thermal transference as insulation. Examples of thermosets include phenolic, amino resins, and epoxies; they are often used as adhesives in the creation of laminates and as hard surface finishes. Examples of elastomers include natural rubber, neoprene, silicone, and polyurethane, they tend to age and weather well, and as such are used extensively as seals, gaskets, and protective waterproofing layers. (Illston, 2010) Figures 02.27 to 02.36 gives examples of materials and typical uses.

POLYMER

Contemporary examples of common materials used with image and quality highlights

Figure 02.30 • Silicone
Sealant - Creates a thermal, water, air, and vapour barrier. Structural - used for its high setting strength which allows it to hold objects in place securely such as glazing in curtain walls.

Figure 02.31 • Polyvinyl Chloride
Can be extruded, blown, or injected into many forms. It is used widely in a pipe form, or as protective coatings for wires, or combined with other materials to create protective membranes.

Figure 02.32 • Expanded Polystyrene
In its expanded form polystyrene is rigid and does a good job of preventing thermal transmittance.

Figure 02.33 • Polyurethane
Spray foam insulation, can be applied continuously as a spray, expands and hardens as it cures. Thermal, environmental, and structural performance depends on the cell size and volume.

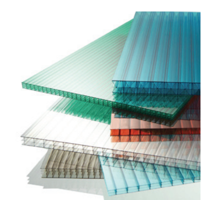


Figure 02.34 • Polycarbonate
Is used in many applications such as furniture, finishes, counter tops, dividers/screens, signs, trim, and cheap glazing.

Figure 02.35 • Acrylic
Comes in many forms ranging from sheet goods to liquid applied paints. Can be clear to opaque, and can be quite strong in its rigid form.

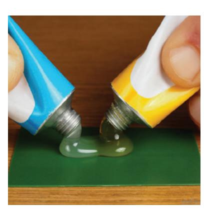


Figure 02.36 • Epoxy
Used primarily as an adhesive between components in layered composites. It can form a hard and tough surface finish. Creates strong bonds that are hard to break.

Glass Fibre Reinforced Concrete

Glass fiber reinforced cement has the appearance of cement with a diversity of colours, and textures. GFRC has high impact resistance but over time looses its toughness and strength. The product shrinks irreversibly during its initial moisture loss; but will remain fairly stable thereafter. It can be formed into many shapes and simulated materials can be manufactured, through the process of being sprayed into molds. (Lyons, 2010. pg. 327)

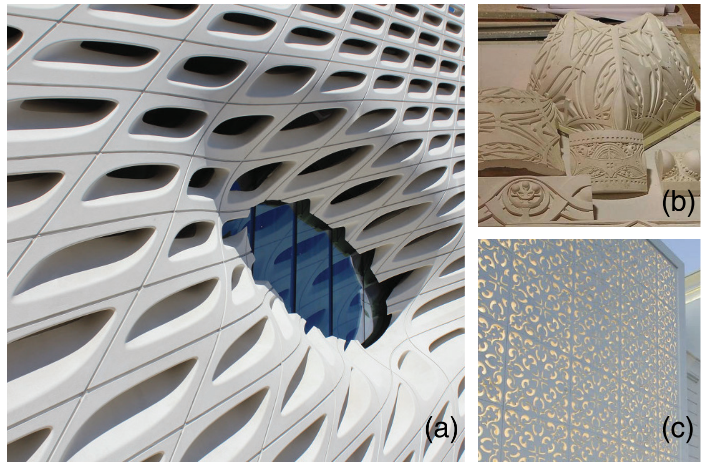


Figure 02.37 • Applications of Glass Fibre Reinforced Concrete
a) custom precast facade element, b)decorative precast finish, c) repetative precast panels.

Steel Reinforced Concrete

Steel Reinforced Concrete utilizes the combination of steel and concrete. Concrete is used for its ability to resist compresive forces. Steel is used for its tensile strengh and performance. It is utilized in structural capacity and forms the baseline use of concrete for the construction industry.

Figure 02.38 • Applications of Steel Reinforced Concrete
a) cast in place columns and floor slap, b) pre-cast structural floor slabs, c) cast in place bridge.

CORIAN

Corian is a composite of polymers and ceramics (natural minerals) which combine together to produce a highly durable and tough material. A typical composition is 33% acrylic polymer and 67% alumina trihydrate. it is usually used for interior applications where natural stone is desired and can be manufactured in large sheets and joined with the composing polymers. The material provides the visual appearnce of stone, but does require precautions due to the polymer components.

Figure 02.39 • Applications of Corian
a)interior wall, ceiling, and counter finish, b)solid surface sink and counter, c)interior kitchen counter finish.

o2.2.6 Properties of Composites

Composites consist of two or more materials that are processed separately and then bonded together to achieve properties superior to those of its constituent parts. The usual structure of a composite consists of particles or fibres of one material mixed with another. These materials include metal matrix composites, ceramic matrix composites, polymer matrix composites as well as laminates. Material properties vary considerably between composites and rely heavily on the individual properties of constituent parts to create a product of superior behaviour.

Polymers are noted for their relative strength, but lack stiffness. They can be combined with fibres of high strength to form composites with the properties of both. Popular materials for reinforcement include glass fibres, carbon fibres, and aramids (Kevlar); the use of which increases the strength to weight ratio and impact resistance of the composite they are a part of. Ceramics perform extremely well under compressive forces but fail tensile forces due to their brittle nature. They can be reinforced with fibres (GFRC) or other materials such as metal (steel reinforced) to increase their ability to resist tensile forces. Laminates are commonly layers of plastic reinforced by woven fibre membranes or layers of metal and polymer fused together.

Composites are used widely in architecture. Steel reinforced concrete composite is used widely for structural applications. Laminates of PVC, VCT, or TPO with fibre reinforcement are used as resilient flooring or roofing products. Fibre reinforced polymer and composites are used for façade elements as well as structural components which need to be lightweight yet strong. Composites occur naturally such as wood, and also produced synthetically such as resin reinforced with carbon fibre. (Groover, 2013. pg. 11) Figures 02.37 to 02.46 gives examples of materials and typical uses.

COMPOSITE

Contemporary examples of common materials used with image and quality highlights

Figure 02.40 • Concrete
A combination of ceramic material cement, and natural stone, sometimes with additives for improved strength or colour. Highly resistant to UV and strong in compression, typically used with steel to improve structural ability in tension. Durable, strong and is used for load bearing walls, screens, finishing int./ ext., floors, roadways. It comes in many shapes, sizes, textures, and colours.

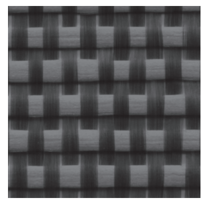


Figure 02.41 • Carbon Fiber Comp.
A combination of carbon fibers in a resin epoxy matrix. This material typically has woven fibers with excellent structural capabilities laid along the direction of stress. Pieces are crafted specifically to the fibers to allow for excellent properties and light weight elements. Used in highly specialized situations.

Figure 02.42 • Wood
A natural composite of cellulose and lignin, wood is widely used for its structural capacity. It performs well in compression and tension. It can be used as a high quality finish or a solid substrate.

Figure 02.43 • Laminate Tiles
Laminate tiles form the bulk of resilient flooring. They can be composed of PVC or other polymers. Have a robust finish, come in many colours and sizes.

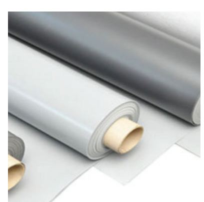
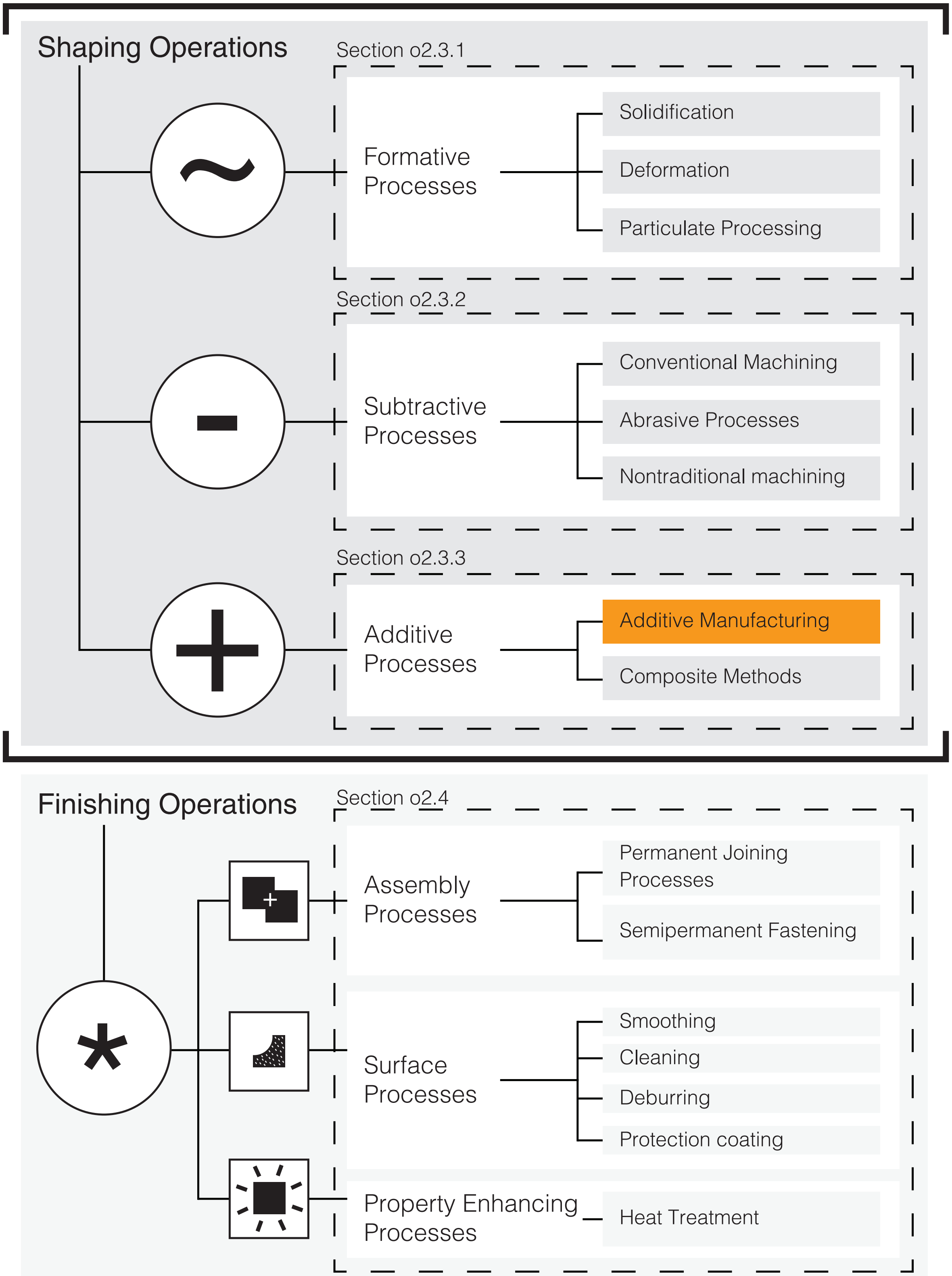


Figure 02.44 • Roof Membranes
Composites of fibre mesh with polymer coatings, these membranes create water impenetrable layers. Depending on the composition they may be left exposed or covered to protect from uv damage.

Figure 02.45 • Engineered Stone
Can be used in locations where natural stone would typically be used. Provides a solid durable surface that performs well in compression. Can be used in exterior applications with the proper composition.

Figure 02.46 • Eng. Wood Products
Product composed of wood products with polymer adhesives. Products of light weight and high strength can be produced. Effected by water exposure, humidity, and UV.



Shaping Operations
Section o2.3.1
Formative Processes
Solidification
Deformation
Particulate Processing
Section o2.3.2
Subtractive Processes
Conventional Machining
Abrasive Processes
Nontraditional machining
Section o2.3.3
Additive Processes
Additive Manufacturing
Composite Methods
Finishing Operations
Section o2.4
Assembly Processes
Permanent Joining Processes
Semipermanent Fastening
Surface Processes
Smoothing
Cleaning
Deburring
Protection coating
Property Enhancing Processes
Heat Treatment

o2.3 Shaping Operations

Manufacturing is built around shaping operations. These processes deal with the transformations of a volume from its starting form into the desired shape with functional performance and increased value.

Finishing operations take these shaped objects and refine them to desired specifications. Figure 02.47 shows the division of these categories and a high-level breakdown of the processes. The following sections expand upon these processes with examples.

This section covers the three categories of shaping operations as well as the three categories of post-processing operations.

Figure 02.47 • Manufacturing Operations
High level diagram for manufacturing operations.

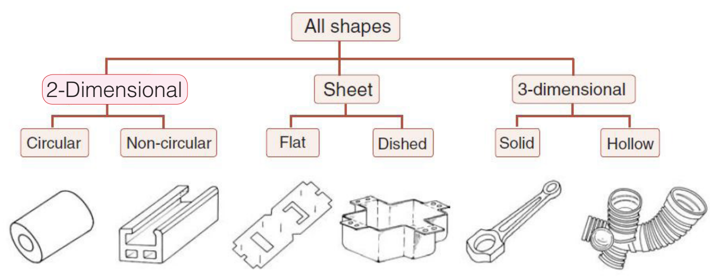


Figure 02.48 • Shapes
A general overview of the shapes desired through manufacturing processes. This can be used as a tool to derive what manufacturing process will be appropriate to achieve the desired result. Adapted from Ashby.

Formative Processes

Solidification

Casting methods

- Expendable-Mold Casting
  - Permanent Pattern
    - Sand Casting
      - Green sand mold
      - Dry-sand mold
      - Skin-dried mold
      - Chemically bonded mold
    - Shell Molding
    - Vacuum Molding
    - Slurry Molding
    - Plaster Mold Casting
    - Ceramic Mold Casting
  - Expendable Pattern
    - Expanded Polystyrene Process
      (Lost-foam process)
      (Lost-pattern process)
      (Evaporative-foam process)
      (Full-mold process)
    - Investment Casting
      (Lost-wax process)
- Permanent-Mold Casting
  - Die Casting (Hot Chamber Machines ↕ Cold Chamber Machines)
    - Gravity sand casting
    - Slush casting
    - Low pressure die casting
    - Vacuum die casting
    - Pressure die casting
      (Squeeze casting)
      (Semi-solid metal casting)
  - Centrifugal Casting
    - True centrifugal casting
    - Semi-centrifugal casting
    - Centrifuge casting

Glassworking

- Spinning
- Pressing
- Blowing
  - Press-and-blow
  - Blow-and-blow
- Casting
- Rolling flat plate glass
- Float Process
- Drawing Glass tubes
- Centrifugal Spinning

Molding methods

- Extrusion
  - Solid sections
  - Tubes
  - Wire coating
  - Sheet and flat film
  - Blown film
  - Coating
- Calendering
- Spinning
- Injection molding
- Blow molding
  - Solid sections
  - Tubes
  - Wire coating
- Rotational molding
- Compression molding
- Transfer molding
  - Vacuum
  - Pressure
  - Mechanical
- Thermoforming
  - Thermoplastics
    - Dip
    - Slush
    - Rotational
    - Centrifugal
  - Thermosets
- Casting
- Foam processing
  - Elastic
  - Flexible
  - Rigid

o2.3.1 Formative Processes

Figure 02.49 • Formative Processes
Tree diagram of formative processes.

Formative manufacturing is well established in the history of manufacturing with the oldest known examples being weapons. Formative manufacturing refers to processes such as casting or forging. The category covers the processes that depend on the plastic deformation of materials due to heat or curing time/conditions. This allows for the shape to be given to material by pouring the material as a liquid state into the desired shape (solidification), forcing it through a substrate of the desired section or beating it into shape with another object (deformation), or fusing powders into the desired volume (particulate processing). In formative processes, the volume of material and finished product remains constant. (Groover, 2010. pg. 4) Figure 02.50 identifies the wide breadth of formative processes used in manufacturing.

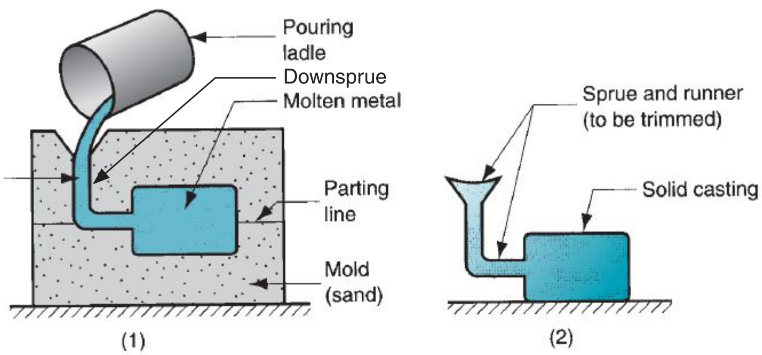


Figure 02.50 • Casting and Molding
The start material is in a liquid of semi liquid state.
(1) Liquid material is poured into the mold cavity and
(2) the solid casting is removed from the mold after having solidified.

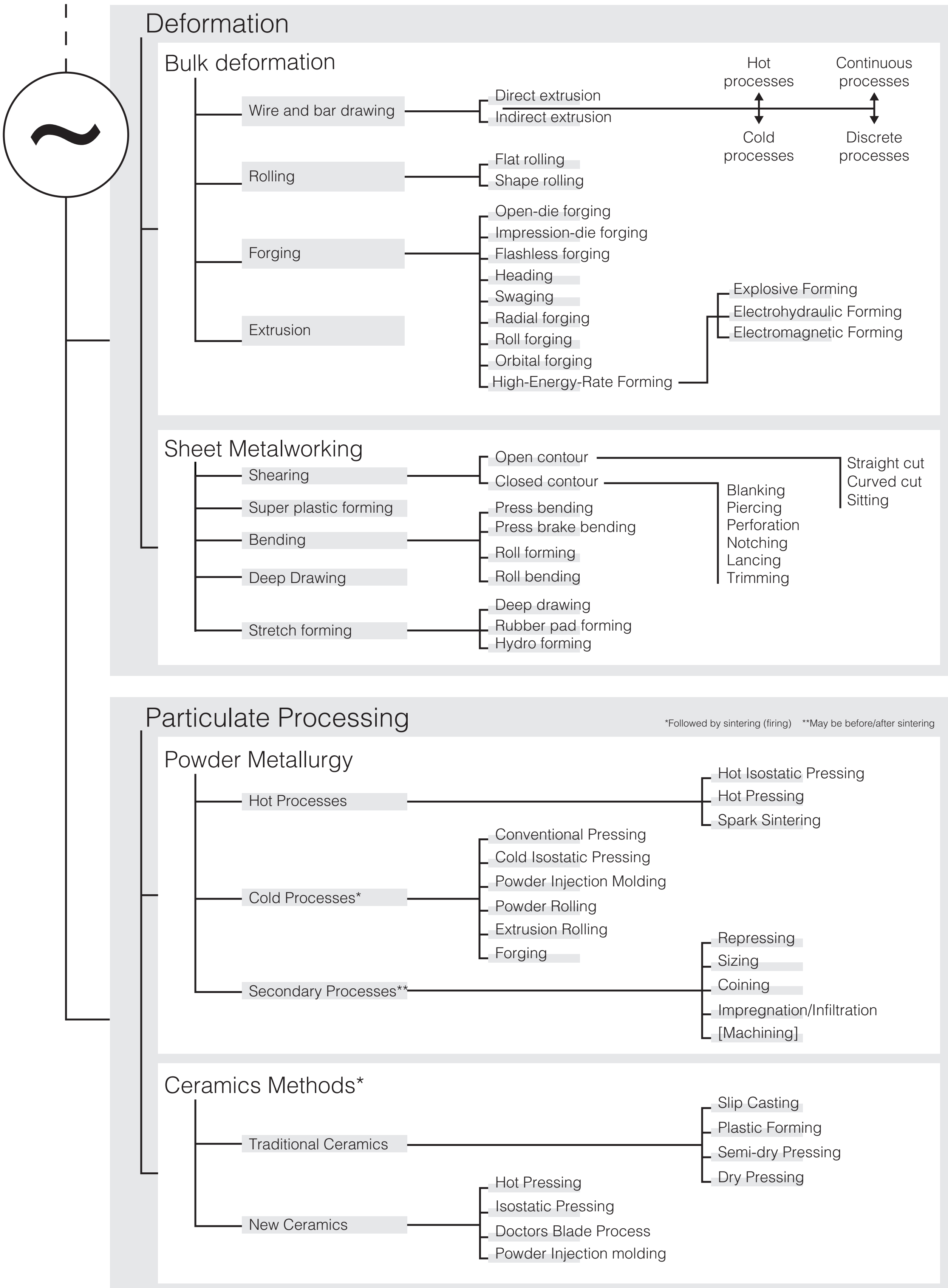
Solidification:

Solidification is the shaping process which utilizes the liquid state of materials to shape them before turning solid. The part is then removed from the mould and (in some cases) prepared for further operations. The solidification family has three sub-categories; casting methods, glass-working, and moulding methods.

Casting methods in general deal with metal materials, but does include others, for plastics the process falls under moulding methods. Examples include investment casting and sand casting, which are commonly used to produce steel components.

Glass-working is the process of shaping the liquid state ceramic material glass. The float process is a standard method which produces float glass, large flat sheets of glass.

Moulding methods typically refer to the solidification processes as they pertain to plastic materials. A typical example is injection moulding where the plastic is introduced into the cavity rapidly with air to ensure the material coats the interior of the mould and provides a hollow part.


Deformation
Bulk deformation
Hot processes
Continuous processes
Cold processes
Discrete processes
Wire and bar drawing
Direct extrusion
Indirect extrusion
Rolling
Flat rolling
Shape rolling
Forging
Open-die forging
Impression-die forging
Flashless forging
Heading
Swaging
Radial forging
Roll forging
Orbital forging
High-Energy-Rate Forming
Explosive Forming
Electrohydraulic Forming
Electromagnetic Forming
Extrusion
Sheet Metalworking
Shearing
Open contour
Closed contour
Straight cut
Curved cut
Sitting
Blanking
Piercing
Perforation
Notching
Lancing
Trimming
Super plastic forming
Bending
Press bending
Press brake bending
Roll forming
Roll bending
Deep Drawing
Stretch forming
Deep drawing
Rubber pad forming
Hydro forming
Particulate Processing
*Followed by sintering (firing) **May be before/after sintering
Powder Metallurgy
Hot Processes
Hot Isostatic Pressing
Hot Pressing
Spark Sintering
Cold Processes*
Conventional Pressing
Cold Isostatic Pressing
Powder Injection Molding
Powder Rolling
Extrusion Rolling
Forging
Secondary Processes**
Repressing
Sizing
Coining
Impregnation/Infiltration
[Machining]
Ceramics Methods*
Traditional Ceramics
Slip Casting
Plastic Forming
Semi-dry Pressing
Dry Pressing
New Ceramics
Hot Pressing
Isostatic Pressing
Doctors Blade Process
Powder Injection molding

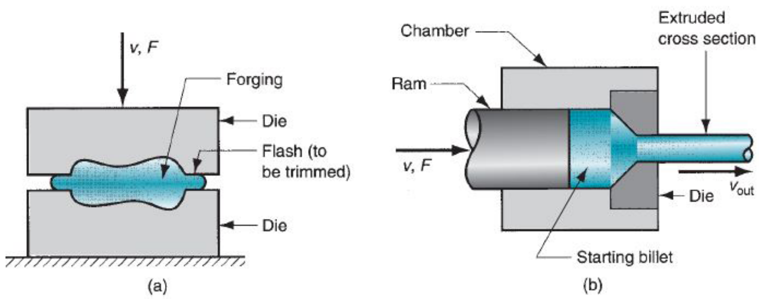


Figure 02.51 • Deformation
(a) forging: two halves of a die squeeze the material forcing it into the shape of the die cavity.
(b) extrusion: a billet (base form of material) is forced through the opening of a die thus taking on the cross-sectional shape desired.

Deformation:

Deformation is the shaping of an object by compressing or stretching it to the final shape with the original volume maintained. This uses mechanical stress to press, pound, forge, pull, and morph the material into shape. There are two sub-categories: bulk deformation and sheet metal working.

Bulk deformation refers to processes which take standard material billets and work them into the desired shape. Typical examples include rolled steel, extruded aluminium or wrought iron.

Sheet metalworking refers to processes which transform sheet goods. This would include processes such as shearing, punching and bending.

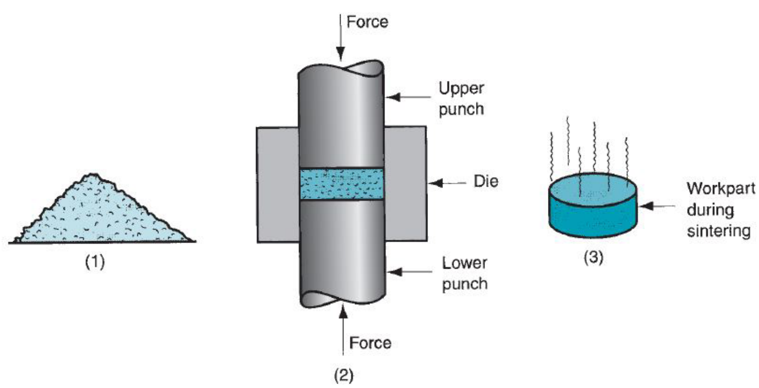


Figure 02.52 • Particulate Processing
(1) starts with powder material (2) the material is pressed between dies, temporarily taking on the desired shape, and is (3) sintered, thus being permanently set in shape.

Particulate Processing:

Particulate processes use a powdered form of material and press it into shape either as a suspension or loose grains. These green parts need to be sintered (or fired) to become fully solid. There are two sub-categories: powder metallurgy and ceramic methods.

Powder metallurgy shapes metal powders in processes similar to forging. The semi-solid object has the benefit of being produced as an alloy or to stringent tolerances.

Ceramic methods use a slip or suspended clay particles in a liquid suspension. This is formed to shape, dried to remove the water (from the suspension) and fired to make solid.

Figure 02.53 • Formative Processes
(pg. 62)
Tree diagram of formative processes.

Subtractive Processes

Conventional Machining

- Cylindrical
  - Turning (Lathe)
  - Boring
  - Drilling
    - Friction Drilling
    - Reaming
    - Countersinking
    - Tapping
- Flat
  - Sawing
  - Planer, Shaper, Slotter
  - Milling machines
    - Peripheral
    - End
  - Broaching
- Special
  - Thread cutting machines
  - Gear cutting machines

Abrasive Processes

- Grinding
  - Surface grinding machines
  - Cylindrical grinding machines
- Micro Finish
  - Honing
  - Superfinishing
  - Lapping machines

Non-traditional machining

- Mechanical energy processes
  - abrasive jet machining
  - water jet cutting
- Electrochemical machining
  - Electrochemical grinding
- Thermal energy processes
  - Laser cutting
  - Laser drilling
  - Ultrasonic machining
  - Electron beam machining
- Chemical machining
  - Photochemical machinery
  - biomachinery

o2.3.2 Subtractive Processes

Subtractive processes deal with the removal of material from a block of base material. These processes remove volume from the original as it produces an object of the desired form. This category includes conventional machining, abrasive processes and non-traditional machining.

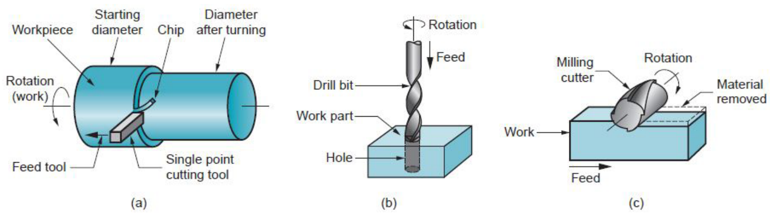


Figure 02.54 • Machining Operations
common operations include (a) turning; working material is rotated along a central axis with a cutting tool used to remove material from the side. (b) drilling; a rotating bit designed to remove material as it rotates and is pressed into the material. (c) milling; material is fed passed a tool which cuts on the long axis of the tool, rather then the end such as drilling.

Conventional Machining:

Conventional machining is the processes of refining an objects shape through the removal of material. This includes processes such as milling, turning, and carving. Manual uses such as carving are long established in trades that require craft and skill.

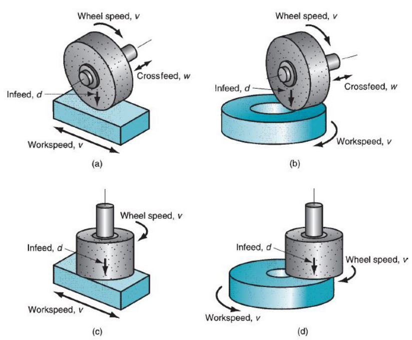


Figure 02.55 • Surface Grinding
Four examples of surface grinding: horizontal spindle with (a) reciprocating table or (b) rotating table, and a vertical spindle with (c) reciprocating table or (d) rotating table.

Abrasive Processes:

Abrasive processes utilize properties between different materials to refine a shape with friction. Through the rubbing of a hard, durable, rough surface against a softer material, the later will be slowly removed and shaped as desired.

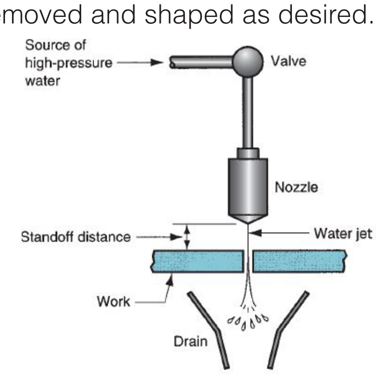
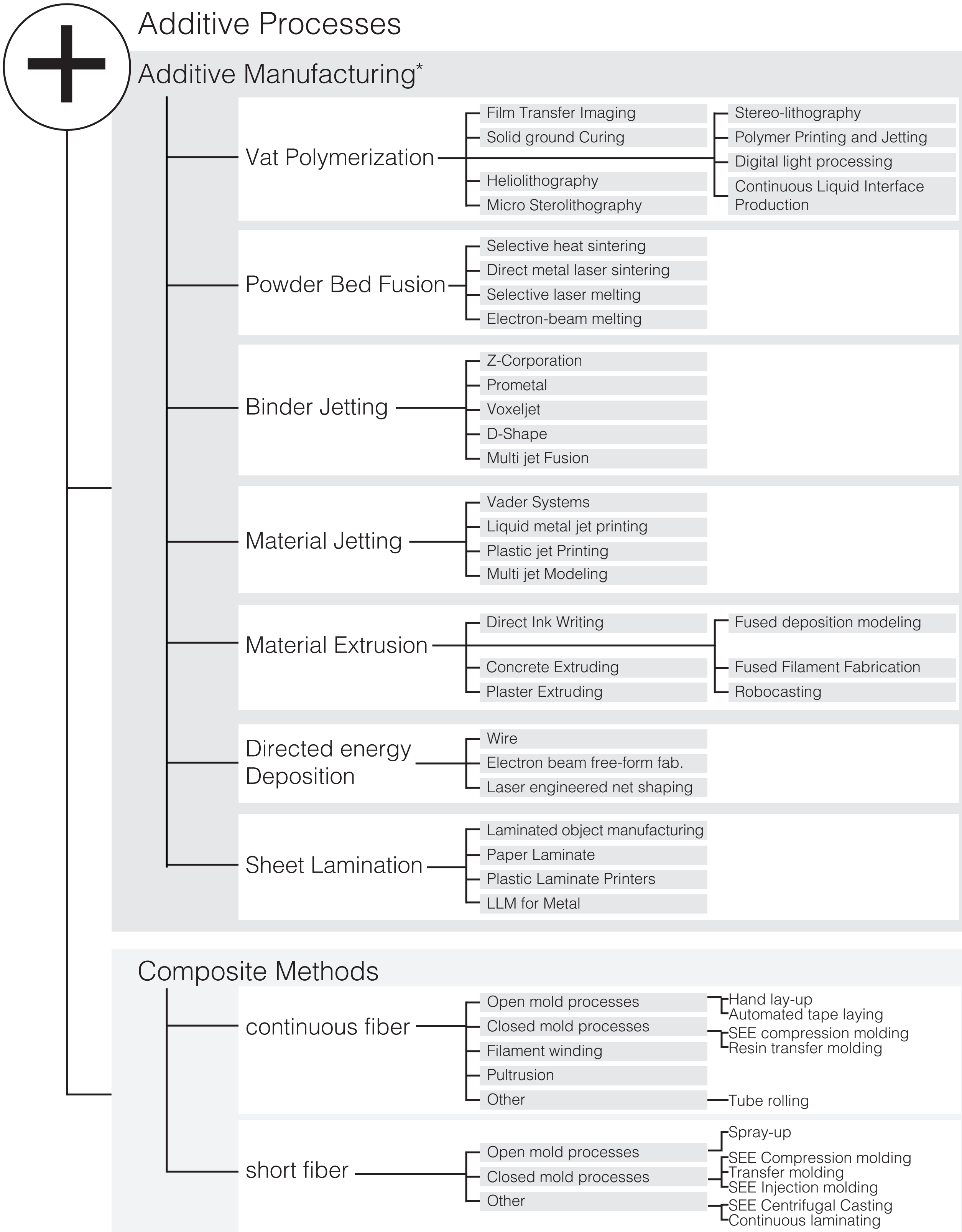


Figure 02.56 • Water jet cutting
Water jet cutting uses a focused beam of water to cut through sheet goods. Used to cut through strong and hard materials such as metal.

Non-traditional Machining:

Similar to machining processes, though the energy used comes from a non-traditional source, such as electron beams or water jetting. These processes allow the shaping of harder materials then can be processed with tradition tool bits.

Figure 02.57 • Subtractive Processes



*Discussed further in section o4

o2.3.3 Additive Processes

Additive processes shape objects through the layering of material in a controlled manner. The layers may be added using the same materials or a mixture of materials. There are two sub-categories: additive manufacturing, and composite methods.

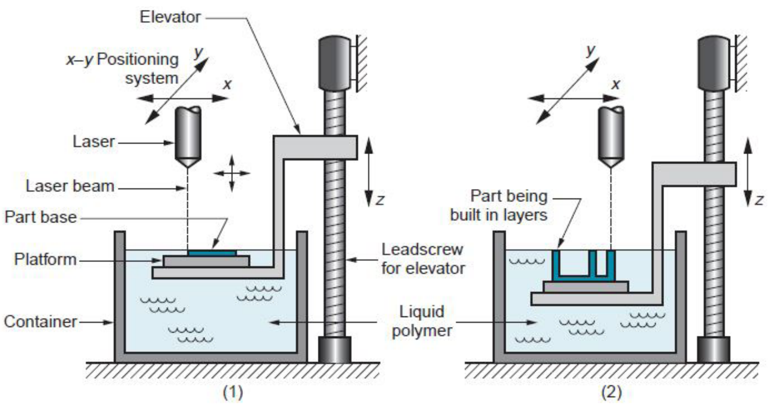


Figure 02.58 • Stereolithography
(1) the starting position has the platform near the surface of the polymer resin, ready to have the initial layer contour added, the progress (2) can be seen over time as the layers build up the desired shape.

Additive Manufacturing:

Additive manufacturing [covered in more depth in Section o4] is the process of creating an object through depositing material in a way that the desired shape emerges. It is technically described as a "layer based (but not limited to) automated fabrication process for making scaled three-dimensional physical objects from 3D-CAD data without using part-dependent tooling" (Gebhardt, 2012. pg. 2) The sub-categories are: vat polymerization, powder bed fusion, binder jetting, material jetting, material extrusion, direct energy deposition, and sheet lamination.

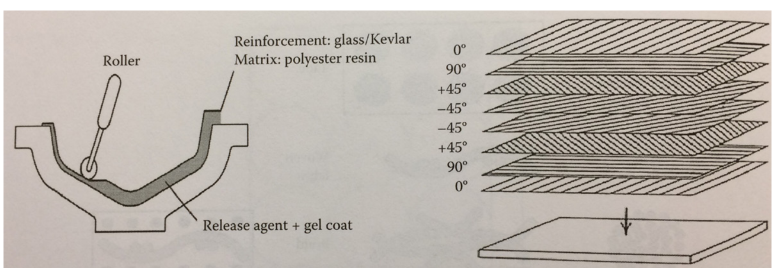
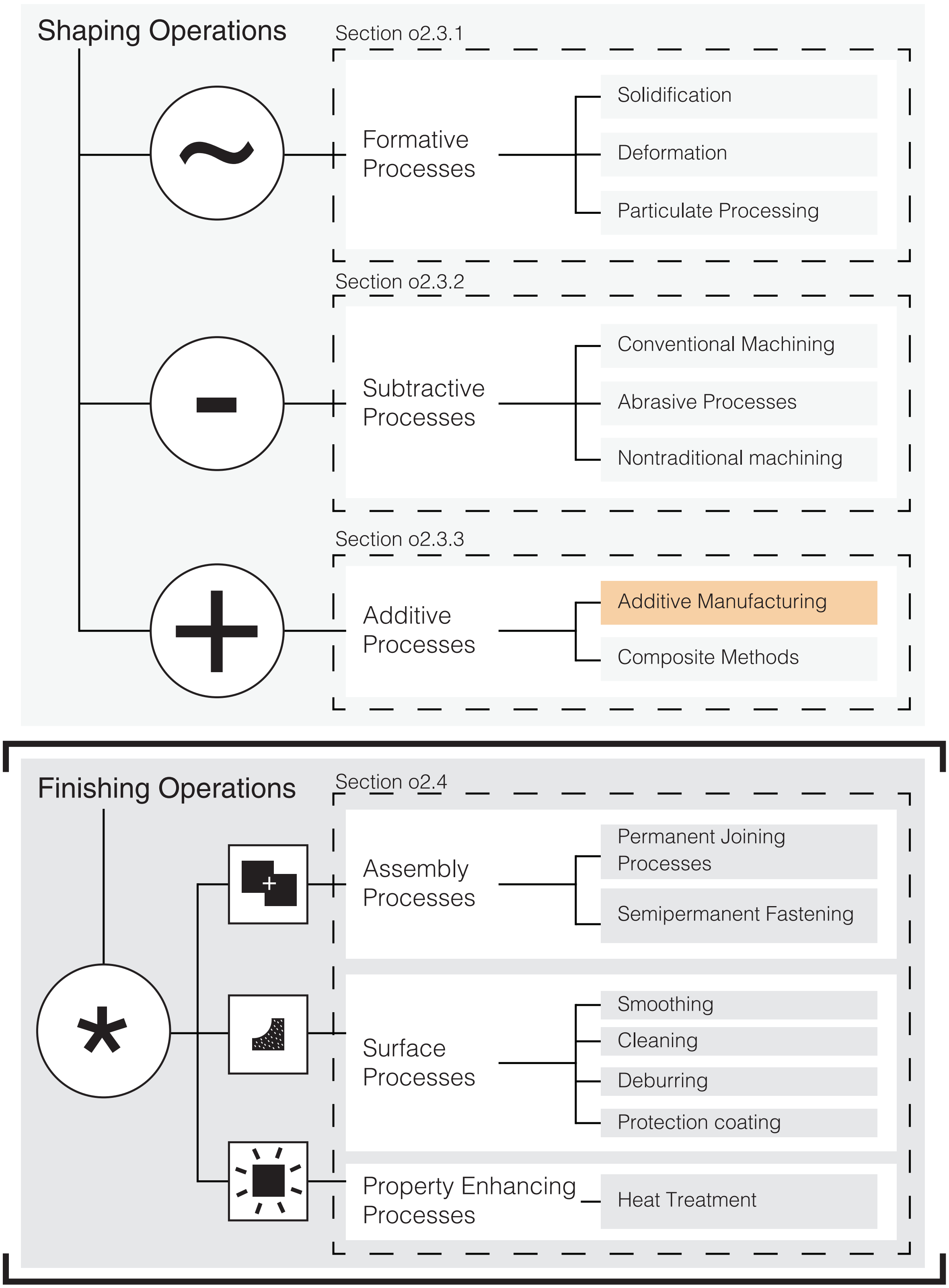


Figure 02.59 • Lay-up
layers of material are stacked on top of each other and adhered with polymer materials. The final shape is dependent on the form used. The diagram shows how alternating directions of fiber weaves helps the final object have better strength.

Composite methods:

Composite methods cover the processing of multiple materials into one end product. These are commonly seen in the production of composites such as fibre reinforced plastics using the lay-up process.

Figure 02.60 • Additive Processes



Shaping Operations
Section o2.3.1
Formative Processes
Solidification
Deformation
Particulate Processing
Section o2.3.2
Subtractive Processes
Conventional Machining
Abrasive Processes
Nontraditional machining
Section o2.3.3
Additive Processes
Additive Manufacturing
Composite Methods
Finishing Operations
Section o2.4
Assembly Processes
Permanent Joining Processes
Semipermanent Fastening
Surface Processes
Smoothing
Cleaning
Deburring
Protection coating
Property Enhancing Processes
Heat Treatment

o2.4 Finishing Operations

Finishing operations come after shaping processes and put the final touches of an object in place. They are also commonly known as post-processes as they come after the initial processing operations. There are three categories of post-process; assembly processes, surface processes, and property enhancing processes. [See Figure 02.29]

The finishing operations allow for a high degree of precision on the final part. Tolerance is the term used to control the physical dimensional differences between multiple parts. As with many industries, there are international standards which guide individual operations to align their production practices. The ISO 2768-2 sets standard tolerances for a variety of geometric shapes. See Figure 02.61. These allowable differences are often measured in the millimetres but often depends upon the size of the final object.

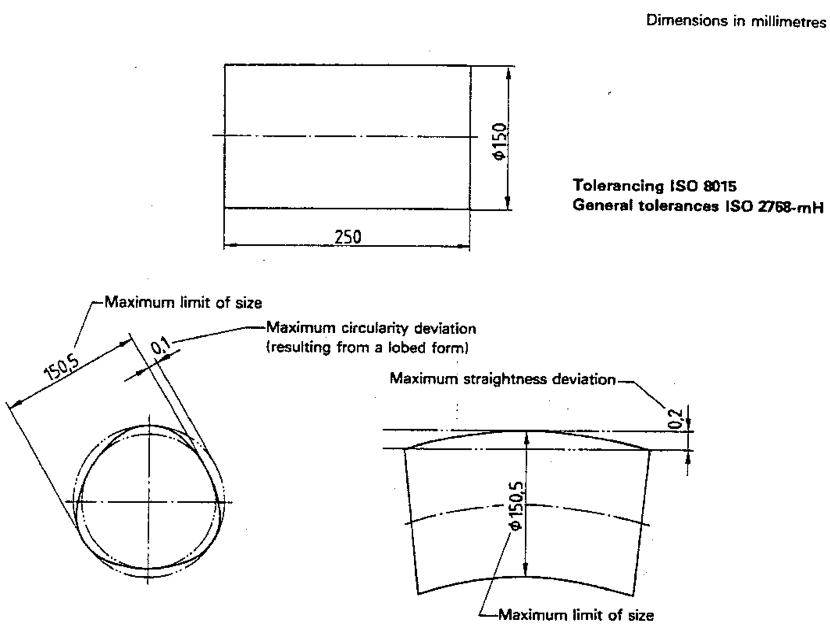
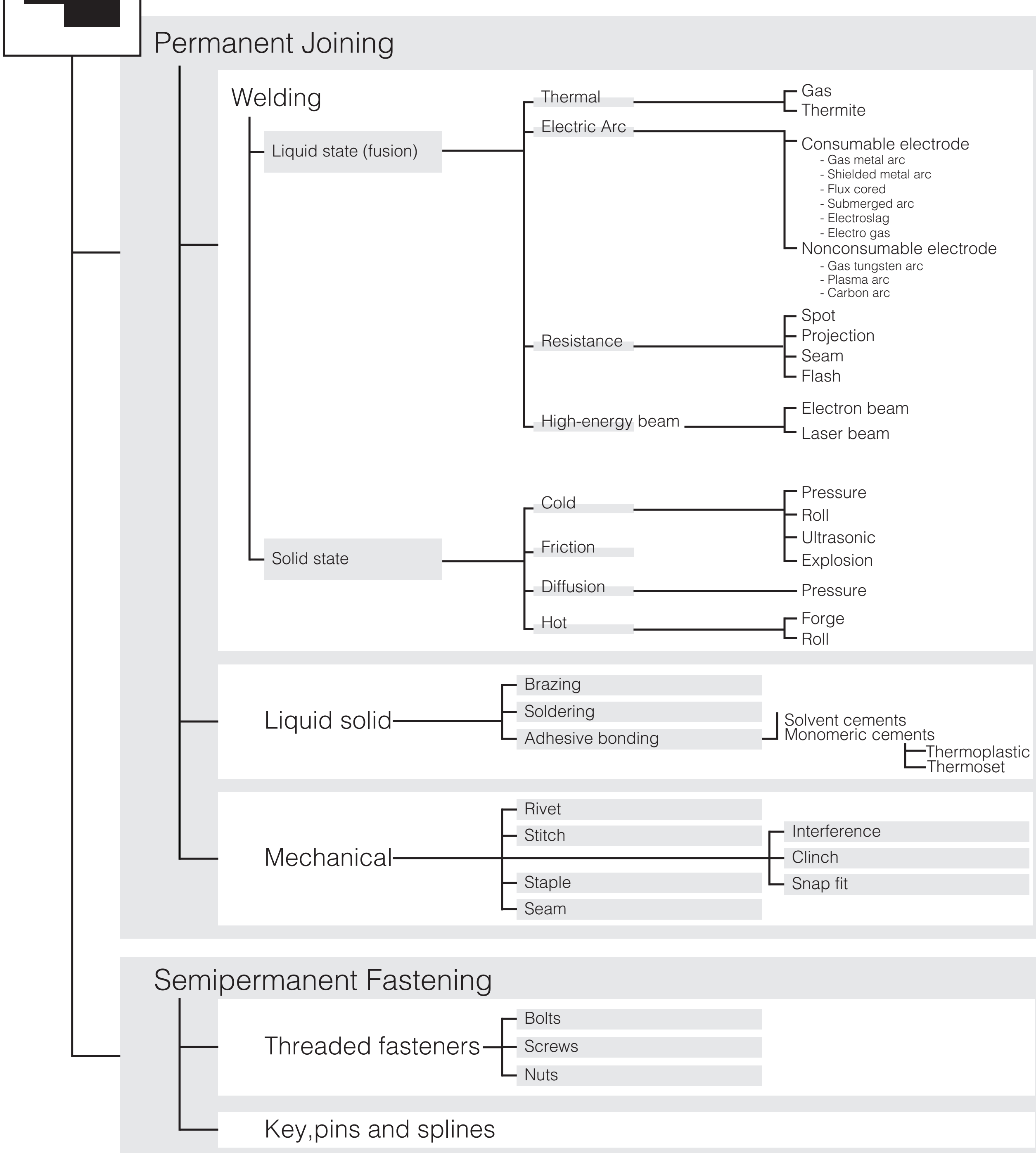


Figure 02.61 • Principle of independency
This figure shows the maximum permissible deviations of a feature across multiple objects. Either produced by one machine of completely separate ones.
[Internation Standard. ISO 2768-2. 1989]

Figure 02.62 • Operations: Finishing

Assembly Processes



o2.4.1 Assembly Processes:

Assembly processes focus on the joining of parts into objects or components. Almost all objects in today's society rely on assembly operations as they have a complex form or are composed of multiple materials. There are two sub-categories: Permanent joining and semi-permanent fastening.

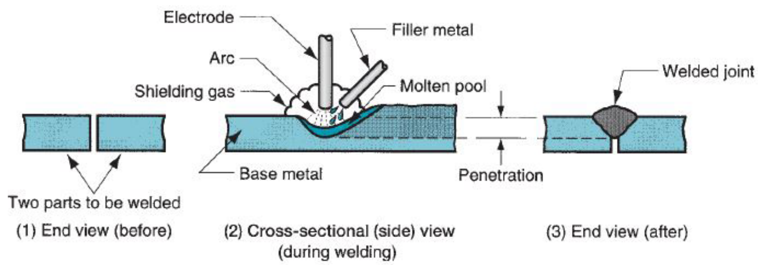


Figure 02.63 • Welding
Process of producing a welded joint

Permanent Joining:

Permanent joining combines parts of an object in a manner that ensures a lasting union. There are multiple ways to achieve this. First can be a complete bonding of the materials (welding), where the two materials are fused together. These methods work with metal and plastic materials excellently. Another is through polymer adhesives or solvents. This manner bonds the two objects permanently together. The last is with mechanical fasteners, these pin pieces together, such as rivets or staples.

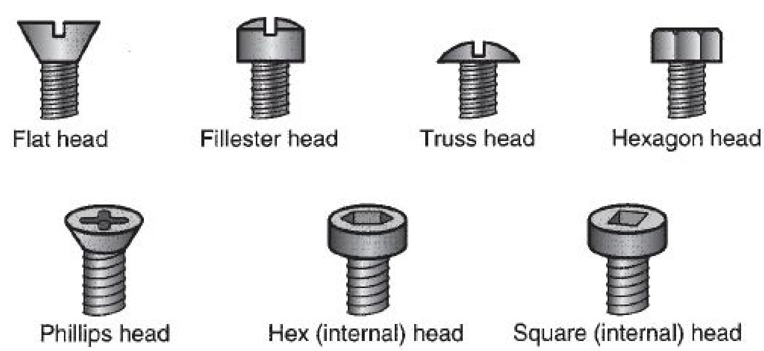


Figure 02.64 • Types of Screws
Examples of various head styles for screws and bolts.

Semi-Permanent Joining:

Semi-permanent joining methods combine pieces in a way that they could be removed again at a later date. This does not guarantee that these parts will be removed later. Typical examples are screws, bolts, and nuts. These methods of attachment offer flexibility and the ability to replace components of a part. They also can be easier to install then mechanical fasteners.

Figure 02.65 • Assembly Processes

Surface Processes

Smoothing
- Wire brushing
- Grinding, belting, sanding
- Polishing, buffing, burnishing
- Electropolishing

Cleaning
- Peening
- Tumbling
- Ultrasonic cleaning
- Chemical cleaning

Deburring
- Manual
- Machining
- Wire brushing
- Tumbling
- Peening
- Ultrasonic deburring
- Abrasive jet machining
- Electropolishing
- Electrochemical deburring
- Thermal energy deburring

Protection coating
- Sacrificial
- Direct
  - Conversion
    - Oxidization
    - Phosphate
    - Chromate
    - Anodizing
  - Electroplating
  - Organic coatings (Paints)
    - Oil paints
    - Lacquer
  - Vitreous
    - Enamels
  - Vapor deposition
    - Physical
    - Chemical
  - Metallizing
    - Flame
    - Arc
    - Plasma
  - Cladding

Property enhancing processes

Heat Treatment
- Annealing
  - Full annealing
  - Spheroidizing
  - Process annealing
  - Stress relieving annealing
  - Soft annealing
  - Finish annealing
- Normalizing
- Tempering
  - Surface Hardening
  - Toughening
- Hardening
  - Full-depth hardening
    - Toughening
  - Anticrack
    - Martempering
    - Austempering

o2.4.2 Surface Processes:

Surface processes provide a surface treatment with little to no shape change. Previous to finishing, parts will be verified for required tolerances and visual defects, possibly a machine stress test as well if structural requirements deem necessary. Typically finishing is the final step, to avoiding damage to the surface.

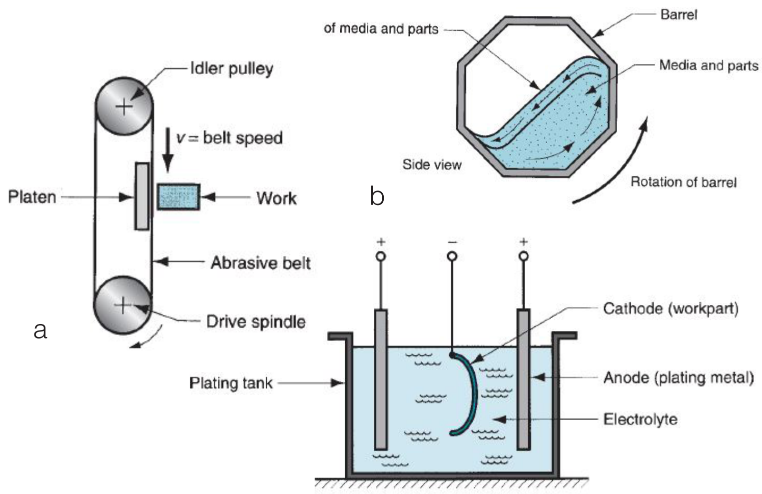


Figure 02.66 • Finishing Operations
(a) Grinding, (b) Polishing, (c) Electroplating

o2.4.3 Property Enhancing Processes:

Heat treatment can accompany many processes, utilizing the heating and cooling of metal objects to induce desired properties. The primary objectives are to: refine grain size, improve machinability, relieve induced stresses due to cold working, relieve induced stresses due to welding operations, improve mechanical properties (such as strength, toughness, hardness, shock resistance, fatigue strength, etc.), improve magnetic and electrical properties, increase wear resistance, heat resistance and resistance to corrosion, and produce extra-hard surface on a ductile interior. (Youssef, 2010. pg.91)

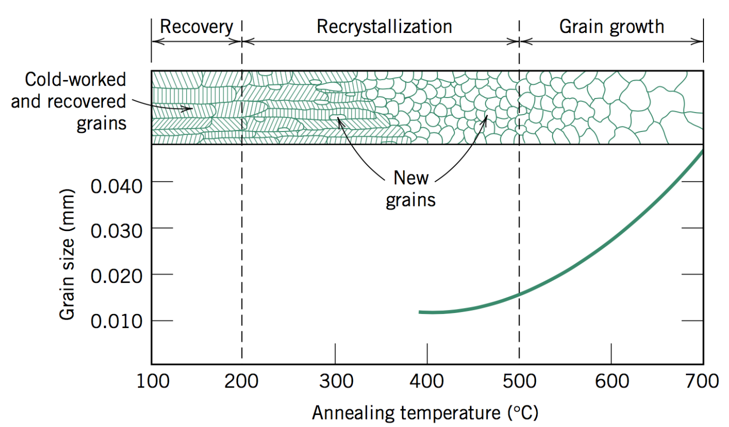


Figure 02.67 • Annealing
Schematic diagram of the grain size as effected through the annealing process, during recovery, recrystallization, and grain growth stages for brass.

Figure 02.70 • Milling - Architectural Millwork

Figure 02.71 • Milling - Nominal Lumber

o2.5 Shaping Architecture

Throughout the complete spectrum of shaping operations, there is a vast array of products explicitly produced towards architecture. This section will quickly highlight the most common objects and their production method, with a synopsis of what materials are chosen to be produced this way.

o2.5.1 Milling - Architectural Millwork

Architectural millwork is produced with the cutting of sheet goods into the desired lengths and widths. Finalized dimensions are fed into a milling machine which can quickly cut custom dimensions to suit each application. Variability can be found within the material choice of the units; be it MDF, plywood, or solid wood, as well as the finishing surface; be it plastic laminate, wood veneer, or Corian. Standards for the assembly and construction of millwork are updated and distributed by the Architectural Manufacturers Association of Canada. This allows for a basis of design standards achievable across fabricators throughout the country. See figure o2.

o2.5.2 Milling - Nominal Lumber

Wood lumber is used throughout the architectural world from residential construction through to commercial. From a single fallen tree, many individual pieces are strategically removed and dried to provide pieces of nominal size and strength. Through specific research and testing, the limits of these standard parts have produced structural manuals used to produce building elements of desired strength. Woods biggest weakness within the construction industry is fire, being primarily limited to the realm of combustible construction. As a natural composite, composed of cellulose and lanolin, wood incorporates the linear strength of polymers with the compressive strength of the binder.

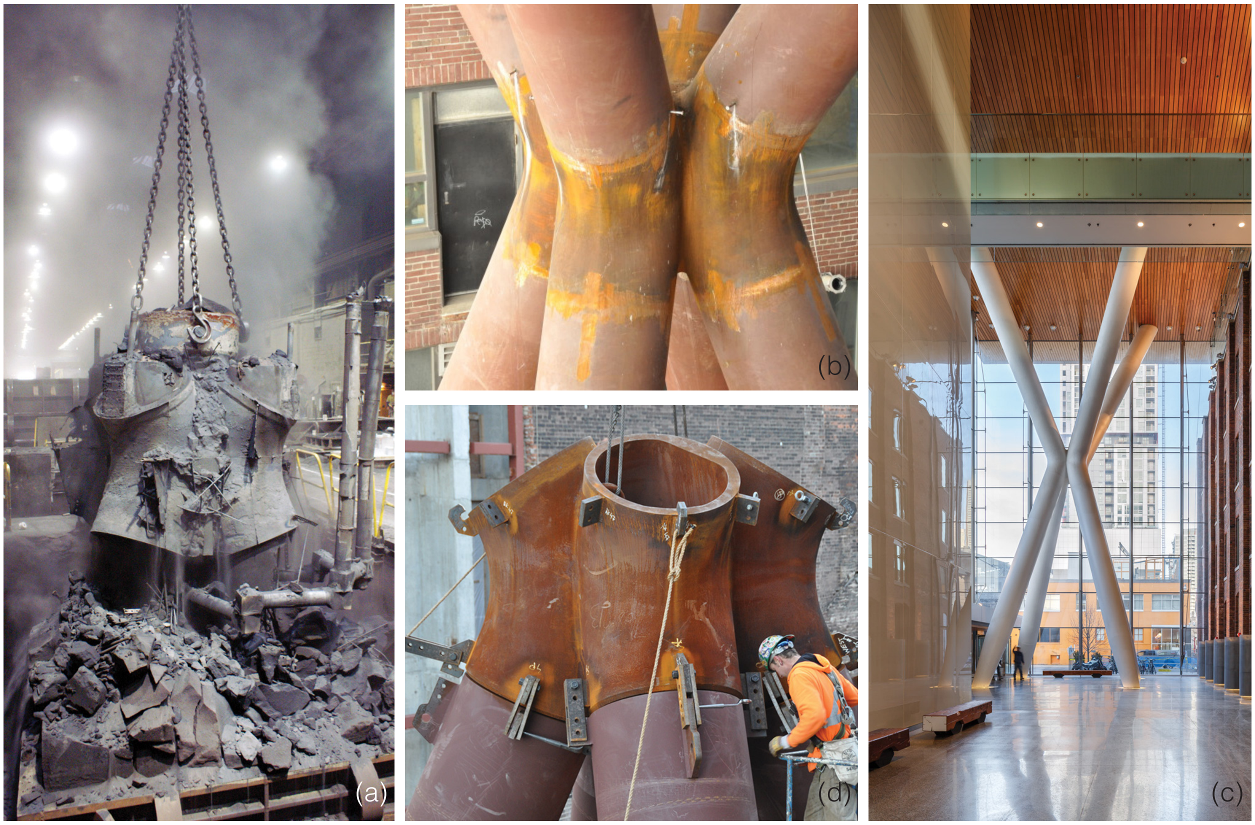


Figure 02.72 • Casting - Steel Connection

Figure 02.73 • Extruding - Aluminum

o2.5.3 Casting - Steel Connection

Cast steel has traditionally been used within architecture for the production of mechanical piping and servicing. Recently this part of the market has shifted towards using plastic-based products for their ease of manual installation. The cast connection by Cast Connect (See figure 02.72) utilizes the traditional idea of a cast steel element and utilizes it structurally. The part is cast into a foundry sand mould, broken out upon successfully cooling. The joint was then cleaned and prepared for connection to the eight column legs and arms. After temporarily setting the piece in place, it was then permanently fixed, with temporary fixtures removed. Upon final finishing operations received on-site, the column successfully reads as one continuous element. Cast steel is strong, workable, and able to hold a high-quality finish. This allows it to be an excellent choice for a signature column within the central atrium of a luxury Toronto highrise.

o2.5.4 Extruding - Aluminum Channels

Aluminium can be extruded to extremely high tolerances, whereas its counterpart, steel is better suited to hot rolling methods. Extruded aluminium produces long length products which have a consistent section. Aluminium itself is a lightweight, rigid, and durable metal. One of its most significant assets is that when oxidization occurs on aluminium does not degrade the strength of the metal, whereas rusting steel becomes week and brittle. Long lengths of aluminium channels can be found within curtain wall, window wall, or interior glass partition systems. Due to aluminium’s ability to hold a high degree of detail, it is often used as a finishing part, receiving a prefinished paint coating or anodized finish.

Figure 02.74 • Pressing - Steel Sinks

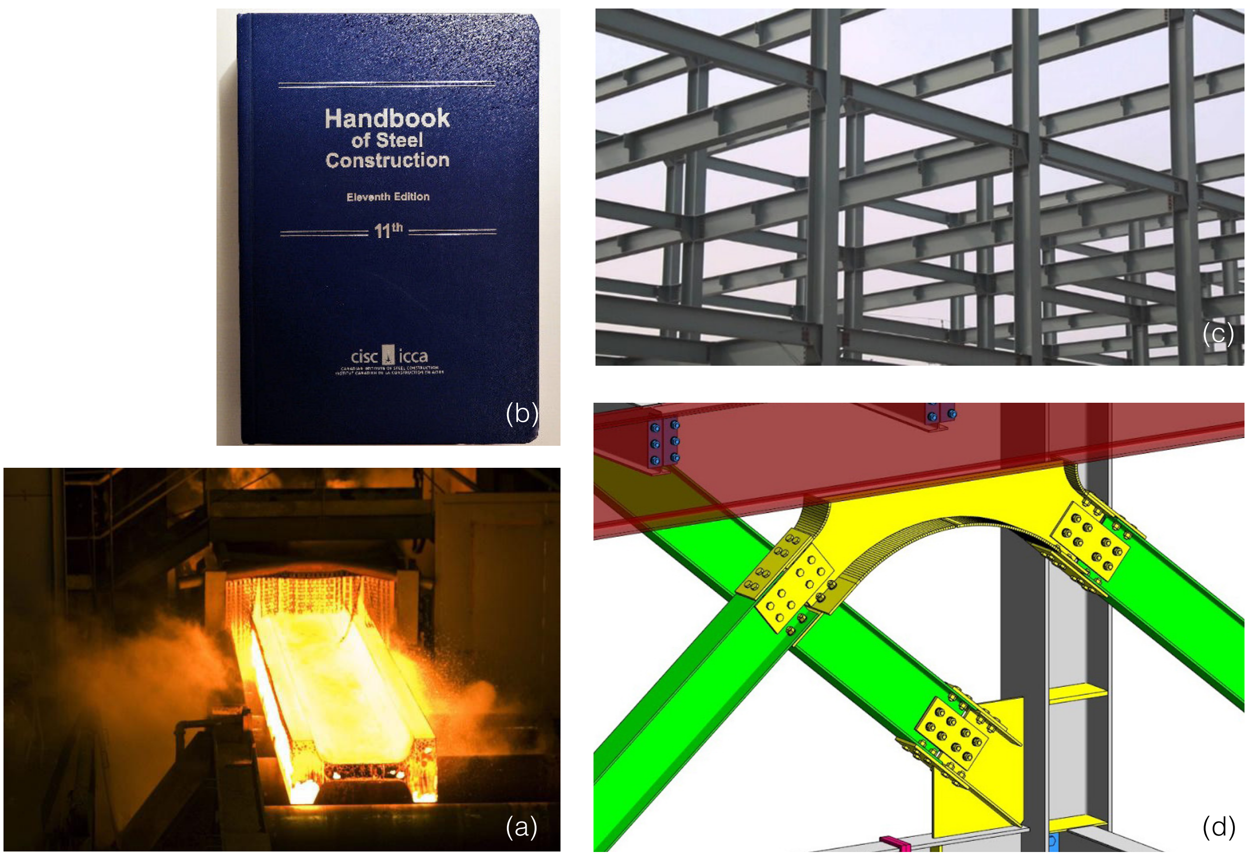


Figure 02.75 • Hot Roll Forging - Hot Rolled Steel

o2.5.5 Pressing - Steel Sinks

Pressed steel is often used to produce volumetric objects from a flat sheet. With steel sinks, the blank (steel sheet) is inserted and run through a series of hydraulic press units. In incremental steps, the flat sheet is pushed into the initial form and refined thereafter. Finishing details such as bevelled edges, drain, and faucet locations are cut out after shaping the basin. Finishes are applied at the end of the shaping process to give the underside of the sink protection from condensation, and the basin receives a buff to remove manufacturing marks and produce a glossy finish.

o2.5.6 Hot Rolled Forging - Hot Rolled Steel

Hot rolled steel is a staple to the design and construction of buildings. Being one of the three most common construction methods, the other being concrete or wood construction. Steel and standard sized beams and columns are ubiquitously known for their strength. Similar to lumber, standard steel sections can be found in a consolidated Handbook of Steel Construction. Tables list the standard sections, weight, and various strengths of I-beams, channels, etc. Having a database of standards allows for a focus on the joints of different structural elements. The erection and joining of steel require large cranes and many skilled labourers. Joints can be mechanically fastened, but need to support the structural requirements of the floors and walls. These vary from rectilinear systems to unique joints which can be designed with the help of computer assistance.

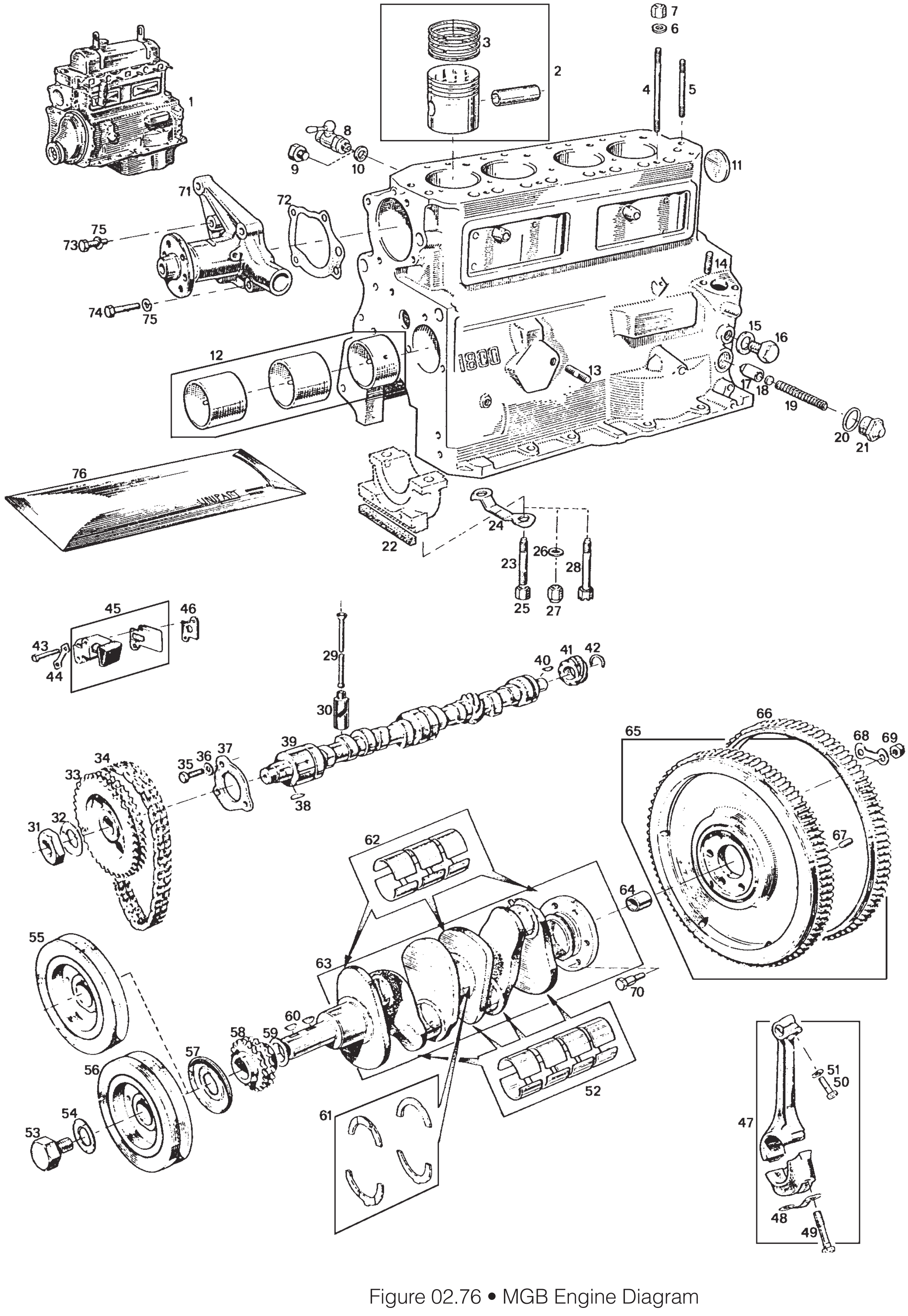


Figure 02.76 • MGB Engine Diagram

o2.6 Conclusions

Materials are categorized and defined by their chemical makeup and subsequent physical properties. Through an understanding of these properties, manufacturing operations have developed to take advantage of shaping specific materials. Choosing the best method is dependent upon navigating the two constraints of physical performance and shape requirements of the object. As such, there is a clear connection between; materials which are strong and hard being used in structural applications, or materials that resist UV degradation used in an exterior application. The manipulation of the combination of materials allows for the benefit of multiple performance criteria but adds the complication of tolerance and assembly.

The manufacturing of materials uses knowledge of material properties to shape them effectively. Materials which are liquid at specific temperatures can be forced into shapes when they are semi-liquid or when they cool. Some materials are easy to cut, while others require special operations. Considerable research has gone into the processes used in shaping various materials, allowing for an extensive database and inventory of common products which are both economically produced and meet a minimum standard of performance and tolerance.

Technological advancement has continued to build off of these established methods and pushed them to evolve. The next section reviews the ways we discover to automate and digitize these manufacturing processed.

Systems Of Production

03

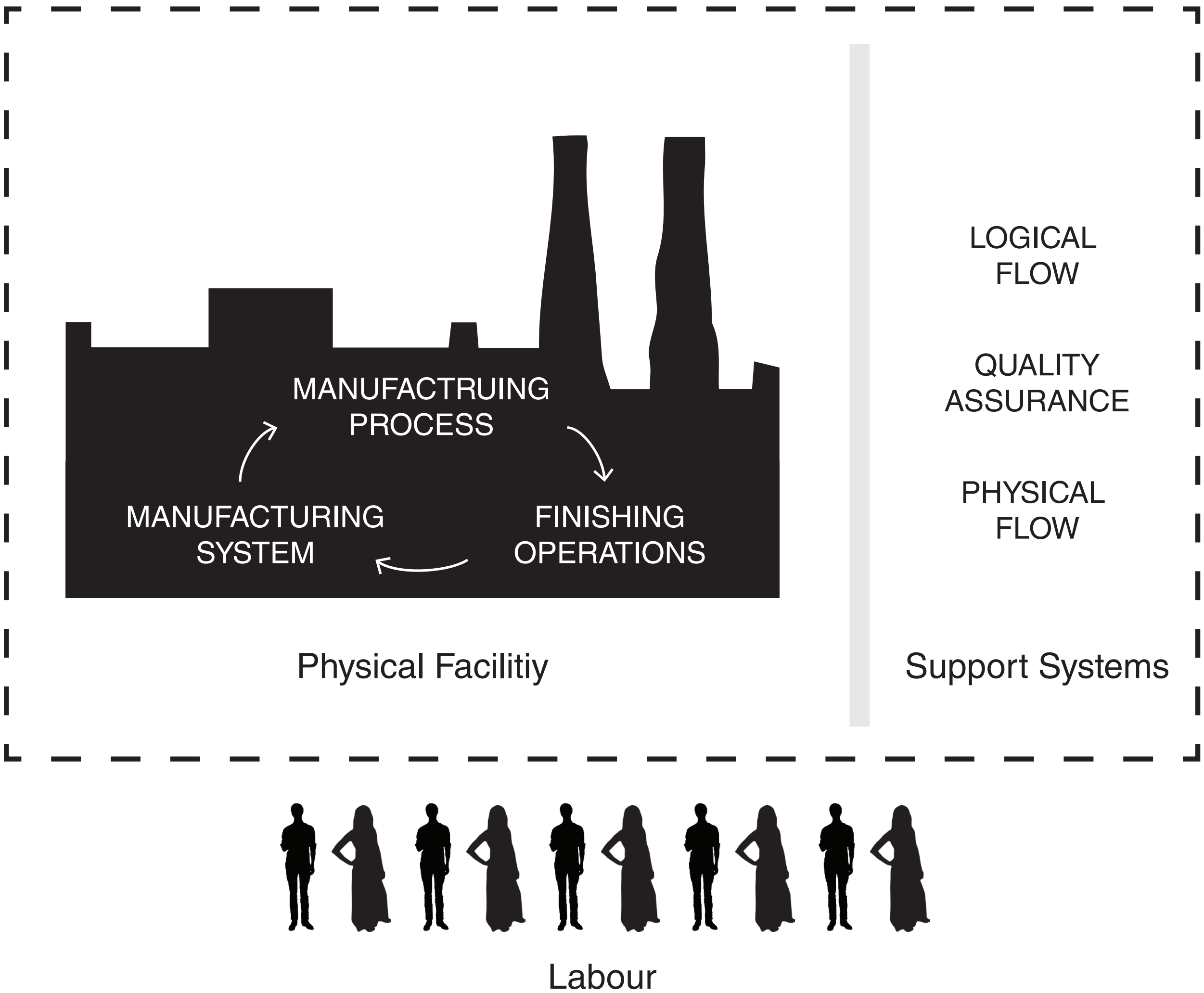


Figure 03.1 • Systems of Production
The two parts of systems of production; the physical facility and support systems, relying on labour to organize and implement it.

o3: Systems of Production

o3.1 Introduction

Over the last two and a half centuries the advancement of society and the production of objects have been dependent upon each other. Production is driven by societies demand for more through its continued expansion and growth. This growth allows room for improvement and advancement of technologies. With the many manufacturing operations available the choice is reduced to its appropriateness to produce the desired form. Constraints such as the scale of production (quantity) and quality, factor into the equation to decide a manufacturing process. The production of a few objects does not directly correlate to the production of many as both have their own challenges independent of the object. In today's industry, much thought has been given to the development of systems of production which pair objects with production. A system of production is a way of organizing people, procedures, and equipment so that production can be performed more efficiently, producing more while using less labour, material, or time, and simultaneously saving money, producing less waste, and improving product quality. (Groover, 2013. pg.2) There are two parts to production systems: the production facility, and the support systems within it. Opportunities for efficient manufacturing lie within optimizing the systems in place to organize it spatially and logically for the given product.

Production facilities encompass the physical elements of manufacturing processes (composed of the equipment) and manufacturing systems (arrangement of the equipment). The equipment used in manufacturing encompasses the production machines, material handling/positioning devices, and computer systems. Human resources are required either full-time or part-time to keep equipment operating. Manufacturing systems are composed of the equipment and human resources which perform the physical operations and assembly for the product; transforming its physicality from raw material to product. (Groover, 2013. pg.886)

Support systems encompass the quality control systems (standards) and the manufacturing support systems (logical and physical flow of the factory). The implementation and control of these factors change depending on the quantity and type of product being produced. People provide the labour, overview and direction within both categories. (Groover, 2013. pg.17)

The current strategies have primarily been developed

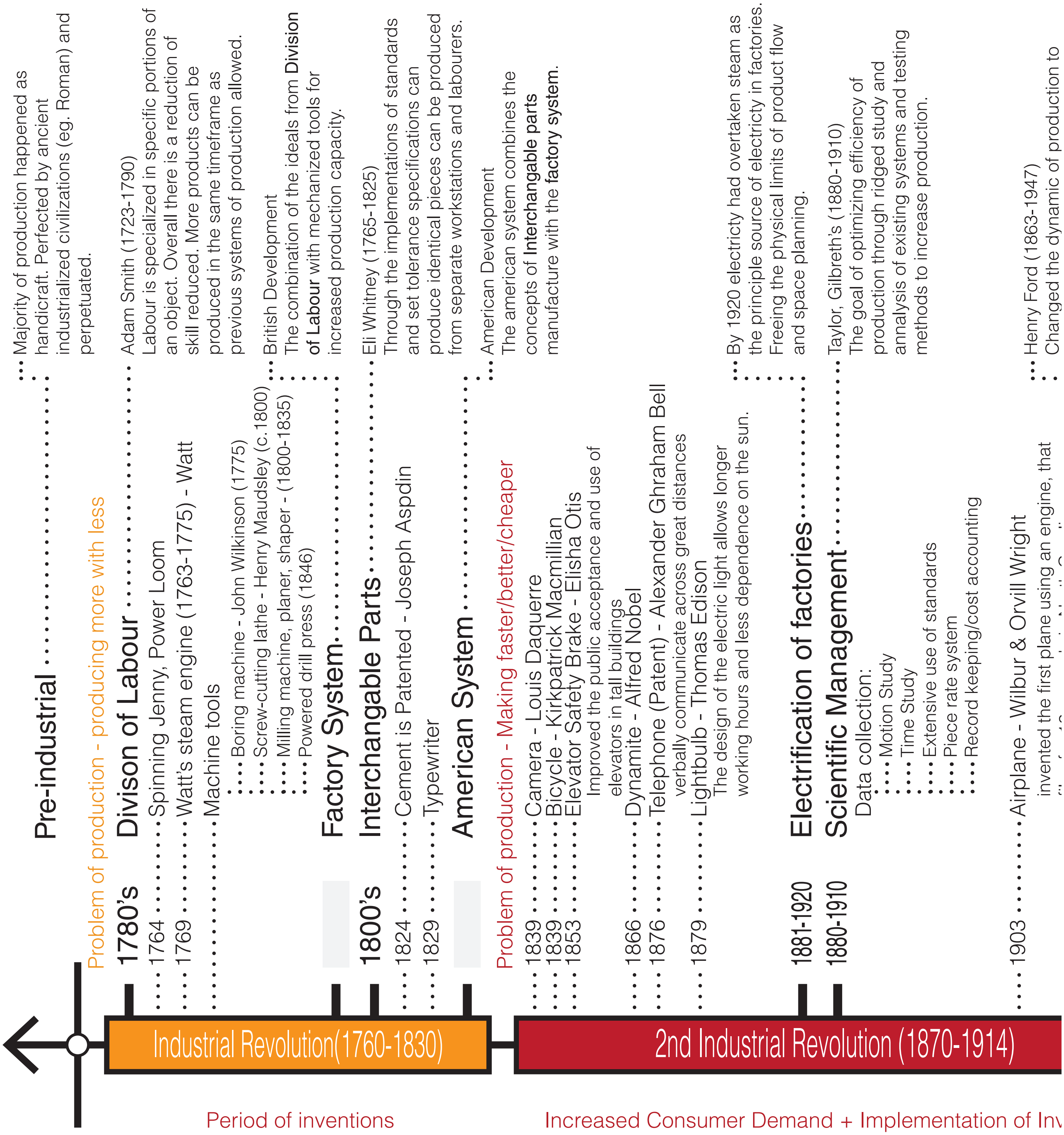


Figure 03.2 • Transformation of Production

Time-line showing key events throughout the development of systems of production.

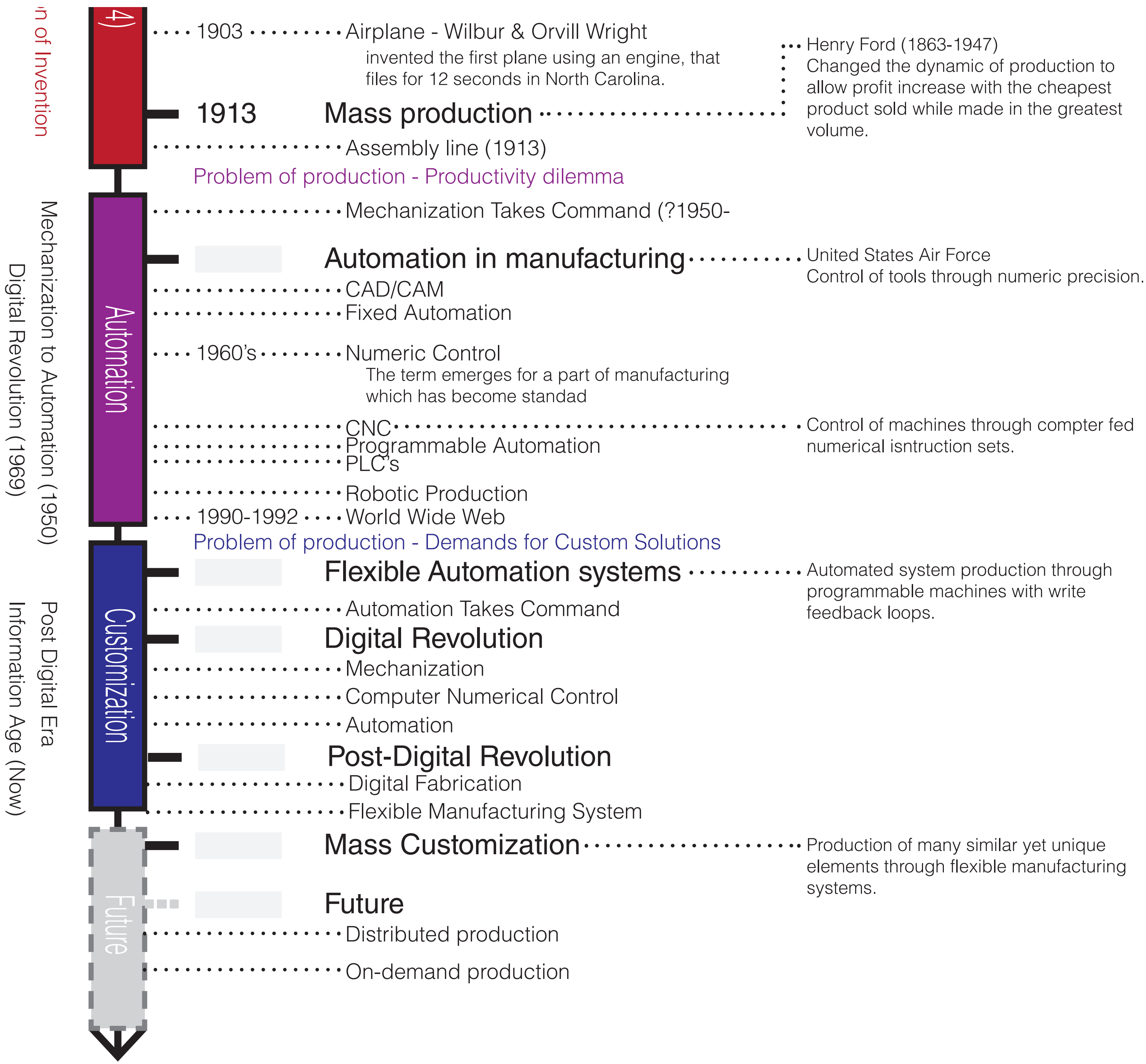

n of Invention
4)
1903
Airplane - Wilbur & Orvill Wright
invented the first plane using an engine, that files for 12 seconds in North Carolina.
1913
Mass production
Henry Ford (1863-1947)
Changed the dynamic of production to allow profit increase with the cheapest product sold while made in the greatest volume.
Assembly line (1913)
Problem of production - Productivity dilemma
Mechanization to Automation (1950)
Digital Revolution (1969)
Automation
Mechanization Takes Command (?1950-
Automation in manufacturing
United States Air Force
Control of tools through numeric precision.
CAD/CAM
Fixed Automation
1960's
Numeric Control
The term emerges for a part of manufacturing which has become standad
CNC
Control of machines through compter fed numerical isntruction sets.
Programmable Automation
PLC's
Robotic Production
1990-1992
World Wide Web
Problem of production - Demands for Custom Solutions
Post Digital Era
Information Age (Now)
Customization
Flexible Automation systems
Automated system production through programmable machines with write feedback loops.
Automation Takes Command
Digital Revolution
Mechanization
Computer Numerical Control
Automation
Post-Digital Revolution
Digital Fabrication
Flexible Manufacturing System
Future
Mass Customization
Production of many similar yet unique elements through flexible manufacturing systems.
Future
Distributed production
On-demand production

Figure 03.3 • Handicraft

Skilled workers labour over the creation of individual objects. Each individually experienced and seeing the creation of a complete object.

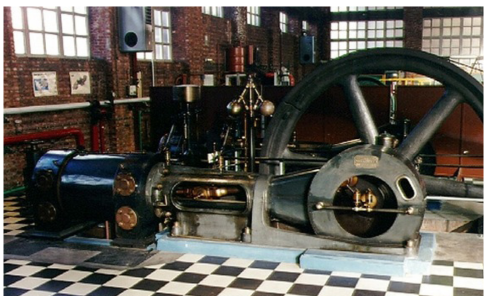
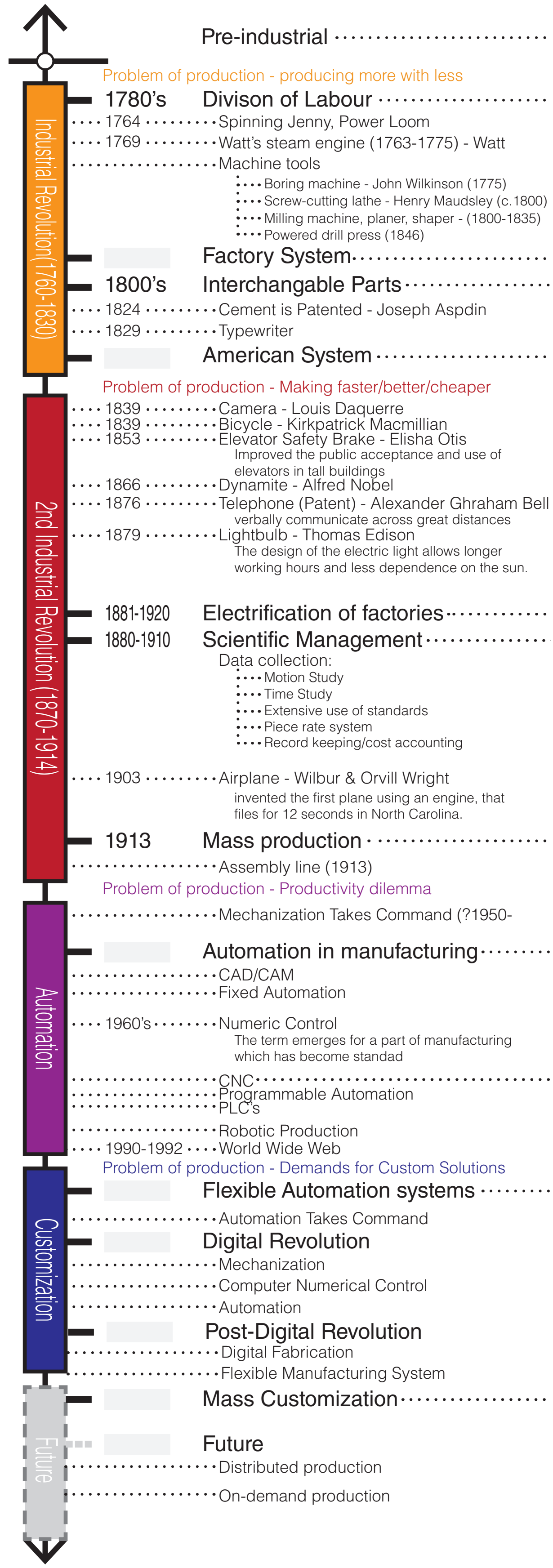


Figure 03.4 • Watts Steam Engine

Figure 03.5 • Line Shaft

A line shaft would transfer the mechanical energy from a turbine or engine and drive the factory equipment.



over the last two decades; this section will review the logical and spatial transformations which affected the present systems of production. Then it will explore the nature of objects and their production in relation to volume. It will showcase this with architectural components charted against current methods of production. Finally, it will conclude with opportunities for customization within the current system of production.

o3.2 Transformations of Systems of Production

Systems of production are inevitably dependent on the manufacturing technology of their time. Technical progression is linked to its impact on everyday life, whether it is proven or seen as a future potential. Gilles Deleuze states, “any technology is social before it is technical.” (Moe, 2015. pg. 153) Meaning that the social impacts play a significant role in the acceptance of a technology, larger then many expect. For a technology to become fully developed, it first must have the social potentials realized and accepted. Over time there have been notable shifts in the social ideals which allowed for and implemented technology changes in production. The following describes the major transformations to how we produce items, highlighting ideas and technological shifts as they impact systems of production.

o3.2.1 Pre-Industrial (before 1700)

In a pre-industrial world, production was dependent on hand tools and individual labour or small groups of labourers. (See Figure 03.3) Ancient Romans had systems similar to what we would call factories today for the production of weapons, scrolls, pottery, and glassware, but these procedures were still primarily based on ***handicraft***. (Groover, 2013. pg.2) As a result of this human tooling, each object was unique. Repetition, or the ability to create identical objects consistently, depended on the individual’s refined skill for the method. Craftsmen developed into trades; metal work, carpentry, masonry: with the quality of work indicating the quality of the craftsman, earned through years of practice and apprenticeships under masters in the field. These systems produced objects slowly as the rate depended directly on the quantity a person could make and was influenced by the skill of the individual. Another hindrance to the quantity that could be produced is that a person could only work on one dedicated item. For example, a potter can only spin one item at a time, though being able to produce a batch of products in a day. Complexity, repetition, and experience all weighed heavily on the output potential.

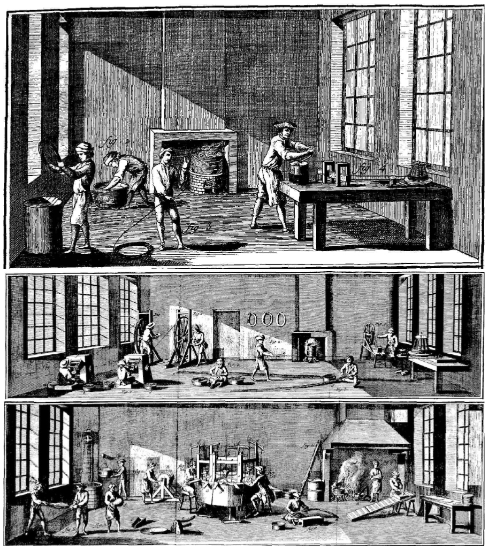
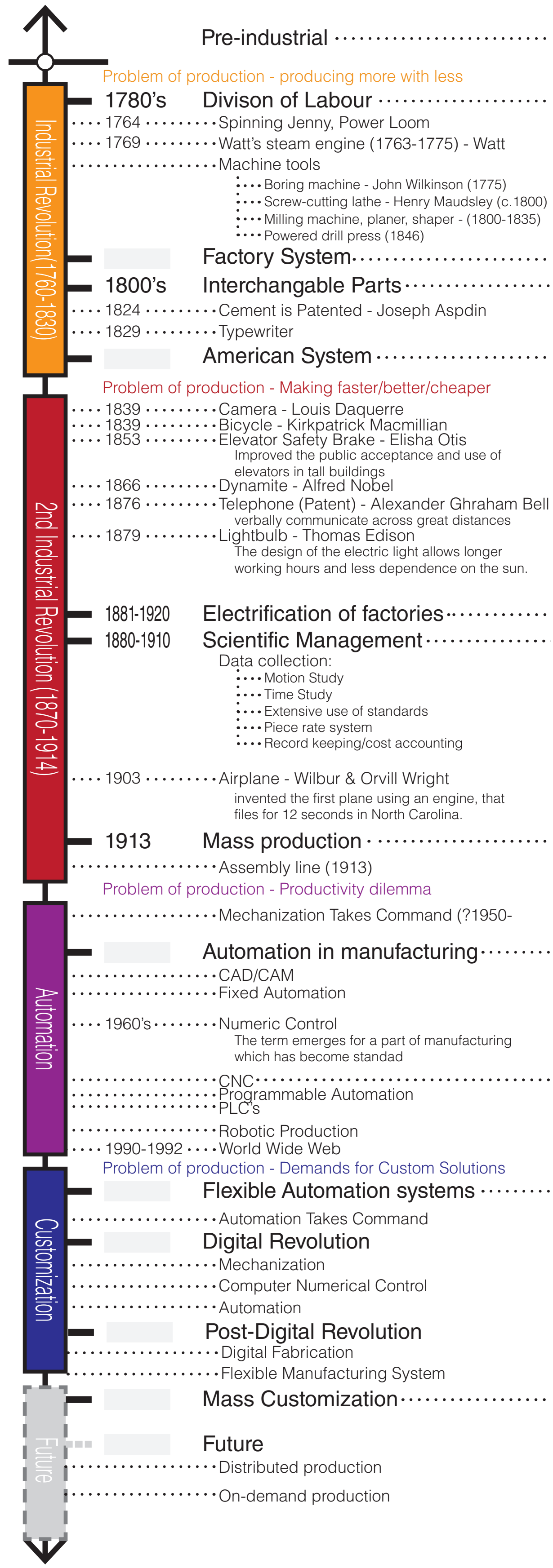


Figure 03.6 • Division of Labour
Diagrams from Adam Smith's story of the pin maker depicting the benefits of dividing small tasks between multiple persons.

Figure 03.7 • Ordnance Department Inspection Gauge
Inspection gauge for the Mississippi Rifle model 1941, by Eli Whitney Jr.



o3.2.2 Industrial Revolutions (1760-1830)

The *Industrial Revolution* (circa 1760-1830) brought with it many inventions and discoveries which impacted the production of goods. This period marked the transition from an economy based on agriculture and handicraft to one based on industry and manufacturing. The hallmarks of these changes were mechanization of operations and new forms of power production. Inventions include Watt's steam engine; (See Figure 03.4) which provided new power operating capabilities for the industry, and John Wilkinson's boring machine; which began the precedent for mechanized tools. Along with these new technologies came ideas that would transform production. The first being division of labour, which when combined with mechanical advancements of the time produced the British "factory system." The second being interchangeable parts which was a stimulant to the American System when combined with the ideals of the "factory system." (Groover, 2013. pg.3)

o3.2.3 Division of Labour (1776)

The establishment of the principle of the ***division of labour*** is the first historical event which led to the development of the modern manufacturing system. Division of labour is the "division of the total work into tasks and having individual workers each become specialized at performing only one task." (Groover, 2013. pg.2) This is credited to the economist Adam Smith (1723-1790) who was first able to explain the economic worth and impact. The division of tasks allowed for a proportional increase in the production powers of labour while requiring less broad skillset from the individuals within the labour force. By dividing the overall skill required by a labourer, it allows for the easy replacement and adaption of new members to the factory. No longer is production tied to one person, but a series of people. Production gets distilled to a repetitive task, with the labourer nothing more than a cog in the wheel. The success of production means either the reduction of workers, the replacement of ones not up to production standards, or the addition of new workers to the team to increase production. The scaling of an operation is radically easier as the dependence of one on one training in multiple skillsets has been reduced to learning and mastering one skill. Entry to a career in the industry is more accessible, as the threshold of training is reduced, and new members can become part of the serial production much faster.

Pre-industrial

Problem of production - producing more with less

Industrial Revolution(1760-1830)

1780's Divison of Labour
- 1764 Spinning Jenny, Power Loom
- 1769 Watt's steam engine (1763-1775) - Watt
- Machine tools
  - Boring machine - John Wilkinson (1775)
  - Screw-cutting lathe - Henry Maudsley (c.1800)
  - Milling machine, planer, shaper - (1800-1835)
  - Powered drill press (1846)

Factory System

1800's Interchangable Parts
- 1824 Cement is Patented - Joseph Aspdin
- 1829 Typewriter

American System

Problem of production - Making faster/better/cheaper

2nd Industrial Revolution (1870-1914)

- 1839 Camera - Louis Daquerre
- 1839 Bicycle - Kirkpatrick Macmillian
- 1853 Elevator Safety Brake - Elisha Otis
  Improved the public acceptance and use of elevators in tall buildings
- 1866 Dynamite - Alfred Nobel
- 1876 Telephone (Patent) - Alexander Ghraham Bell
  verbally communicate across great distances
- 1879 Lightbulb - Thomas Edison
  The design of the electric light allows longer working hours and less dependence on the sun.

1881-1920 Electrification of factories

1880-1910 Scientific Management
- Data collection:
  - Motion Study
  - Time Study
  - Extensive use of standards
  - Piece rate system
  - Record keeping/cost accounting
- 1903 Airplane - Wilbur & Orvill Wright
  invented the first plane using an engine, that files for 12 seconds in North Carolina.

1913 Mass production
- Assembly line (1913)

Problem of production - Productivity dilemma

Automation

- Mechanization Takes Command (?1950-

Automation in manufacturing
- CAD/CAM
- Fixed Automation
- 1960's Numeric Control
  The term emerges for a part of manufacturing which has become standad
- CNC
- Programmable Automation
- PLC's
- Robotic Production
- 1990-1992 World Wide Web

Problem of production - Demands for Custom Solutions

Customization

Flexible Automation systems
- Automation Takes Command

Digital Revolution
- Mechanization
- Computer Numerical Control
- Automation

Post-Digital Revolution
- Digital Fabrication
- Flexible Manufacturing System

Mass Customization

Future

Future
- Distributed production
- On-demand production

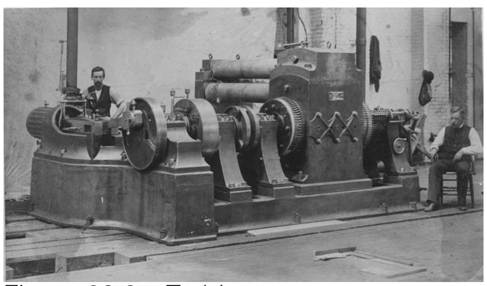


Figure 03.8 • Turbine

Edison's "jumbo dynamo" at the wold's first power station in Lower Manhattan. An example of an early steam turbine used to create electrical power for distribution to city power grids.

Figure 03.9 • Time and Motion Study

The implementation of scientific management required the direct study of how activities were being carried out. In this image managers supervise a time and motion study.

o3.2.4 Interchangeable Parts (1800-1850)

The next major change happened in the United States with the implementation of ***interchangeable parts*** in manufacturing. The goal of interchangeable parts manufacture is the synchronization of part size and quality to enable two separate labourers and/or machines to produce identical parts, within a fixed tolerance, that can be freely assembled. In order for this to be successful three things were required (1) precise machining tools, precision gauge or other instruments of measurements, (2) uniformly accepted measurement standards, and (3) techniques to communicate precise product parameters. (Woodsbury. Pg.247) Achieving a workable tolerance on parts allowed production to be decentralized and could be spread throughout different factories using rail lines for physical distribution and telegraph for information communication. (Moe, 2014. pg. 158)The concept of interchangeable parts is traditionally credited to Eli Whitney (1765-1825), while modern historians viewing its origins as the culmination of a "number of economic, social, and technical forces brought to bear on manufacture by several men of genius, of whom Whitney can only be said to have been perhaps one." (Woodsbury, pg.251)

The practical feasibility of interchangeable parts manufacture took many years to develop and successfully implement fully, but it forever altered methods of modern manufacturing. (Groover, 2013. pg 3) It is an explicit case of where numerical control over a products property (i.e. dimensions, strength) is necessary for success. With the rising demand of consumer machines in the late to mid-1800s; such as the sewing machine, bicycles, and automobile; implementation of this new manufacturing system was adopted across industries to manage the production and meet consumer demands. (Hounshell, pg.4)

The use of interchangeable parts manufacture, also known as the 'American System' is a prerequisite for the implementation of mass production methodologies. (Groover, 2013. pg 3)

o3.2.5 2nd Industrial Revolution (1870-1914)

Demand for new consumer-focused machines (i.e. sewing machines, bicycles, and automobiles) drove a need for more efficient production methods. This triggered what some historians consider the ***second industrial revolution***. The second industrial revolution is characterized by the developments of electricity in factories, scientific management, assembly lines, and mass production. (Groover, 2013. pg.3)

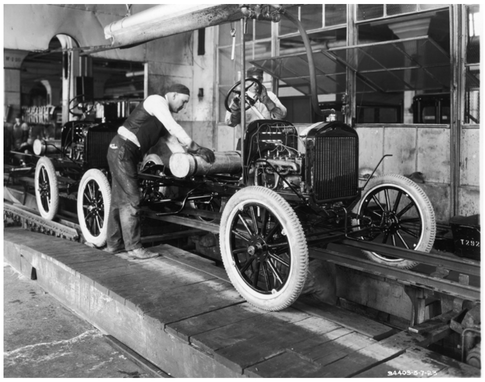


Figure 03.10 • Assembly Line
The assembly line strung the operations of production into a logical sequence in which the product would move and the labourers stay in one location.

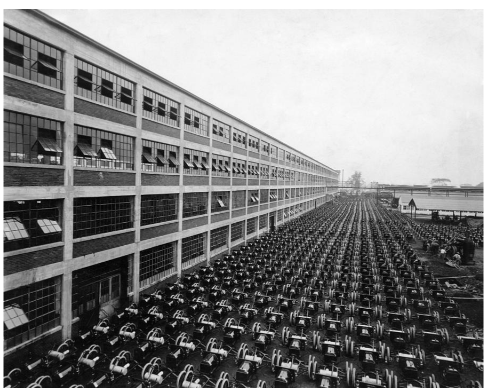
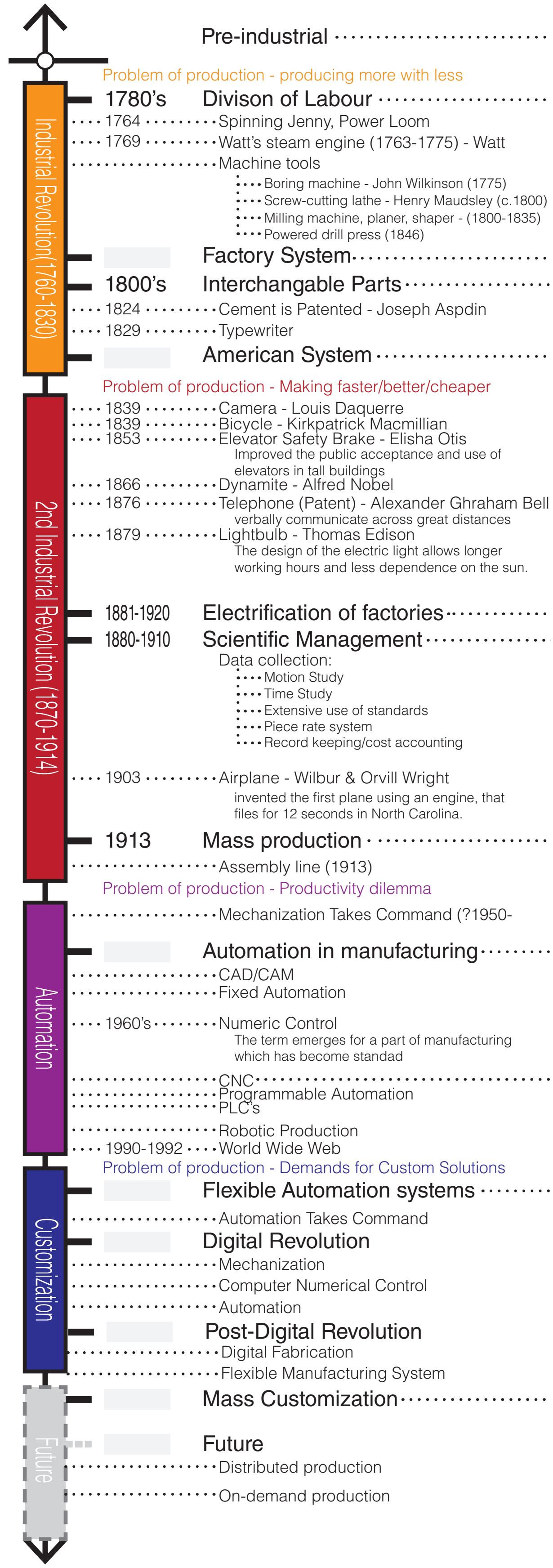


Figure 03.11 • Mass Production
One day of production at the Ford factory.



o3.2.6 Electrification (1880-1950)

The adoption of ***electricity in factories*** happened at a rapid rate after the implementation of generation stations. In 1881 the first electric power generation station was built in NYC, by 1920 electric power had overtaken steam power as the principle power source in U.S. factories. Figure 03.9 shows the worlds first turbine for power production. (Groover, 2013. pg.3) Electricity meant the adoption of the electric motor, a device which could be used in many ways and adapted to different processes with less operational expenses and hassle than previous methods. This allowed for freedom from the existing factory layout based on the line shaft providing mechanical energy (See Figure 03.5).

o3.2.7 Scientific Management (late 1800's)

Scientific management was developed in the late 1800s as a method of planning and controlling the activities of large numbers of production workers. Developed by Frederick W. Taylor (1856-1915), Frank Gilbreth (1868-1924) and his wife Lilian Gilbreth (1878-1915), it focused on: motion, time, implementation of standards, the piece-rate system, and extensive data collection on cost accounting. Motion studies aimed to find the best method of completing the task; time studies allowed for an allotted standard to be set for worker performance. The application of standards allowed for quality control in production; the piece rate system introduced an incentive for completing labour in a timely manner.

o3.2.8 Assembly Line and Mass Production (1913)

In 1913, the ***assembly line*** was introduced by Henry Ford (1863-1947) at his automobile plant in Detroit. It used the conveyor belt system to move parts through production continuously. The labourers would stay in place, finishing their task on the product in front of them, and send it along when complete. By streamlining the division of labour into a logical set of sequenced operations, the assembly line was the final puzzle piece to the goal of mass-production. (Groover, 2013. pg.3)

Mass-production, as described by Ford's office, "focuses on the principles of power, economy, continuity, and speed." (Hounshell, pg.1) The success of mass production can be attributed to three factors: the use of interchangeable parts, the adoption of cheap production methods, and a new system of assembly. The individual knowledge Ford may have had about the jig, fixture, and gauge technologies is debatable, but

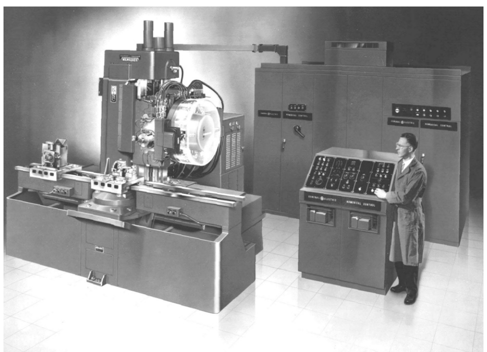


Figure 03.12 • CNC Machine
A CNC machine from 1952 required a large bank of dedicated controls.

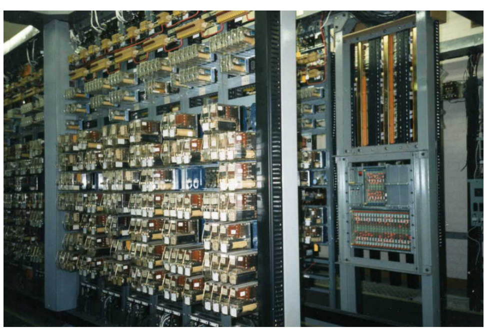


Figure 03.13 • Relay Room

Pre-industrial

Industrial Revolution(1760-1830)

Problem of production - producing more with less

1780's Divison of Labour
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  - Powered drill press (1846)

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American System

2nd Industrial Revolution (1870-1914)

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Automation

Problem of production - Productivity dilemma
- Mechanization Takes Command (?1950-

Automation in manufacturing
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Customization

Problem of production - Demands for Custom Solutions

Flexible Automation systems
- Automation Takes Command

Digital Revolution
- Mechanization
- Computer Numerical Control
- Automation

Post-Digital Revolution
- Digital Fabrication
- Flexible Manufacturing System

Mass Customization

Future

Future
- Distributed production
- On-demand production

he was able to implement seamless interchangeability within the Ford Motor Company by hiring mechanics who knew what was required to achieve that goal. Burlingame states that the production methods used to achieve mass-production must be "coordinated and applied with intelligent economy – economy in time, space, men, motion, money and materials." (Burlingame, pg. 3.) Ford's techniques could make parts at a cheaper price point and faster production rates, for example using sheet steel punch and press work rather than forging and casting methods. How to put these parts together was the final bottleneck, solved with the assembly line, simplifying the process through rigidly repetitious continuity. (Hounshell, pg.10)

The adoption of mass production came with significant gains and losses. "Ford engineers witnessed productivity gains ranging from 50 percent to as much as ten times the output of static assembly methods." (Hounshell, pg.10) However, the Ford Company saw an annual labour turnover reach 380 percent in 1912 and even higher in 1913. This was a result of dull rigorous labour and was eventually resolved through substantial wage increases. (Hounshell, pg.11)

o3.2.9 Fordism

Ford's work "demonstrated for the first time that maximum profit could be achieved by maximizing production while minimizing cost." (Hounshell, pg.10) Ford's products targeted the masses making the adoption of mass production two-fold appropriate. "Unlike Singer (sewing machines), McCormick (farming equipment), and Pope (bicycles), Ford sought to manufacture the lowest priced automobile and to use continuing price reductions to produce ever greater demand." (Hounshell, pg.9) Proving that the cheapest made, and lowest priced product, provided in greatest numbers, could swiftly dominate the market. Creating the baseline desire for products on the market to be affordable.

The main restriction of mass production was its lack of variety or customization, as often said about the model-T "it would come in any colour as long as it was black." Hounshell concludes that America could not be tied to the idea of a singular product. They demanded revision, change, and as such the idea of an annual model. He states this friction as the "productivity dilemma": "the problem of choosing between frequent product changes and lower productivity or no change and higher productivity." (Hounshell, pg.13) This dilemma was the downfall

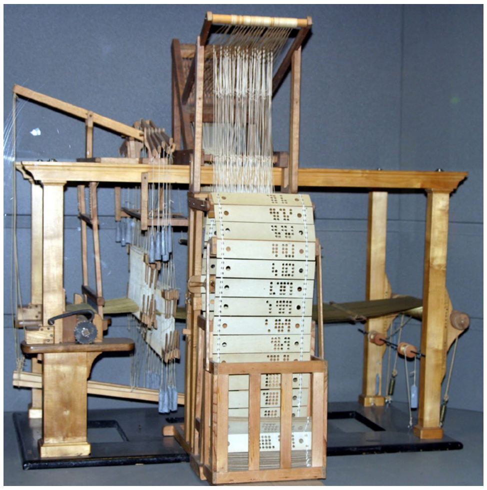


Figure 03.14 • Jacquard Loom

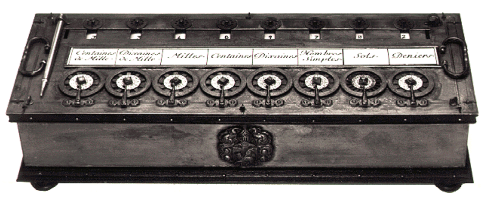
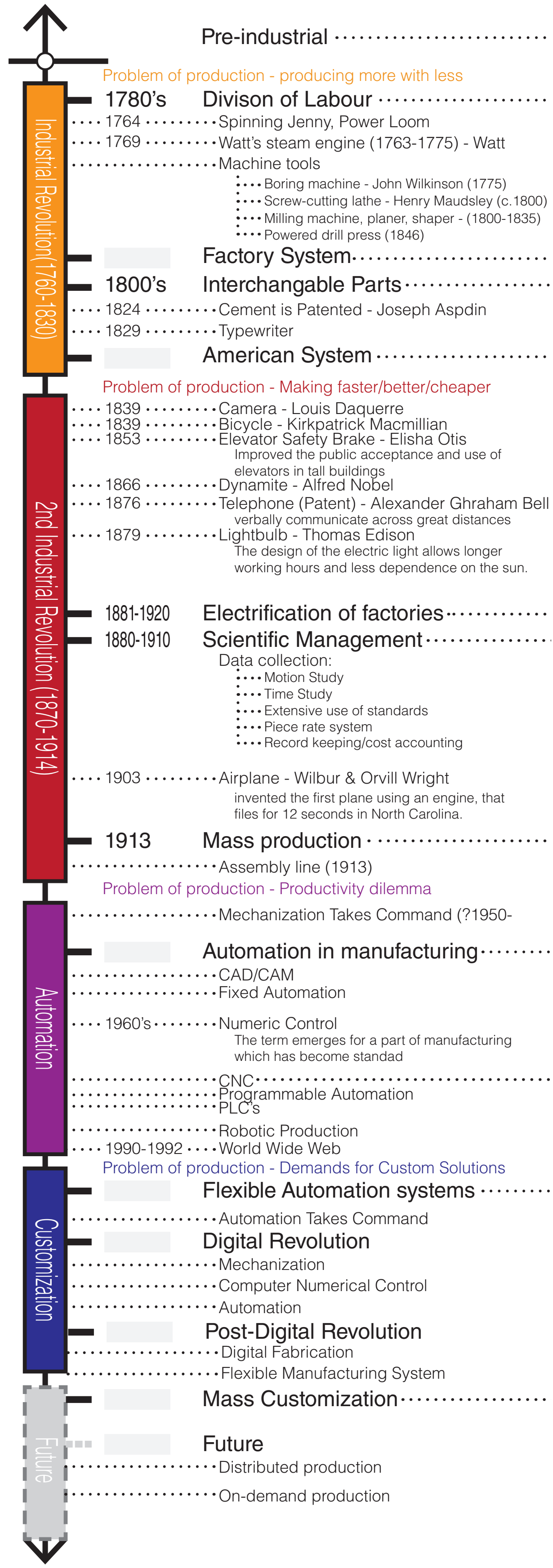


Figure 03.15 • Pascal's Calculator

Figure 03.16 • Early CAD Software



of Ford's dominance of the automobile industry, as the ability to adapt production on a regular basis worked directly against the principles of 'mass production.' Hounshell, reflecting from his vantage point in 1985, stated that "indeed, the dilemma itself may be insoluble." (Hounshell, pg.13) This begins the shift from production challenges not being centred on how, the product is made, but to how it can be made similar yet distinct.

o3.2.10 Digital Revolution

The digital revolution tracks the mechanization of production from analogue to digital. It starts with digital components such as the transistor, which make products like relays and PCB's possible. It builds off Mechanization, to CNC and leads to automation of factories.

o3.2.11 Numerical Mechanization

Development of automation systems was not a linear progression of history, as some examples dating as far back as during the industrial revolution. The Jacquard loom (year 1801, see Figure 03.14) is a famous example which utilized punched card programs for the warp and weft. Other examples include Pascal's calculator (17th century, see Figure 03.15)) and Charles Babbage's difference engine (1822) which showed the drive for machines which would analyze, manipulate, and control numbers. When combined with materials having numerically qualified properties, machines could have controlled effects on materials. (Moe, pg.156)

o3.2.12 Automation in Manufacturing (1947)

With the development of technology, manufacturing continued to improve systems regarding speed and efficiency. All these developments lead to the ultimate result of the automation of manufacturing. Numerical control evolved to become more than control over a machine, but control over data; analyzing material properties, measuring them, and being able to deliver and receive specific dimensions.

General Motors established the use of automation after establishing its Automation Department in 1947. ***Automation*** uses both digital and physical technology to perform a process or procedure without human assistance. There may be an aspect of human observation or participation (feeding/placing stock), but the process operates under its own direction. The requirements of automation are; a control system, a program of instructions (executed by the control system), and power to operate the

Figure 03.17 • Plasma Cutter

Figure 03.18 • 3D Printer

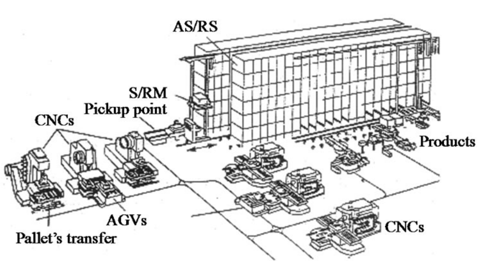


Figure 03.19 • Diagram of FMS

Pre-industrial

Industrial Revolution(1760-1830)

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Automation

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Future

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control and to drive the process. (Groover, 2013. pg.886)

The activities of an automated process are determined by the program of instructions. These may be simple tasks, such as maintaining a variable (e.g. temperature), or complicated sequences of activities, such as positioning along an axis (linear or rotational), turning a motor on or off, or controlling the flow of a fluid. Automated systems rely upon parameters in which the processes will operate as inputs to the process. These may be continuous, which would allow for a range of appropriate variables, or discrete: on or off. The values of the process parameters have a direct effect on the process variables – which is the output of the manufacturing system. Flexibility in process variables allows for different classifications of automation.

Fixed automation is best applied in situations of hard product variety (e.g. coins), programmable automation is applicable to medium product variety (e.g. millwork), and flexible automation can be used for soft product variety (e.g. cars). (Groover, 2013. pg. 890)

o3.2.13 Computerization Numerical Control (1950s)

The United States Air Force was a major player in developing the demand for processes which could meet consistent production of machined components. Funds were poured into research and development with the first Computer Aided Drafting (CAD) and Computer Aided Manufacturing (CAM) systems. (Moe pg.159) This produced many firsts; the use of a computer-aided drafting program (see Figure 03.16), an intercontinental network design and production practice, and [computer] numerically-controlled milling machines (see Figure 03.12). The computer-aided drafting and drawing program allowed for the digital input of a schematic and formed the basis of many CAD programs and parametric systems in use today. Through trickle down adoption, these technologies passed through the aeronautical industry and eventually to architecture and other disciplines. (Moe, pg 160) CAD has become ubiquitous in its adoption across industries, though CAM has had a much slower implementation. The adaption of numerically-controlled milling machines “resulted in significant labour disputes, a recurrent theme when implementing numerically controlled fabrication techniques.” (Moe, pg 160) This could be tied to the social construct that the replacement of labour can cause friction on the manufacturing floor. The dream was a fully automated floor consistently producing complex

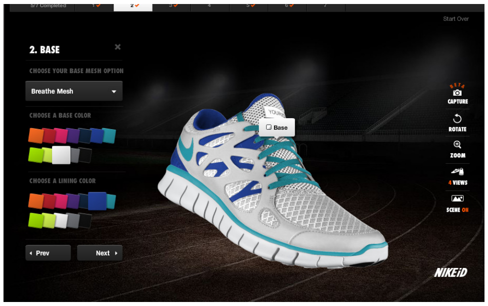
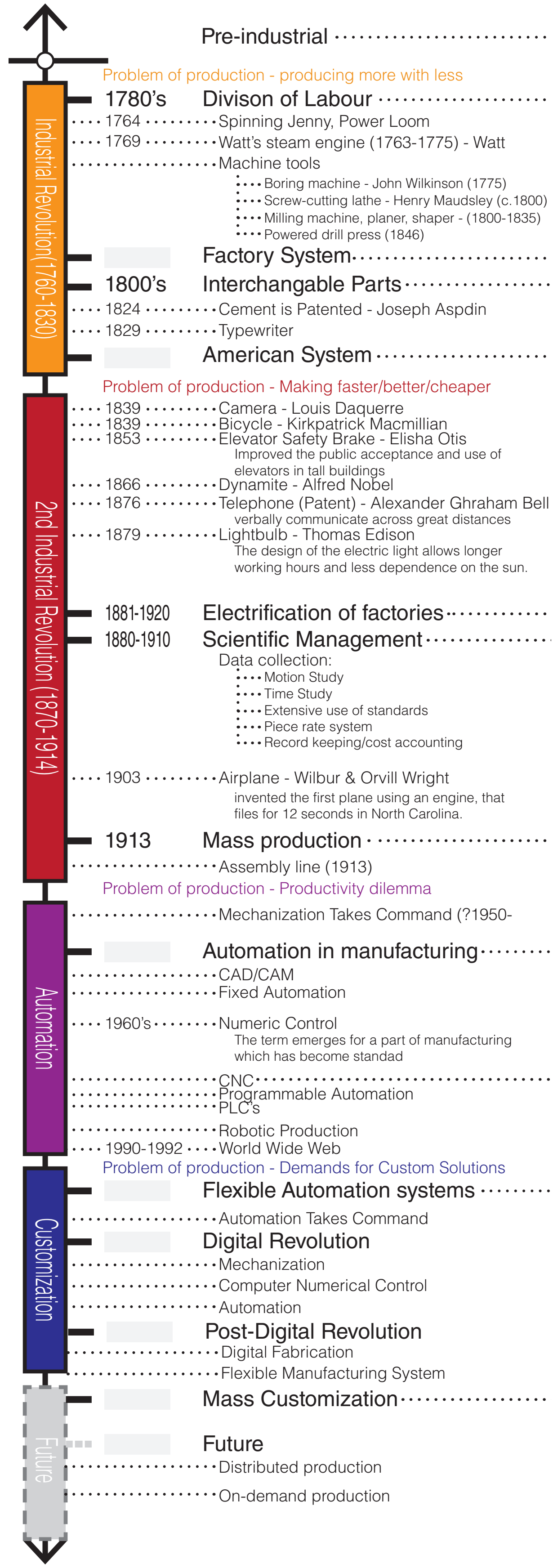


Figure 03.20 • NikeID Customization Interface



components. This allows for direct control of the machine through design data, reducing information to a commodity controlled by management, emphasizing the hierarchy of production.

Parallel to the introduction of numerical control runs a transformation of labour and production. In the process to automate machine production to a process with minimal human interaction; labour is seen to shift from human production to tool production and then from the tool to the computer program. "Directly associated with this technical progression is a digression in the required knowledge and skill required of human labour." (Moe pg. 162) A shift which mirrors that of Division of Labour and Fordism.

o3.2.14 Post Digital

Post-digital era sees manufacturing in a place where information is easily transferable, and machines can be easily changed to produce individual or small batch items - for customers themselves. This brings with it the concept of Digital Fabrication, flexible manufacturing systems and lastly Mass customization.

o3.2.15 Digital Fabrication

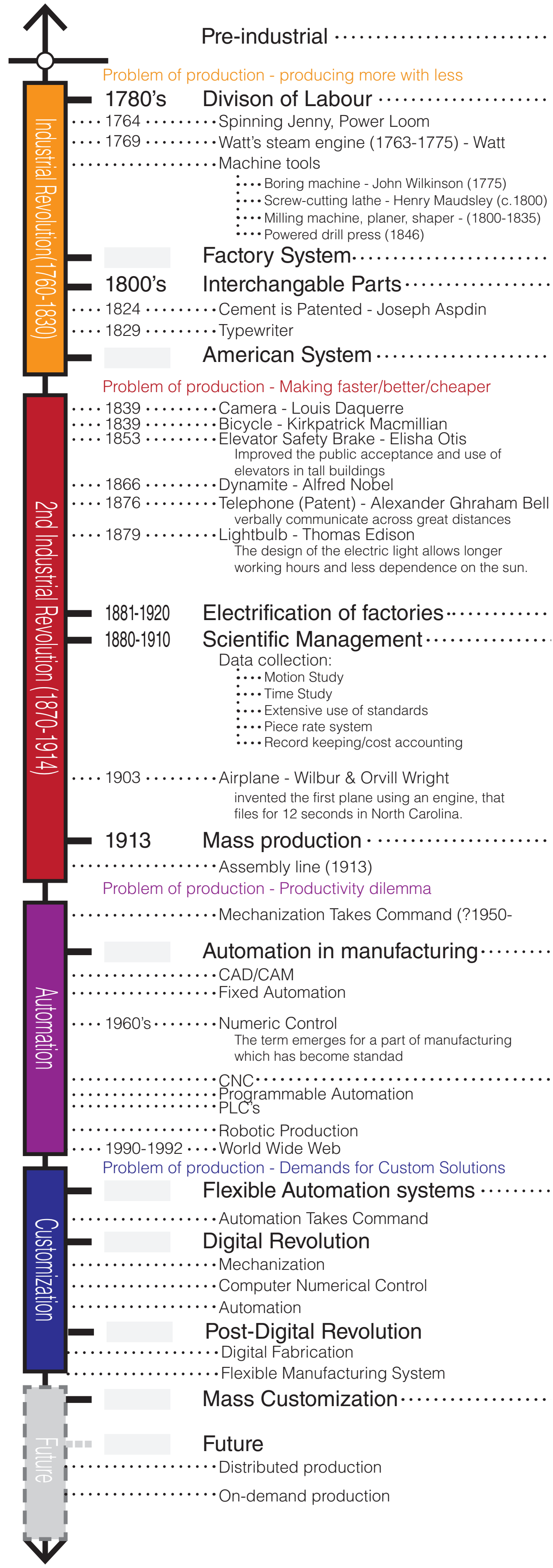
Digital fabrication refers to Computer Assisted Manufacturing (CAM) control of processes such as machine milling, laser/arc/plasma cutting, and 3D Printing. There are many different processes which can be computer numerically controlled in these systems, and the common links that these processes share are that they can be reliably programmed to make consistent products form digital designs. (OpenDesk, 2016)

With the advent of digital fabrication as its own method of manufacturing, certain avenues were opened when a computer is the only interface required for production. Through the implementation of digital technology, mass customization was now achievable, as it is potentially capable of producing individualized products for each customer. (Groover pg 6) The 1930s saw the establishment of mass production, this gave ground to the economic benefits of volume production but also shined a light on the vulnerability of a customers demand for 'different,' previously stated as the "Productivity Dilemma."

o3.2.16 Flexible Manufacturing System

Automation can be implemented at a larger scale throughout the manufacturing system, allowing for what is called a *Flexible Manufacturing System* (FMS). In this sort of system highly

Figure 03.21 • 3D Hubs Producers
Map showing the location of 3D Hubs printing centers, these are individually run locations each available to be utilized for on-demand part production.



automated machine cells consisting of (1) multiple processing stations (typically computer numerically controlled) are networked by an (2) automated material handling and storage system, and controlled through an (3) integrated computer system. FMS' are capable of processing multiple different parts at the same time under CNC programming at different workstations. (Groover, 2013. pg.1016) The two main types of flexibility are Machine and Routing. The first easily adapts to the production of differing parts, and the second easily adapts to different operations or control of production volume.

o3.2.17 Mass Customization

The simplification of mass production is that it can produce large quantities of one product style, when pushed to the extreme, flexible manufacturing systems are capable of taking a large product variety and producing a unique product style for each customer. This has become known as mass customization in which, "a large variety of products are made at efficiencies approaching those of mass production. Each product is individually customized according to specifications of individual customers." (Groover, 2013. pg. 1020) Mass customization is the production system that is capable of producing individualized products for each customer. (Groover, 2013. pg.7)

With mass customization, many unique parts can be created on the same machine. This is the ultimate realization of flexible automation. "In the extreme, mass production is the production of very large quantities of one product style. Similarly, mass customization involves large product variety and only one unit is produced of each product style." (Groover, 2013. pg. 1020)

"The successful mass customizer can use a number of strategies to operate efficiently in the face of a large product variety. They include: (1) soft product variety, (2) design modularity, (3) postponement, and (4) designing the product to be easily customized." (Groover pg. 1021)

It is interesting to see that Groover singles soft product variety as the only type accessible to mass customization. With conventional manufacturing processes, this does hold true. "Indeed, mass customization would not be feasible unless soft product variety were practiced by the company that offered customized products to its customers. The differences may appear significant to the customer, but to the company, they are easily managed in production." (Groover, 2013. pg. 1021)

Examples of this can be seen with clothing companies

Pre-industrial

Problem of production - producing more with less

Industrial Revolution(1760-1830)

- 1780's — Divison of Labour
  - 1764 — Spinning Jenny, Power Loom
  - 1769 — Watt's steam engine (1763-1775) - Watt
  - Machine tools
    - Boring machine - John Wilkinson (1775)
    - Screw-cutting lathe - Henry Maudsley (c.1800)
    - Milling machine, planer, shaper - (1800-1835)
    - Powered drill press (1846)
- Factory System
- 1800's — Interchangable Parts
  - 1824 — Cement is Patented - Joseph Aspdin
  - 1829 — Typewriter
- American System

Problem of production - Making faster/better/cheaper

2nd Industrial Revolution (1870-1914)

- 1839 — Camera - Louis Daquerre
- 1839 — Bicycle - Kirkpatrick Macmillian
- 1853 — Elevator Safety Brake - Elisha Otis
  Improved the public acceptance and use of elevators in tall buildings
- 1866 — Dynamite - Alfred Nobel
- 1876 — Telephone (Patent) - Alexander Ghraham Bell
  verbally communicate across great distances
- 1879 — Lightbulb - Thomas Edison
  The design of the electric light allows longer working hours and less dependence on the sun.
- 1881-1920 — Electrification of factories
- 1880-1910 — Scientific Management
  Data collection:
    - Motion Study
    - Time Study
    - Extensive use of standards
    - Piece rate system
    - Record keeping/cost accounting
- 1903 — Airplane - Wilbur & Orvill Wright
  invented the first plane using an engine, that files for 12 seconds in North Carolina.
- 1913 — Mass production
  - Assembly line (1913)

Problem of production - Productivity dilemma

Automation

- Mechanization Takes Command (?1950-
- Automation in manufacturing
  - CAD/CAM
  - Fixed Automation
  - 1960's — Numeric Control
    The term emerges for a part of manufacturing which has become standad
  - CNC
  - Programmable Automation
  - PLC's
  - Robotic Production
  - 1990-1992 — World Wide Web

Problem of production - Demands for Custom Solutions

Customization

- Flexible Automation systems
  - Automation Takes Command
- Digital Revolution
  - Mechanization
  - Computer Numerical Control
  - Automation
- Post-Digital Revolution
  - Digital Fabrication
  - Flexible Manufacturing System

Future

- Mass Customization
- Future
  - Distributed production
  - On-demand production

such as NikeID and UNMADE. Their manufacturing policies cover the production time, customer order setup, and cost not being prohibitively higher than similar products. (ex. Mass Customization in Action NikeID - $140 vs $200 shoes and UNMADE – "customizable knitwear")

Future systems of production are beginning to be hypothesized. With the globalization of the economy, and digitization of information, production could easily become distributed. The other compelling theory is Direct Manufacturing with a distribution network. This is along the lines of Amazon's network of shipping but rather than a stock house at the centre – it is a production facility consisting of digital fabrication technologies.

o3.3 Production Facilities

Production facilities are composed of the physical elements of the manufacturing process which involves the arrangement of equipment and people. There are three main processes (additive, formative, subtractive) that have an impact on the variety and quantity a facility can manage. Current production systems are organized around the product variety and quantity they hope to achieve. "The quantity of products made by a factory has an important influence on the way its people, facilities, and procedures are organized." (Groover, 2013. pg.5) The manufacturing industry balances demand against profit in order to establish production quantity and variety.

There are three ranges of annual production quantities: low production (1-100 units per year); medium production (100 to 10,000 units); and high production (10,000 to millions of units.) In typical manufacturing arrangements, the production quantity is directly related to the degree of options. (See Figure 03.23): If a factory's product variety is high, then the production quantity is low; subsequently, if the product variety is low, then the production quantity is high. Manufacturing plants tend to specialize in a combination of production quantity and variety level that lies somewhere inside the diagonal band in Figure 3.23. (Groover, 2013. pg.6)

The variable of product variety can be a deceiving device to use quantitatively, as it does not take into account the degree of variation between two products. Variation spans the difference within a specific model (as simple as a colour change between two tablet devices), to the differences between models (such

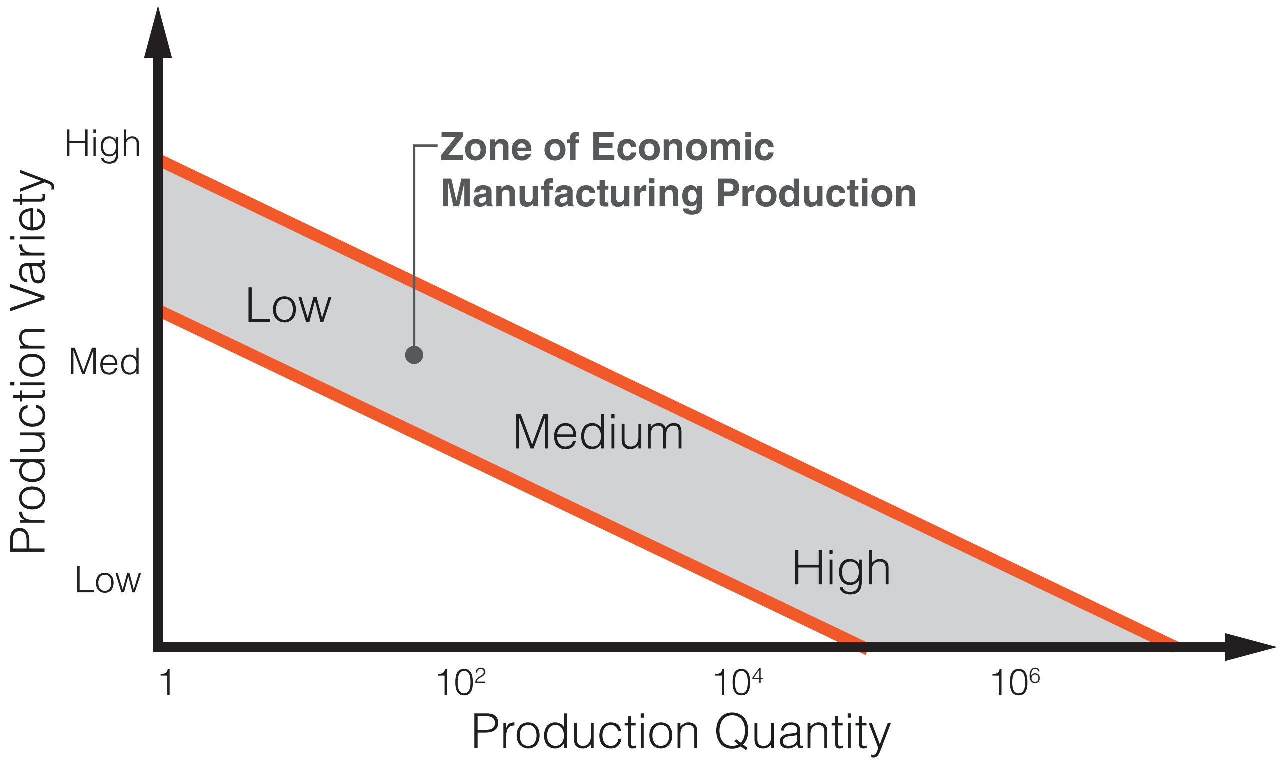


Figure 03.22 • Overlay of Production Methods

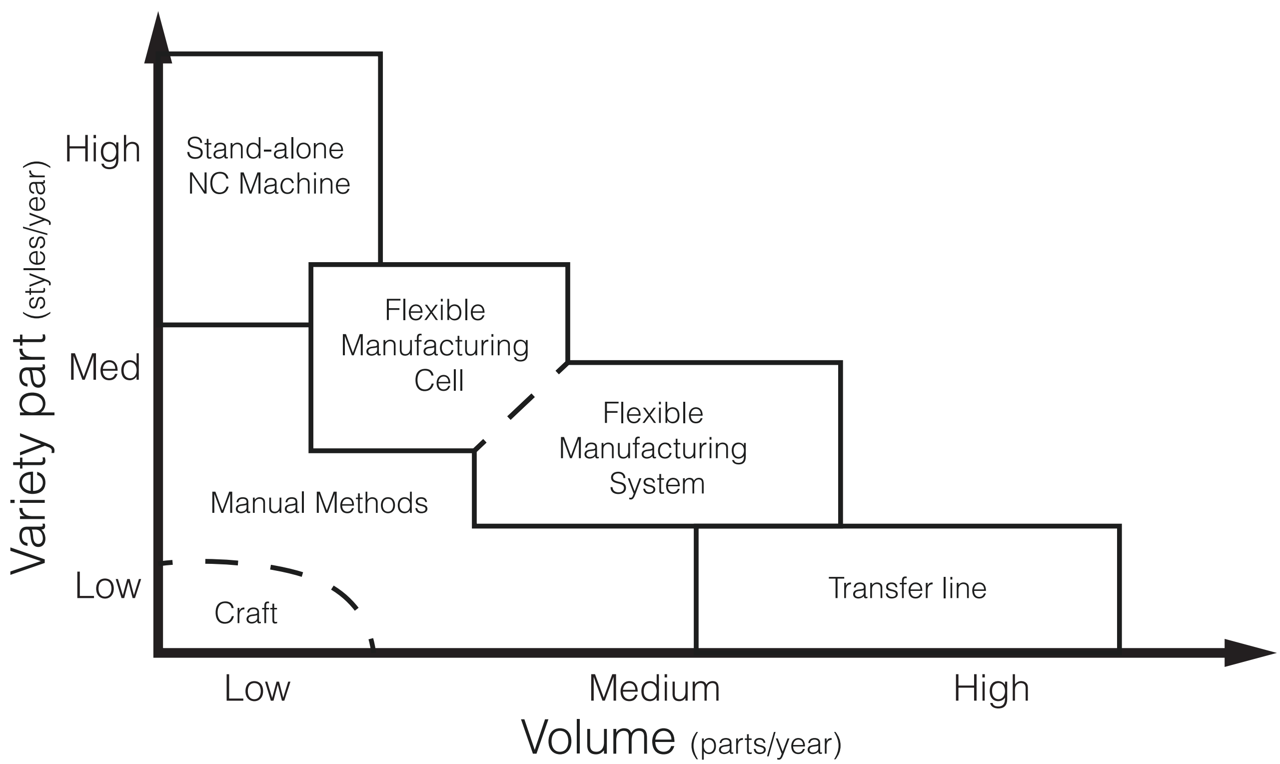


Figure 03.23 • Variety vs ProdQuantity

as a tablet vs a desktop computer.) (Groover, 2013. pg.6) To account for this indeterminacy the terms soft and hard can be used to measure the levels of product variety. Soft product variety encompasses the small differences within a product. Hard product variety establishes the differences between products (Groover, 2013. pg.6). Architecture tends to have hard product variety, as each project has a unique site, program, and style; however, there are components of architecture that lie in the soft category. This can be seen in Figure 03.24 certain product volumes are best met with certain production styles.

o3.3.1 High-Variety / Low-Quantity Production

Production facilities geared towards low production quantity can be described as a job shop. A low-quantity production facility has the ability to make products which are typically specialized, custom, or complex. The equipment in the facility is general purpose, and the labour force is highly skilled. (Groover, 2013. pg.17)

Layouts applied to low-quantity production facilities are designed for maximum flexibility to deal with the wide product variations encountered (hard product variety). In a fixed-position layout, Figure 03.26 the product is typically large and heavy, (rather than moving the product the workers and processing equipment are brought to the product). In a simple situation the product would remain in place for its entire production, typically these large pieces are components to an even bigger product to be assembled. This layout is particularly effective for products such as ships, aircraft, locomotives, heavy machinery, and buildings. Another arrangement is the process layout, Figure 03.27 where equipment is arranged according to function or type. The product is moved through departments in the order required for processing, typically in batches. This type of layout allows for great flexibility in the production of parts, as it allows for a variety of operation sequences. The consequence is that the machinery and processes are not ordered for high efficiency. This is explained more in medium quantity production. Other approaches include manual methods and digital fabrication (standalone NC facilities.)

o3.3.2 Medium-Variety / Medium-Quantity Production

There are two distinct facility layouts for medium quantity production (100-10,000 units) depending on whether there is hard product variety or soft product variety. In a cellular layout, the process of the assembly of parts is achieved through individual

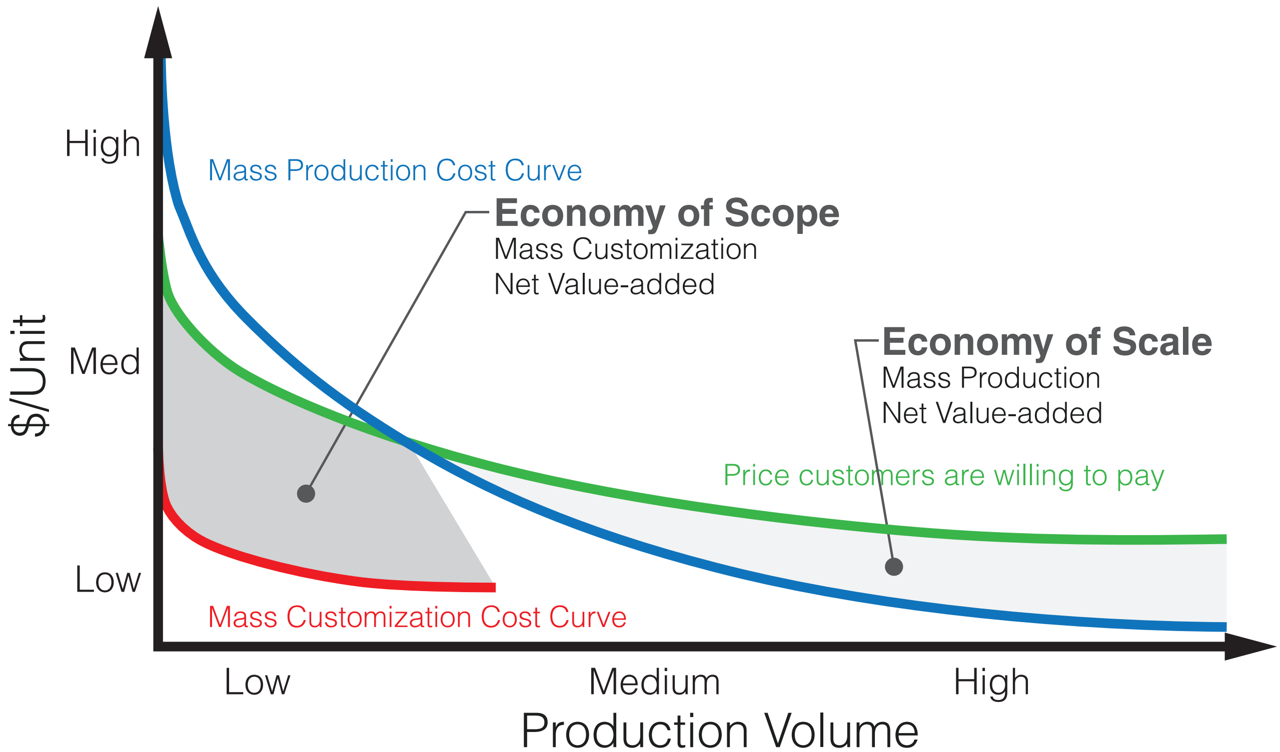


Figure 03.24 • Variety vs Production Quantity

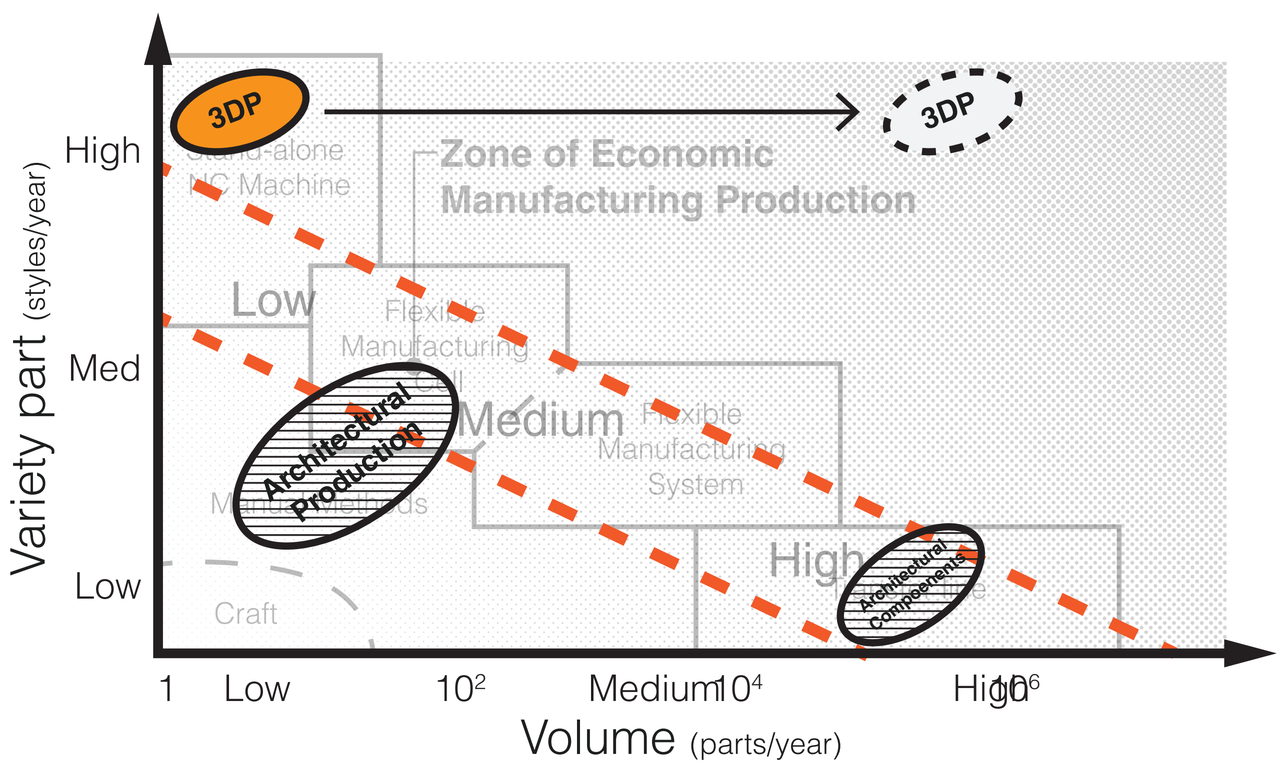


Figure 03.25 • Unit Cost vs Volume

cells with several workstations or machines.

A medium quantity production facility with hard product variety typically utilizes batch production. One batch of product is made, after which the manufacturing equipment is changed over to produce a batch of the next product. This is possible because the production rate of the equipment is higher than the demand for any single product (everyday products are make-to-stock items). The equipment changeover (tooling change and machinery setup) between product runs creates downtime within the facility and as such, lost production time. Equipment is typically arranged in a process layout to accommodate for flexibility between products. (Groover, 2013. pg.17)Figure 03.27

With soft product variety, the use of cellular manufacturing can be used, as extensive changes in machining is not required. In cellular layout "processing or assembly of different parts or products is accomplished in cells consisting of several workstations or machines." Each cell specializes in the production of a given set of similar parts, and because of the similarity between products, machine setup for differing parts can be done without a significant loss of time. (Groover, 2013. pg.18)

o3.3.3 Low-Variety / High-Quantity Production

The high-quantity range consists of 10,000 to millions of units per year. Typically the product is in high demand, and the manufacturing system is dedicated to the production of that single item. Manufacturing items in this quantity is generally referred to as mass production.

The equipment is typically standard but specifically dedicated to the processing of one part type. Layouts for high quantity production range from process layout, cellular layout, and product layout.

Product layout involves multiple pieces of equipment or workstations arranged in one long line or a series of connected line segments with the working product moved through until completion. Figure 03.29 Also known as a transfer line or flow line production. At each station, a small percentage of the work is completed with products moved between stations via mechanized conveyor. The assembly line is a familiar example. If there is no variation in the products made on a line, each one is identical, and the line is referred to as a single model production line. In some cases, there are soft product varieties included within the product, and these can be produced with a mixed-model production line. The modern automobile assembly line is

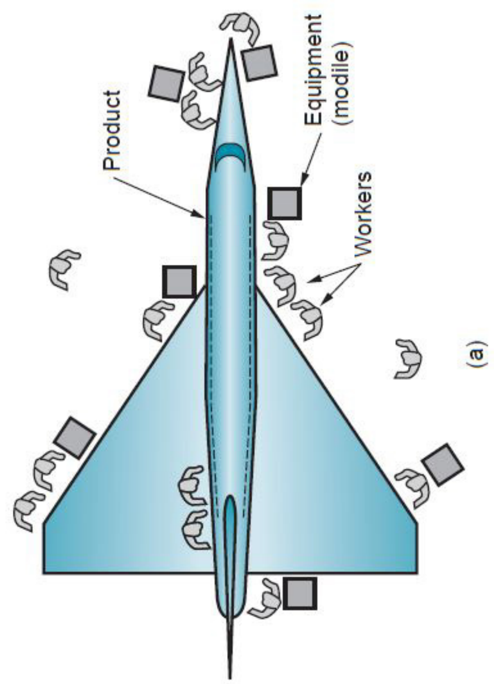


Figure 03.26 • Fixed-Position Layout

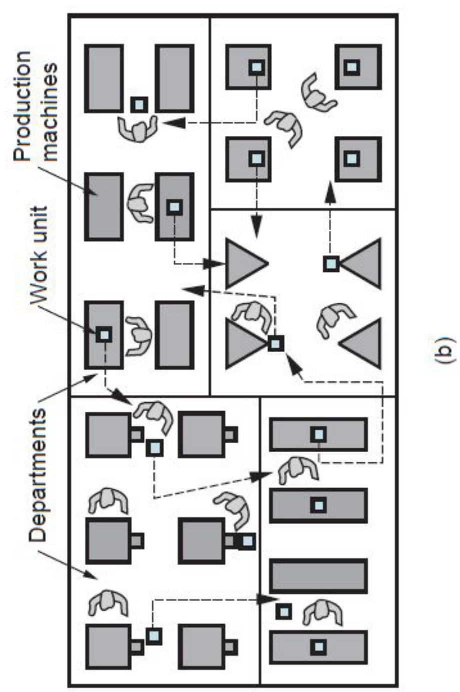


Figure 03.27 • Process Layout

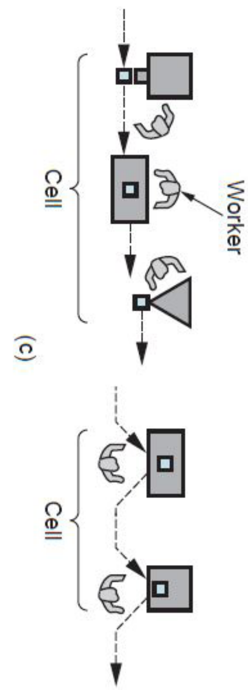


Figure 03.28 • Cellular Layout

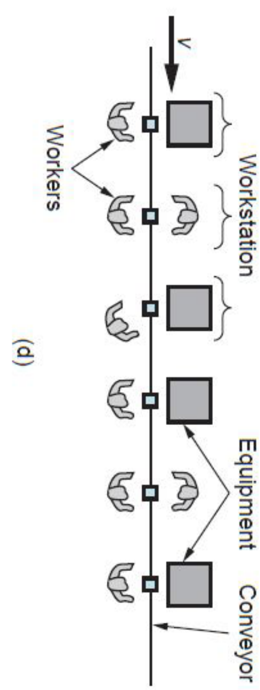


Figure 03.29 • Product Layout

an example of a mixed-model production line, as many vehicles come off the line with slight variations in options. (Groover, 2013. pg.19)

o3.3.4 High-Variety / High-Quantity Production

Within the traditional modes of production, there is a missing category, the one for high-variety with high-quantity products. This graph of units/$ vs. product worth helps to show the boundaries of current manufacturing thought and where future production hopes to fit. The economy of scale is the premise that there is a high volume of production. This is the line ruled by low variety/high product aka mass production. With a large quantity and low unit price, there is an economy maintained. With the adoption of the idea, that customers will pay for variety. We have the economy of scope - where there is flexibility offered by demand for custom. This produces the mass customization cost curve. Mass customization offers the ability to achieve high variety with high quantity as seen in Figure 03.23 as an outline of the productions charts.

CHAIRS MILLWORK

Figure 03.30 • Products of Various Systems: Chairs

Figure 03.31 • Products of Various Systems: Millwork

o3.4 Systems and their Products

This chart summarizes the systems of production and typical products produced with these processes as seen in Figure 03.23. Different volumes of products can be categorized on the quantity/product layout diagram. We have five general categories; Hand-crafted, batch, mass production, mass customization, digital fabrication.

o3.4.1 Hand-crafted

A – this can be produced manually aka “handicraft” (process layout)

B – this can be produced with other methods, but they become economic at volume. (mold/casting/punch/stamping)

C – they can be produced via digital fabrication

D – fixed position layout (one product people move)

For a one-off, the typical choices are A or C

o3.4.2 Batch Production

A- These are difficult to produce manually

B- cell/process layouts utilized with traditional manufacturing processes.

C- it could be provided digitally, but volume may be a hindrance.

o3.4.3 Mass Production

A-Cell layout and product layout – departments reduce the efficiency of production increasing cycle times.

B-manual is too slow

C-digital is too slow (cycle times)

D-fixed automation – flow production

o3.4.4 Mass customization

A-Cell layout

B-Digital fabrication and cell layout

C-Flexible automation is a must

o3.4.5 Digital Fabrication

A-Product Layout

B-Single to volume orders of products custom to a project.

C-Customizable Options – same production but special to one project.

Figure 03.32 • Products of Various Systems: Lights

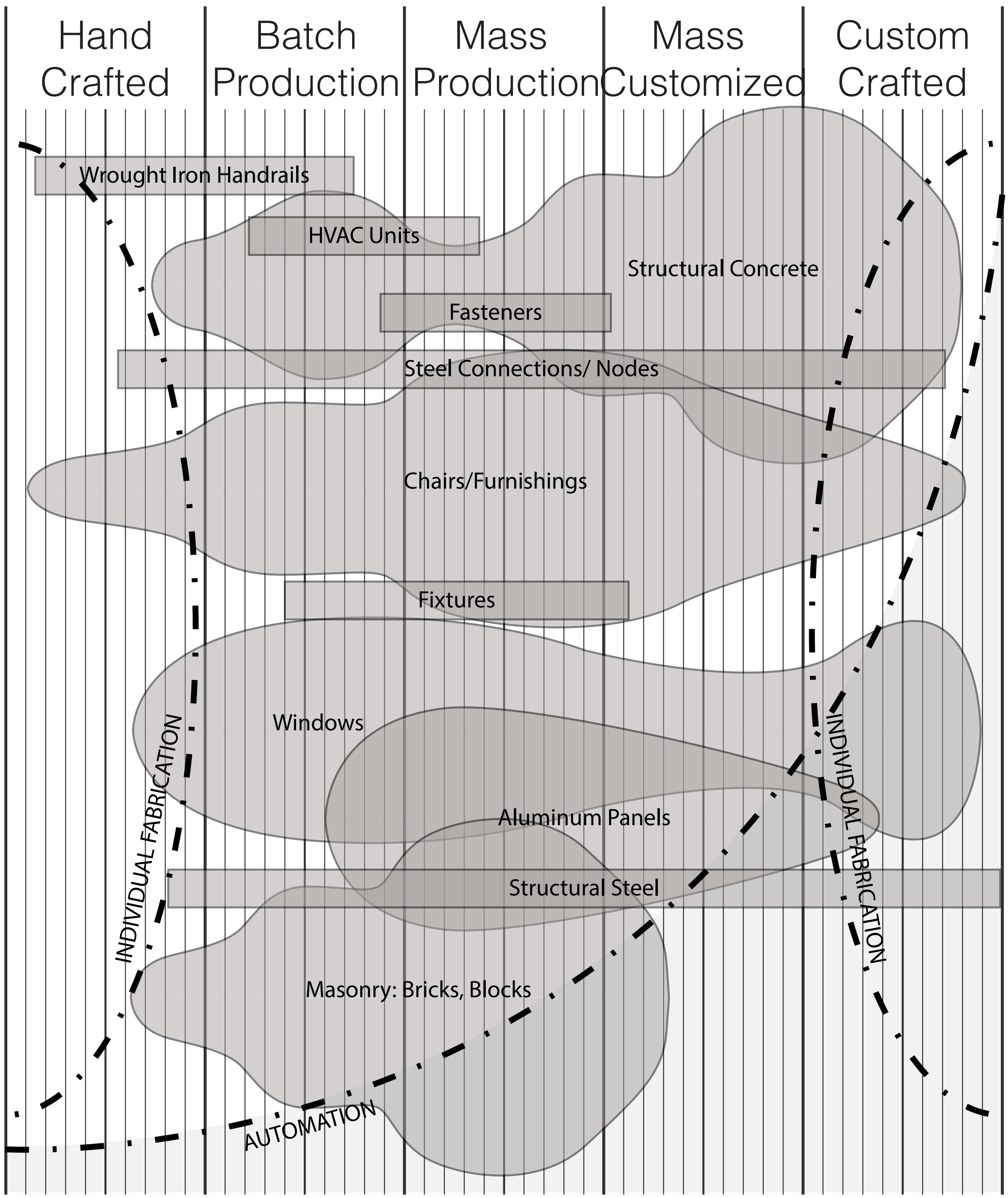


Figure 03.33 • Architectural component production

Plotting the trend of how current building components are produced allows for the visualization of where new technologies can break into the market. This diagram looked at where objects to the refinement of the production quantity and product style. (chairs, light fixtures, HVAC units, reinforced concrete, fasteners, blocks, pre-cast concrete, production home building, insulation, lumber, steel)

o3.5 Fabrication and Architecture

Since the industrial revolution, technical changes have followed a trickle-down effect, starting as an industrial change. Slowly they are adapted into adjacent industries as the technology improves, social acceptance grows, and capital costs fall. For example, the advancement of steel production was focused on improving the locomotive network then later had a significant impact on the production of tall buildings.

With the principles of standardization and automation, there must be a scalable market which can support the high-capital investment needed. These principles (shown in Figure 03.23) are fundamentally at odds with aspects of architecture practice as architecture requires the "customization of building types for particular codes, sites, budgets, performances, and preferences." (Moe, pg. 162) as previously established in Section 02.

Without fundamental shifts in the social and market structures of design practice, digital fabrication technologies will not change building production. Gehry's practice is an example: it was a modification of the contract structure that engendered the techniques and technologies of their work, rather than the adoption of a range of digital technologies. "Architecture lacks most often the economies of scale, massive capital, and government subsidies that optimize these technologies in adjacent disciplines, no matter how much we rhetorically compare our industry to others. Further, the need for customization in architecture through possible in digital fabrication, strains against the uniformity stressed thought the history of numerical control." (Moe, pg.168) A car designer works for the company which produces the car, whereas an architect and contractor cannot be viewed in the same light in typical contractual arrangements, as there is no direct, lasting connection between designer and producer with them typically ending up at odds to each other.

Regarding customization, automation and numerical control could be applied to more than the continuous production of the same product if new technologies are explored. Architecture has historically been too willing to promote the capabilities of technologies while ignoring the culpabilities. This suggests, even demands, an alternate way for designers to understand, practice, and implement technology. As David Noble noted, "there are no technological promises, only human ones, and social progress must not be reduced to, or confused with, mere technological

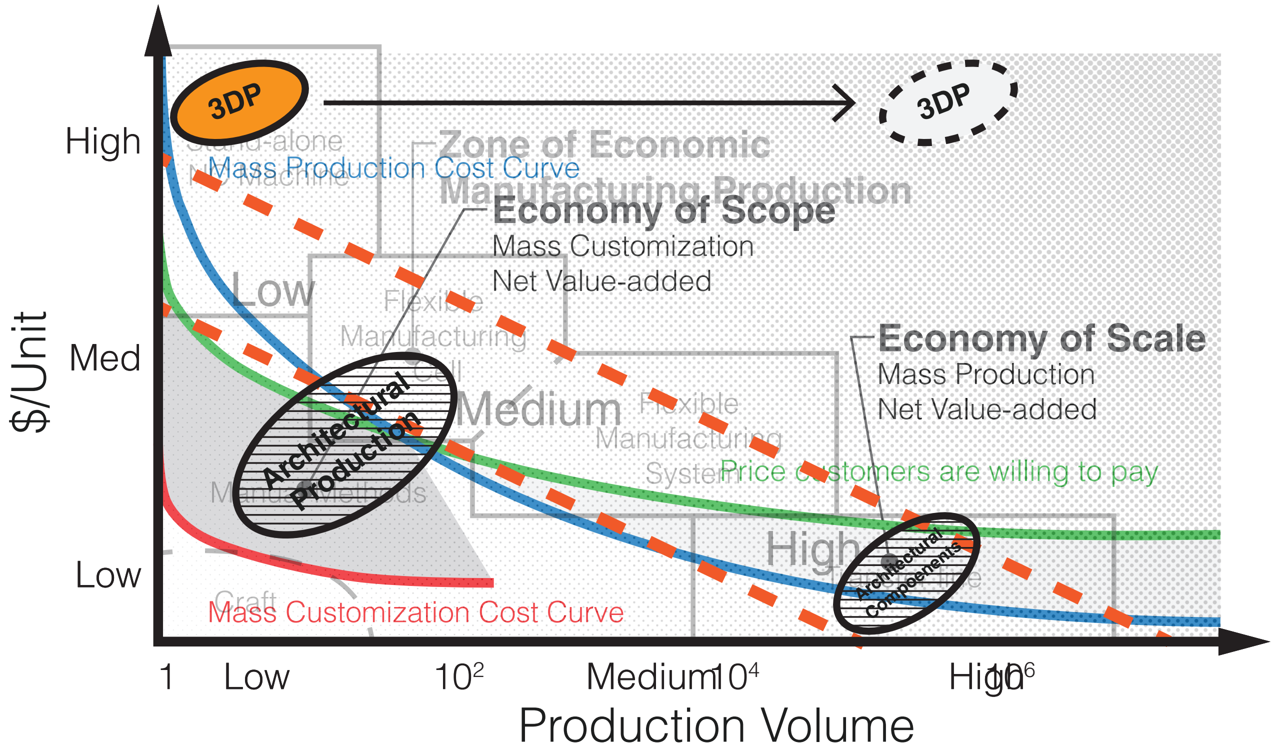


Figure 03.34 • Overlay of Production Scales and 3DP

progress.” (Moe pg. 165) With an adaption of new technologies proven to be successful either economically, materially, or formally, new design pathways open up to designers for the production of architecture. For designers to connect with the manufacturing process, these processes need to become more closely linked. For the link to be possible, we must look at where other possibilities lie.

o3.6 Opportunities for customization

Systems of production that are technically advancing simplify the production of objects. The production of standard simple objects has been mastered with the mass production model, and few production systems would be able to refine this model to greater efficiency. The mass production model applies to the manufacturing of certain aspects of components in architecture. There is a trend that aligns product styles with that which was able to be produced. For example, machines can create clean, crisp planes of glass and straight extrusions of aluminum. The style of the contemporary office matches the aesthetic of the production system. However, this method does meet the need of every component used in architecture as mass production does not enable the production of components that require unique solutions to unique demands. There are building products such as joints and connections that demand to be uniquely produced to respond to structural and architectural constraints. Another area where unique building elements are predominant is within the façade skin, and shape. This speaks to the production of panels, and geometrically complex screens. A third area is interior finishes for luxury spaces focused on complex geometry of space to form the aesthetic atmosphere and presence over that of basic function.

Figure 03.35 • Modern Smart Factory

o3.7 Conclusion

The industry of manufacturing is deeply rooted in societies need to make objects, and there are many established operations used in the endeavour. Most, if not all manufacturing processes today are mechanized or automated versions of ancient techniques. There is an ongoing evolution of the operations we use, transforming through the technical and social development that allows them to adapt to the mainstream industry. The social need for customization has allowed for a platform of production to meet these demands, such as mass customization, and digital fabrication. The transformation to processes as such is closely tied to social developments - architecture requires an infusion of the technology to allow for widespread adaption. With the inherently complex nature of architecture and increasing customer demand, production needs to reflect these changes and react. The following section reviews the various additive technologies and applications to architectural production.

Additive Manufacturing

o4

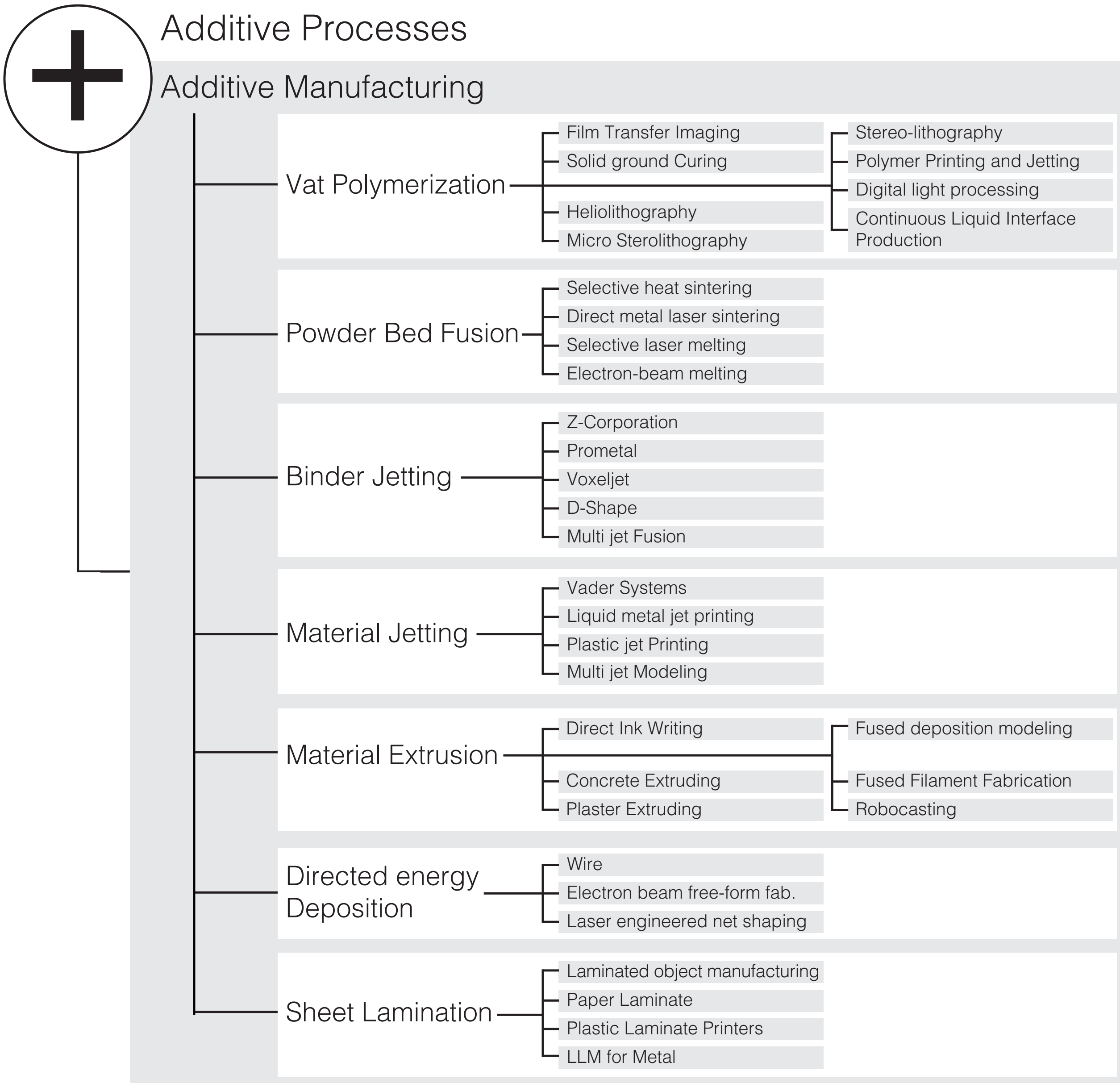


Figure 04.1 • Additive Processes

o4: Additive Manufacturing

o4.1 Introduction

Additive manufacturing is the newest branch within the industry of manufacturing; we see its adaption within existing production workflows, with ongoing research and development producing new techniques. Due to the newness of these technologies and their proprietary nature, additive manufacturing has many names in the industry such as layer-based manufacturing, rapid prototyping, direct manufacturing, digital fabrication, and three-dimensional (3D) printing. (Gebhardt, 2012. pg. 2) Additive manufacturing offers potential in its ability to reduce processes significantly, while at the same time by-passing the daunting technical nature with a simple digital work-flow. Industrialization has increasingly removed the human element from the processing of materials; this causes the tool to become foreign in the human concept of creating. This foreign nature mystifies the simple nature in which these processes operate, reinforced by the reduction of machine interface to that of a computer screen. The promise of 3D printing to change manufacturing is real, but the search for this niche begins with a survey of current 3D printing technology, synthesizing out that which can have a relevant impact to the production of Architecture.

Additive manufacturing is the process of creating an object through the deposition of a material using a pathway which allows the desired shape to emerge. Technically defined, additive manufacturing is a "layer based automated fabrication process for making scaled three-dimensional physical objects from 3D-CAD data without using part-dependent tooling" (Gebhardt, 2012. pg. 2). These processes are dependent on a set of shared variables: having a complete virtual three-dimensional data set, processing this data into a packet of equal thickness layers representing a cross-section of the data set, prototyping a physical copy at any moment within the design of an object. Typically machines have a direct connection between a proprietary process and the material used, due to the protection of developing technologies. (Gebhardt, 2012. pg. 5)

Section 04

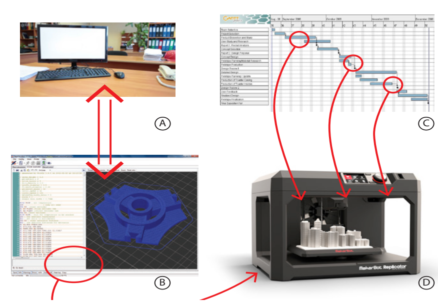


Figure 04.2 • Work flow with Additive Manufacturing Processes
The work flow of additive manufacturing allows for the application of manufacturing at any moment in the design, development, implementation phases. This allows for many prototypes of a final product, or many iterations of a variable design set withing distinct parameters.

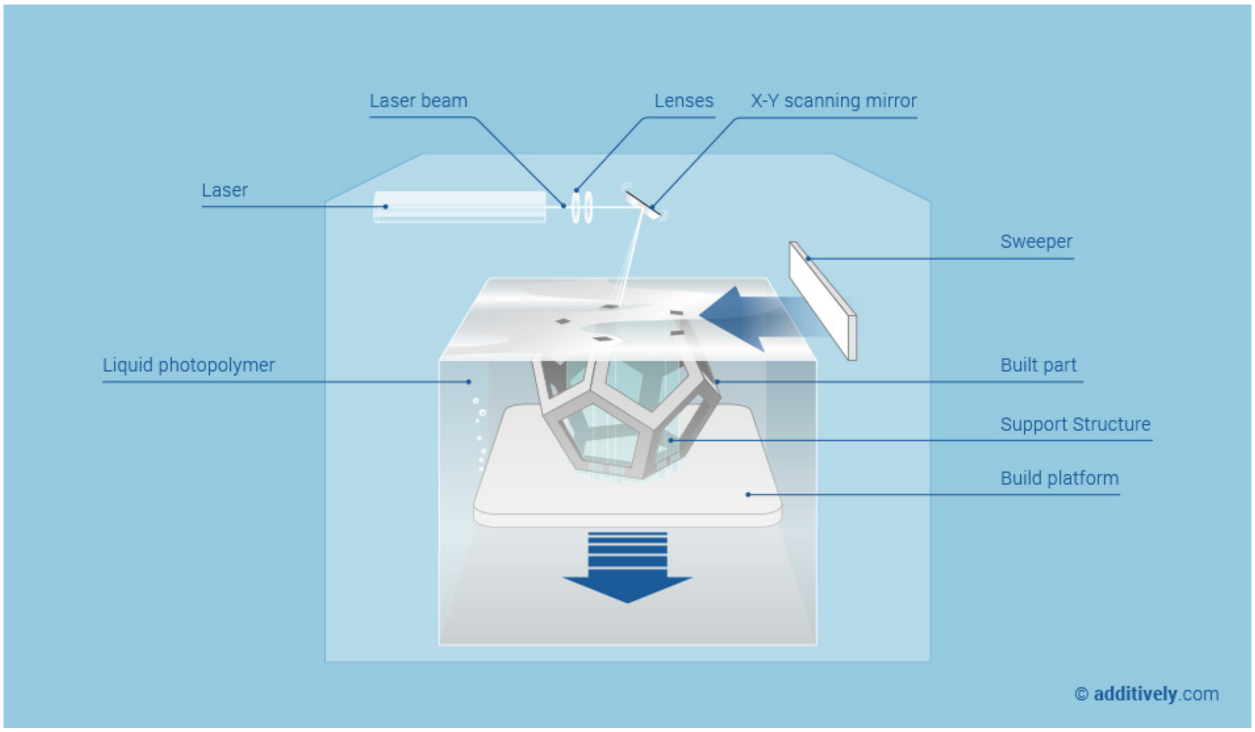


Figure 04.3 • Laser-Stereolithography
Diagram of the component parts to Laser-Stereolithography process.

o4.2 Methods

The following methods for additive manufacturing are separated by their processing operations. See Figure 02.60 • Additive Processes. The operations shown are the fundamental shaping methods; some follow the basics of extrusion, others the deposition of powder and polymers, where others are based upon the curing or fusion of materials.

o4.2.1 Vat Polymerization

vat photopolymerization, n - an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization. (ASTM, 2012. pg. 2)

Vat Polymerization produces objects through the selective solidification of liquid monomeric resin by ultraviolet radiation. Objects are not self-supportive and require supports for overhanging elements, which are physically removed with finishing operations. (Gebhardt, 2012. pg. 34)

Laser-Stereolithography (SL):

Invented in the 1980's, laser-stereolithography is the oldest and still one of the most detailed additive manufacturing process. An ultra-violet laser polymerizes liquid monomers into a solid, leaving a layer of the desired contour and thickness. Contour paths are calculated via digitally slicing a 3D-CAD model; thickness is controlled by properties of the material (e.g. curing rate) and laser (e.g. power and speed). The build chamber contains a laser head which travels on the x/y-axis and a build platform for the z-axis. As each layer is polymerized, the build platform lowers in the z-direction by the desired layer thickness and recoated with resin in preparation for the application of the next layer. See Figure 04.3. (Gebhardt, 2012. pg. 34-36)

Digital Light Processing (DLP):

A variation of photopolymerization where the UV curing is provided by a light projector rather than a laser. Differing from the typical 3D-printing process as one complete contour section (sliced layer) is projected and cured instantaneously. The build material, liquid resin, is in a reservoir with the curing element, the light projector below. The build platform is on top of the assembly located above the material reservoir. With each cured layer the build platform travels up, "pulling" the object layer-by-layer out of the resin. Supports are required (though inverted), and the build area is typically small to accommodate the reservoir volume. See Figure 04.4. (Gebhardt, 2012. pg. 38-39)

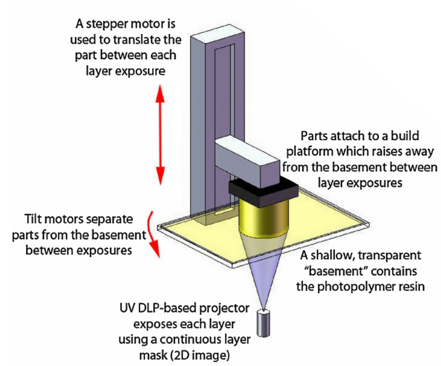


Figure 04.4 • Diagram of DLP

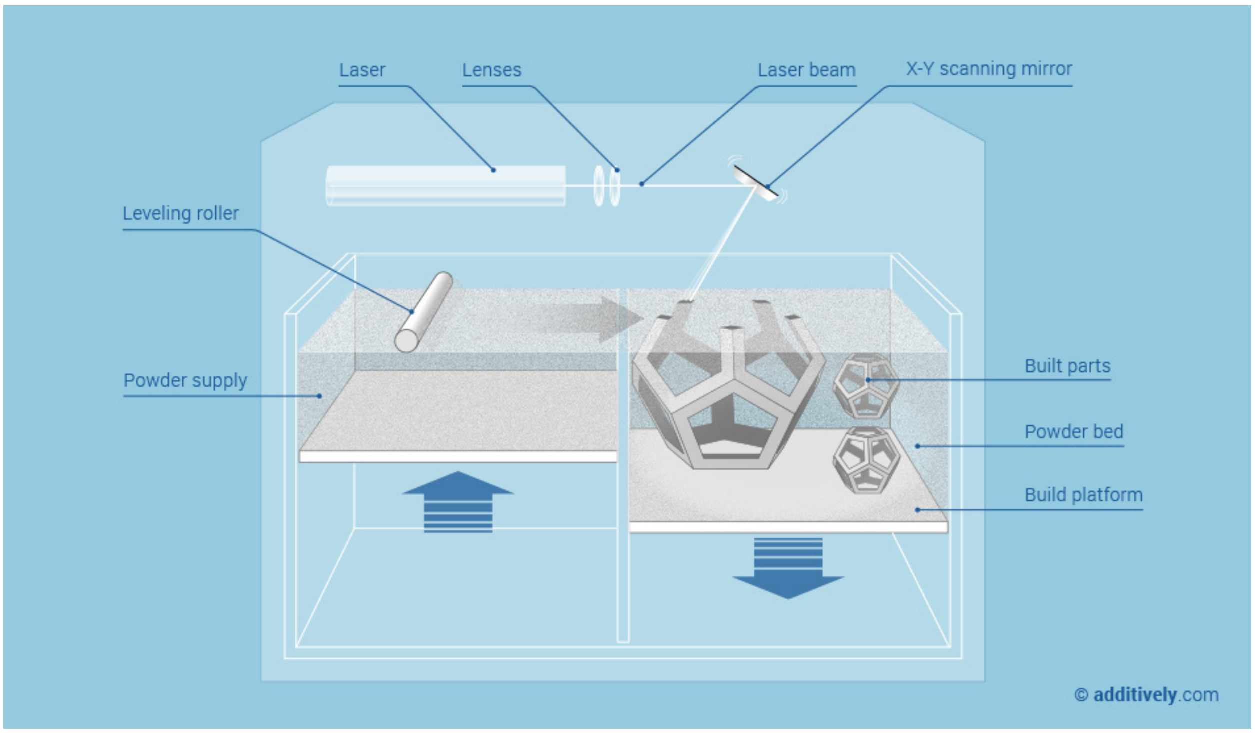


Figure 04.5 • Laser Sintering / Selective Laser Sintering

CLIP (Continuous Liquid Interface Production):

Similar process to DLP. A recently released proprietary version which utilizes the addition of specialized gases to the resin reservoir, allowing semisolid adhesion. Making it possible for a part to emerge from the resin with virtually no layers. Supports are required (though inverted), and the build area is typically small to accommodate the reservoir volume. See Figure 04.5. (Koslow, 2016. 3dprintingindustry.com)

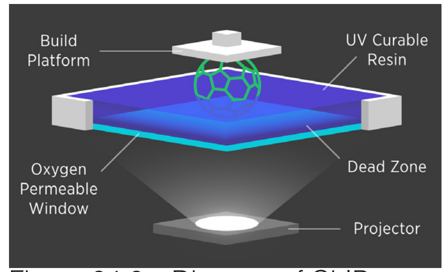


Figure 04.6 • Diagram of CLIP

Film Transfer Imaging:

Similar process to DLP. This process utilizes a thin film of resin is deposited on a glass plate rather than a reservoir of resin. A digital projector is used to cure resin layers through the glass screen onto the movable build platform (z-axis) above. The build platform moves the piece up providing clearance to a scraper which will deposit material across the screen after each layer is successfully cured. The build platform returns and the next layer is cured, repeating for the entirety of the print. See Figure 04.7. (https://www.3dsystems.com/file/3569)

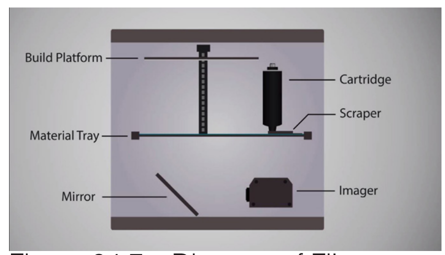


Figure 04.7 • Diagram of Film Transfer Imaging

Heliolithography:

A polymerization process utilizing the principals of DLP. The significant difference pertains to the build platform which both rotates about and moves along the z-axis. They promise continuous builds to the parts which would reduce stratification on the final parts and possibly reduce post-processing. See Figure 04.8. (http://www.orangemaker.com/)

Micro Sterolithography:

The processes of polymerization are applied to create objects microns wide, an area which is primarily under research and development. (Gebhardt, 2012. pg. 39-40)

o4.2.2 Powder Bed Fusion

powder bed fusion, n - an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. (ASTM, 2012. pg. 2)


Figure 04.8 • Heliolithography

The selective melting and re-solidification of thermoplastic powders, or metallic powders by a source of energy. (Gebhardt, 2012. pg. 40) Objects are generally self-supportive as they are produced within the excess material and maintain a bumpy surface texture due to the nature of the particles.

Laser Sintering – Selective Laser Sintering (LS/SLS):

Laser Sintering or selective-laser sintering are terms typically used to refer to the processing of plastic particulate materials. Machines consist of a laser head travelling in two

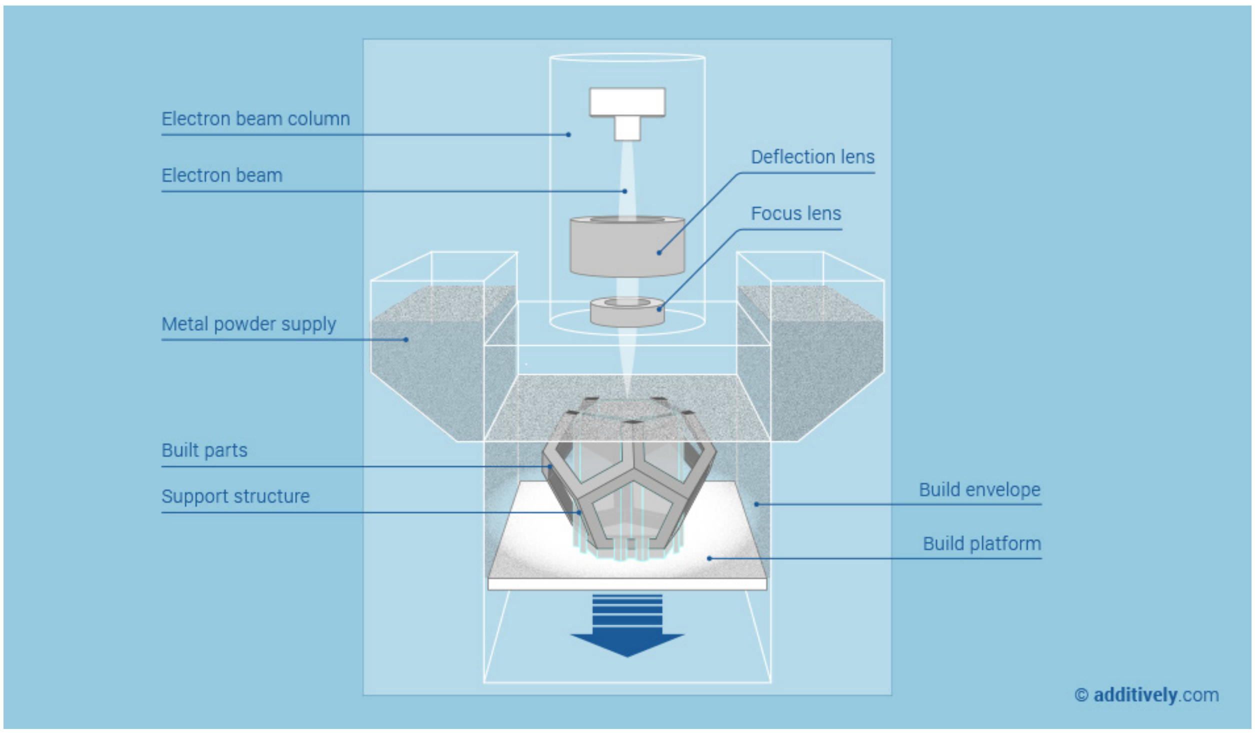


Figure 04.9 • Electron Beam Melting

dimensions on the x-y axis. The build platform consists of a powder bed and descends in layer implements, with a fresh layer of powder deposited on top. The laser fuses (makes solid through thermal transformation) the desired contour into the powdered material. The build platform then lowers down one layer thickness on the z-axis and is re-coated with powder particles. The next layer is then fused in the shaped of the desired contour, and this continues for each successive layer up to the volume of the object. Contours are provided from a sliced version of the digital production model. After the model is finished, it is then removed from the powder bed during the "breakout" process.

A benefit of printing in a powder bed is the extraneous material entirely supports the object throughout the build process. Typically shapes are designed as hollow shells with holes allowing for excess powder trapped within the interior volume to escape. Objects can be sealed post process to help solidify the typically porous material. See Figure 04.5. (Gebhardt, 2012. pg. 40-42)

Selective Heat Sintering (SHS):

Similar process to Selective Laser Sintering; except this process uses less energy, only enough to bond the particles rather than fully fuse them. See Figure 04.10. (Gebhardt, 2012. pg. 40-42)

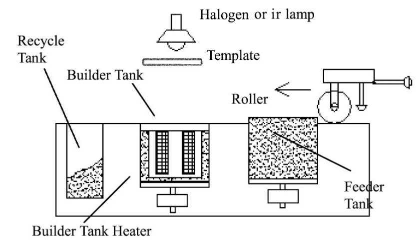


Figure 04.10 • Selective Heat Sintering

Direct Metal Laser Sintering:

Similar process to Selective Laser Sintering except focused on the use of metals, whereas SLS processes generally refer to the use of plastic. See Figure 04.11. (Gebhardt, 2012. pg. 40-42)

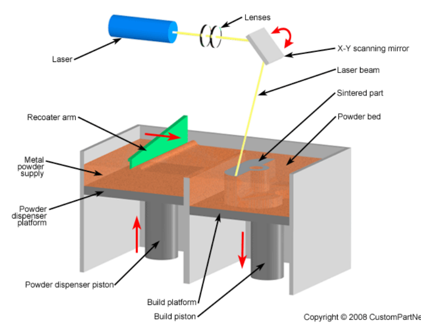


Figure 04.11 • Direct Metal Laser Sintering

Laser Melting – Selective Laser Melting (SLM):

Very similar process to laser sintering, with the specialization of processing metal materials. The process uses a laser to produce a local melt pool which results in a very dense metal products (with >99% density) part after re-solidification. Machines are similar to the Laser Sintering process for plastics; using high quality lasers (moving in 2-dimensions along the x-y axis) which produce a steady energy beam, striking a powdered bed (z-axis) on the build platform, all of which is contained within a sealed build chamber. Sealing the build chamber allows it to be evacuated to a near vacuum state or filled with shielding gas for the processing of sensitive materials, to the benefit of greater material property control. Though supports are not necessary to give the material structure (as it is supported within the powder

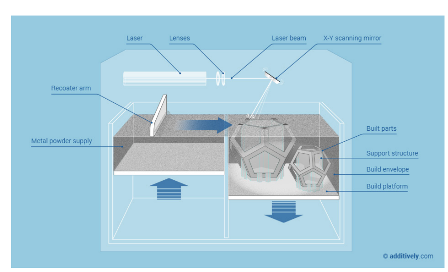


Figure 04.12 • Laser Melting - Selective Laser Melting

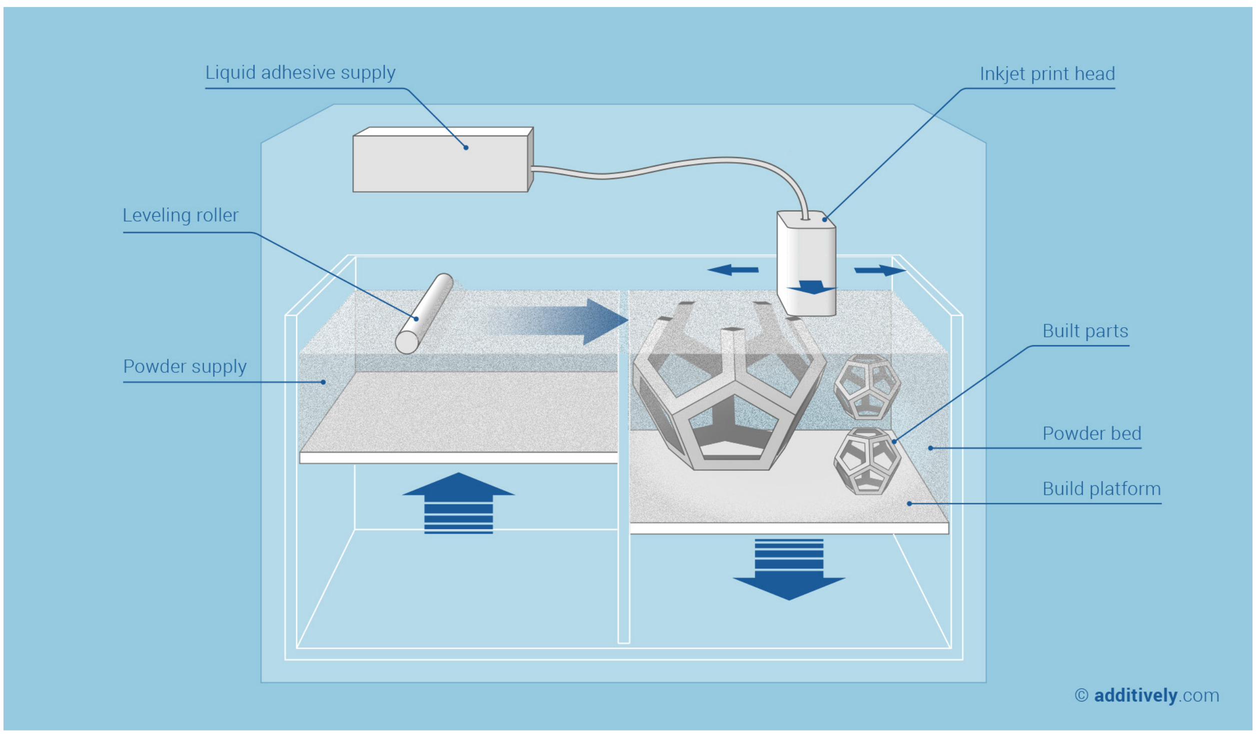


Figure 04.13 • Binder Jetting

bed), they are included when needed to ensure uniform cooling through increased thermal dissipation, reducing the potential of the end product to warp. See Figure 04.12. (Gebhardt, 2012. pg. 42-44)

Electron Beam Melting:

Similar process to Laser Sintering and Laser Melting except, the melting energy is provided by an electron beam. A completely sealed build chamber is required as it is necessary to operate in vacuum conditions. (Gebhardt, 2012. pg. 44)

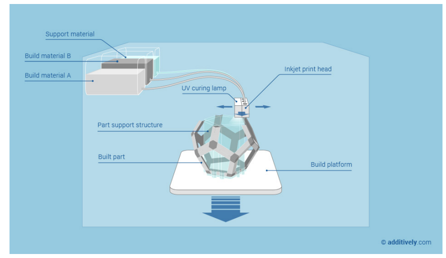


Figure 04.14 • Polymer Printing and Jetting

o4.2.3 Binder Jetting

> *binder jetting*, n - an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials. (ASTM, 2012. pg. 2)

Binder jetting utilizes powder particles bonded layer-by-layer through the selective application of a liquid binder onto a powder bed. Variations can allow the processing of metals, ceramics, and plastics. Many binder jet processes are a two-step process with a “green” state and a cured state. See Figure 04.13. (Gebhardt, 2012. pg. 47)

Z-Corporation – 3D printing:

An inkjet printer deposits a liquid binder onto a field of powder. As the powder is injected with a binder on a print bed, the bed lowers, is re-coated with a new layer of powder, and is ready to receive the next layer. Parts come out “green” and require infiltration with wax or epoxy resin to gain solidarity. Parts are not structurally capable and typically used for concept models. Binders can come in a range of colours allowing a completely coloured and textured part right from the build platform. The build chamber does not require heating or to be evacuated or filled with inert gas, allowing for easy adaption into an office workplace setting. (Gebhardt, 2012. pg. 48-49)

Prometal – 3D printing:

Binder Jet process adapted to treat metal and sand powder particles. When processing metal or metal-ceramic materials, the printer employs a heated bed to help part binding and dimensional stability. Alternately the technology can be used processing ceramic materials only and is known to produce complex curves from foundry sand. The ability to produce complex cores allows for this process to increase the productivity of sand casting for production, not just prototyping. (Gebhardt, 2012. pg. 50)

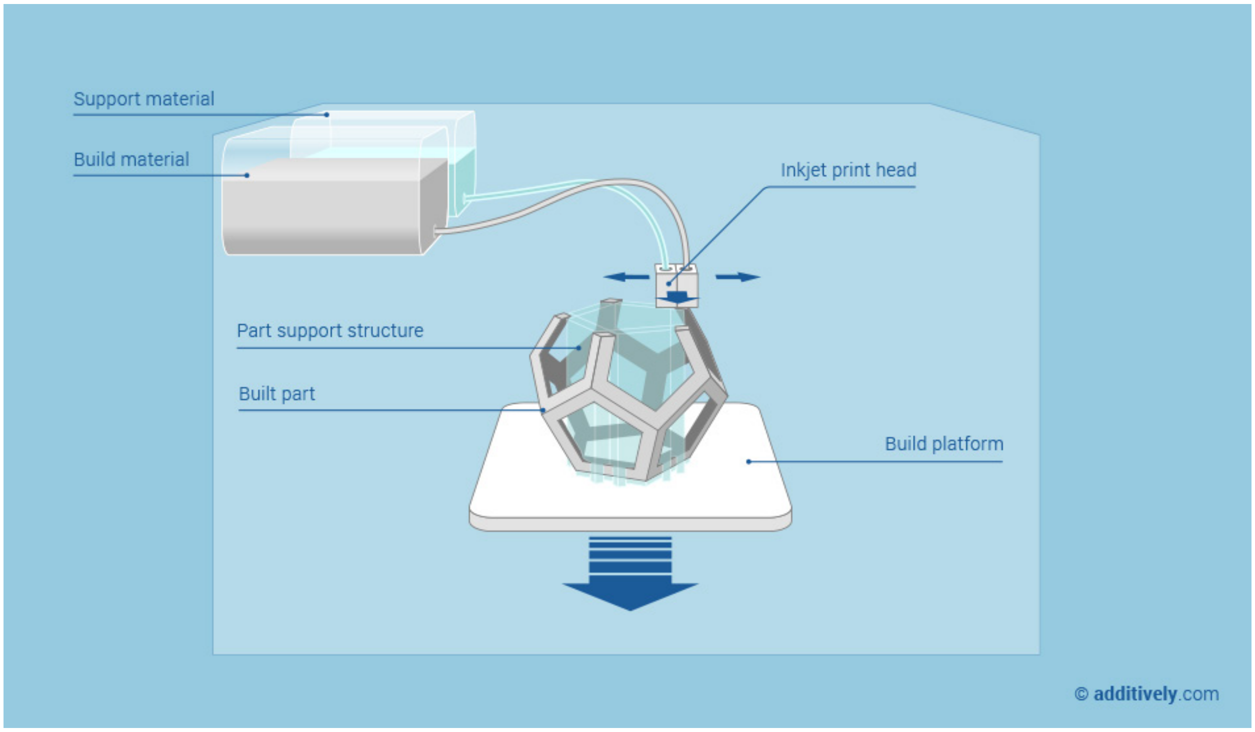


Figure 04.15 • Material Jetting

Voxeljet – 3D printing:

Following the binder jetting process these printers work with polymethyl methacrylate (PMMA) plastics using a solvent-based binder. This allows for straight production of plastic parts. The parts work as functional prototypes as well as lost moulds for precision casting due to the low amount of residual ash. (Gebhardt, 2012. pg. 51)

Polymer Printing and Jetting:

Using a process similar to a standard two-dimensional inkjet desktop printer, a curable resin material is deposited via print heads, hardening (curing) is provided simultaneously with UV lamps attached to the printhead manifold. Thickness is controlled through vertical movement of the build platform in the z-axis and is synchronous with material deposition thickness. Parts require support which can be printed with a second soluble material, simultaneously with the part, and removed with solvent bath in post-processing. This process can be automated and leaves no marks on the final object. Figure 04.14. (Gebhardt, 2012. pg. 37-38)

o4.2.4 Material Jetting

material jetting, n - an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. (ASTM, 2012. pg. 2)

Material jetting utilizes ink-jet printer heads upon a gantry moving in the x/y-axis. Upon application of polymer material upon a build platform, the object begins to take shape.

Multi Jet Modeling:

Material is deposited with ink-jet type printer heads onto the build platform. Multiple materials can be used, allowing for a separate material to build support allowing for easy removal by a solvent bath or similar. The printer head has a UV lamp which cures the part as it prints. See Figure 04.15. (https://www.3dsystems.com/resources/information-guides/multi-jet-printing/mjp)

Magnetohydrodynamics (MHD):

A magnetic field guides liquefied droplets of aluminum to the build plate. The deposited metal droplets fuse with previous layers as they build the part up. See Figure 04.16. (http://vadersystems.com/)

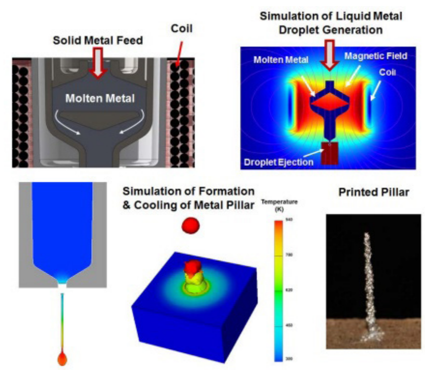


Figure 04.16 • Magnetohydrodynamics

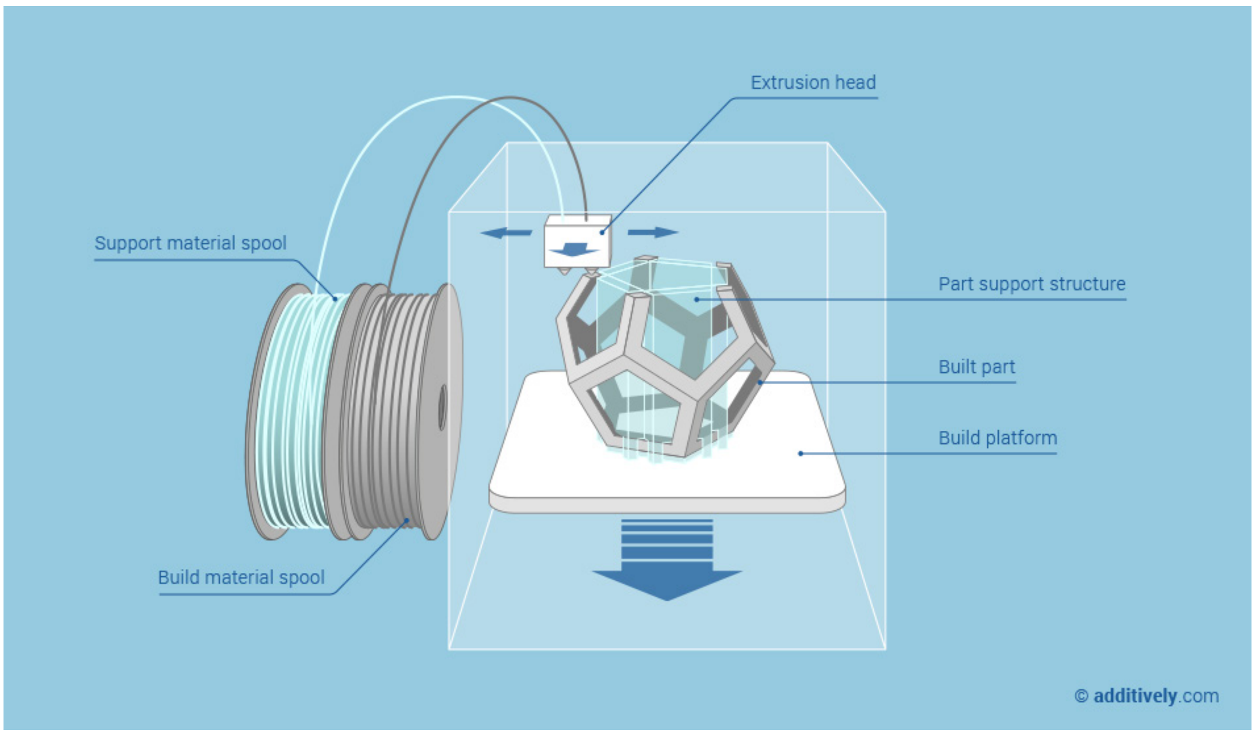


Figure 04.17 • Fused Layer (Deposition) Modeling

o4.2.5 Material Extrusion – Fused Layer Modeling (FLM)

material extrusion, n - an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice. (ASTM, 2012. pg. 2)

With Fused layer modelling an object is made through the continuous deposition of a semi-fluid material layer-by-layer in the desired contour. Objects can be made of thermoplastic material, and are typically processed with a support structure. FLM is the most commonly used form of 3D printing in the consumer market. See Figure 04.17. (Gebhardt, 2012. pg. 45)

Fused Deposition Modeling (FDM):

FDM consists of a heated build chamber equipped with an extrusion head moving in two-dimensions along the x/y-axis and a build platform travelling along the vertical z-axis. The heated head allows for the material to reach a semi-liquid state for extrusion, and deposit it on the x/y-plane following the desired contour path. The build platform lowers along the z-axis to allow for the application of the next layer. Materials are thermoplastics in the form of a filament (wire) of set diameter, controlling the volume to be deposited when a specific length is heated. The molten plastic is pressed through a nozzle of a specific diameter which controls the layer height. Multiple print heads (extruders) can be used for printing of support material or multicolour objects. (Gebhardt, 2012. pg. 45) This process goes by many names, including Plastic Jet Printing, Fused Filament Fabrication, and Fused Layer Modeling. See Figure 04.17.

Direct Ink Writing:

Following the procedures similar to FDM, liquid inks are deposited on a surface to produce the desired structure. The inks and parts operate with extreme precision, allowing for part dimensions in the scale of nm to um. A number of ink materials are available including nanoparticle-filled inks, fugitive organic ink, colloidal inks, polyelectrolyte inks, and sol-gel inks. Once deposited the inks will solidify through various processes such as evaporation, gelation, reactions, or thermal energy. This area is largely under research and development. (Gibson. Additive Manufacturing Technology. New York, Springer. 2010. pg 260) See Figure 04.19.

Robocasting:

process of ceramic in a slurry state by depositing it in the contour of desired s Utilizing the methodology of FLM, it incorporates other materials such as cement, plaster, clay or

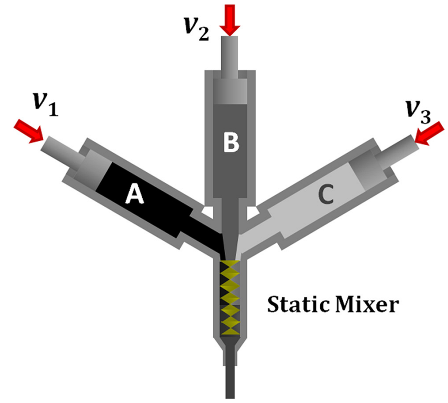


Figure 04.18 • Direct Ink Writing

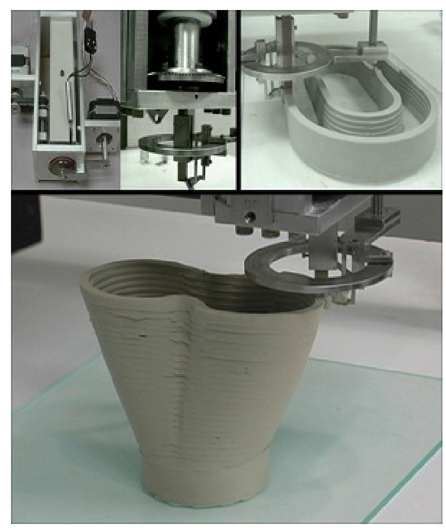


Figure 04.19 • Direct Ink Writing

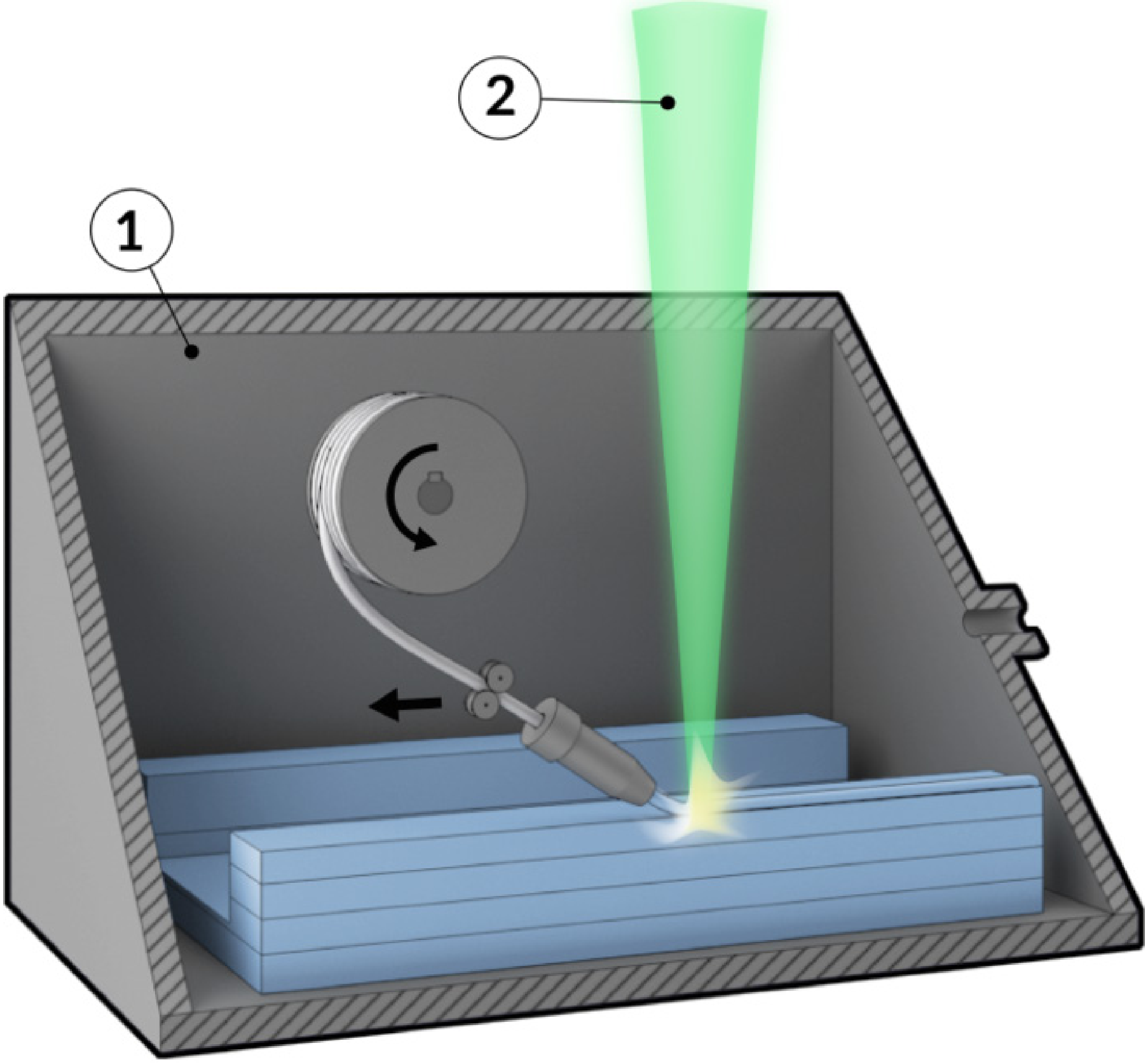


Figure 04.20 • Electron Beam Freeform Fabrication

Objects are built in a vacuum chamber [1], with melting energy supplied by an continuous electron beam [2] to transform a supply of wire [3] into the desired shape. (source: https://www.manufacturingguide.com/en/electron-beam-freeform-fabrication-ebf3) concrete. Operations include small-scale applications through to large-scale applications. A gantry travels along the x/y-axis with a material extruded which will process ceramic in a slurry state by depositing it in the contour of the desired shape. The gantry will travel up along the z-axis to then provide room for successive layers of material. Some variations include the utilization of 5-axis robotic machines in lieu of the typically used 3-axis machine (https://en.wikipedia.org/wiki/Robocasting)

o4.2.6 Direct Energy Deposition

directed energy deposition, n - an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. (ASTM, 2012. pg. 2)

As the material is progressively added it is instantaneously melted to the previous layer. This allows for material to be precisely added to the base stock. Materials include wire filaments and particles, with energy from electron beam or laser. (Gibson. Additive Manufacturing Technology. New York, Springer. 2010. pg 237)

Electron beam freeform fabrication:

With electron beam freeform fabrication, a beam of energy (electrons) is used to melt a supply of metal wire into the desired shape. This type of processing requires a vacuum chamber to control reactions between the metal and energy source. Complex 3D shapes require support material as they are constructed or the use of a multiaxis deposition head. See figure 04.20. (Gibson. Additive Manufacturing Technology. New York, Springer. 2010. pg 237)

Laser Engineered net shaping:

A version of Direct Energy Deposition utilizing steam(s) of particles jointly focused with a laser beam on the point of deposition. Particles are distributed around the circumference of the head by gravity or with pressurized gas. An inert gas shroud is often used to shield the melt pool from oxidization to control the material properties. This process produces objects which retain extreme dimensional tolerance to their digital counterpart. Allowing for freeform production of parts as well as the ability to repair existing parts to their former quality. See figure 04.21. (Mudge, Ward. Lens advances manufacturing and repair. Welding Journal. 2007. pg 44-45)

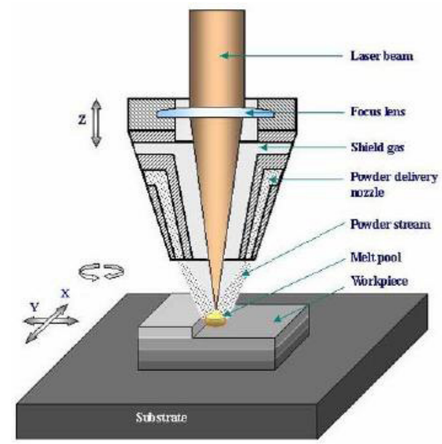


Figure 04.21 • Laser Energy Net Shaping

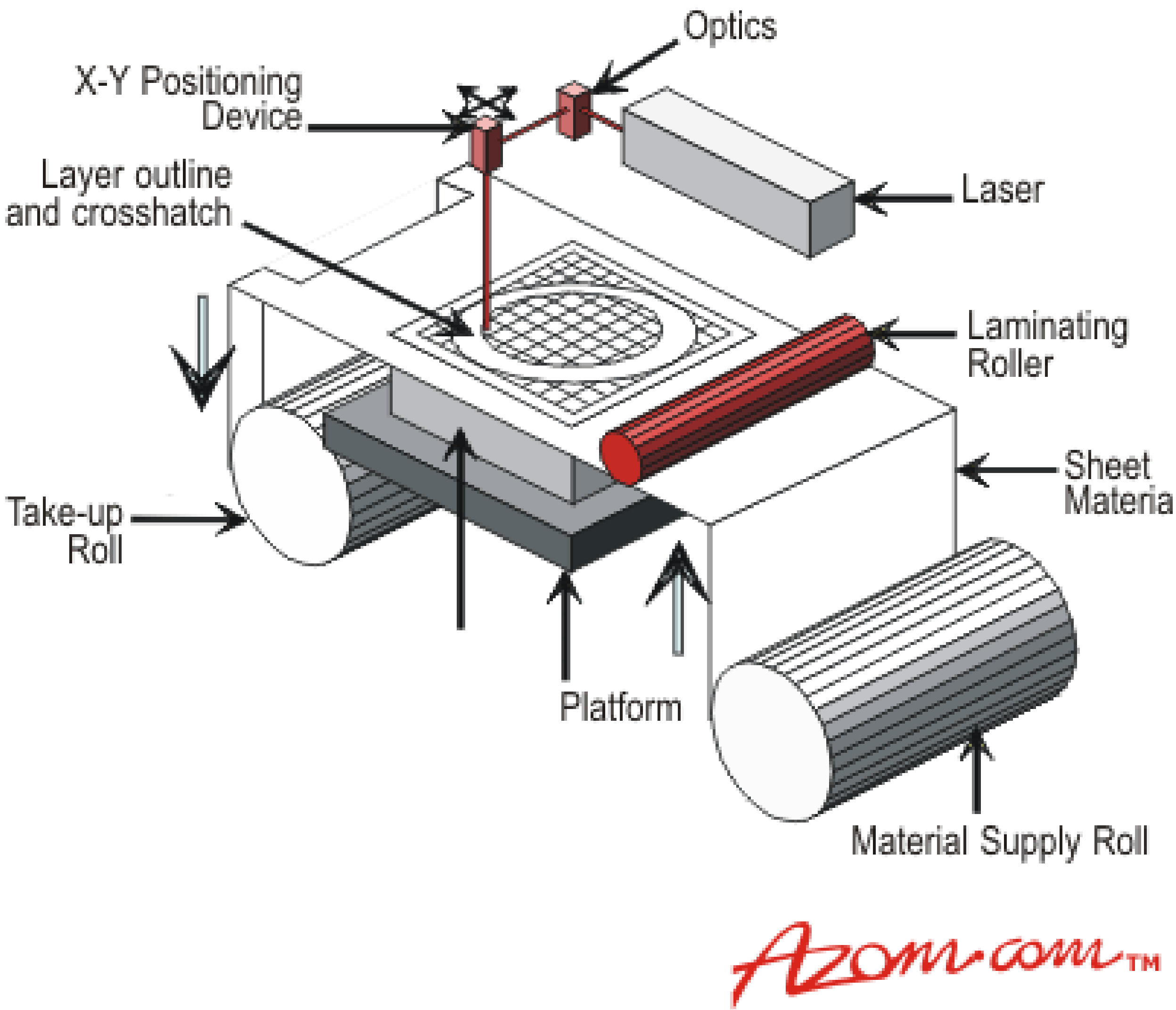


Figure 04.22 • Laminated Object Manufacturing

o4.2.7 Sheet Lamination - Layer Laminate Manufacturing (LLM)

sheet lamination, n - a additive manufacturing process in which sheets of material are bonded to form an object. (ASTM, 2012. pg. 2)

Using preformed foils or sheets of even layer thickness contours are cut out according to the sliced 3d model and bonded to the top of the previous layer. The foils or sheets can be made of paper, plastic, metal or ceramic, and cut with a laser, a knife or milling machine. See Figure 04.22. (Gebhardt, 2012. pg. 52)

Laminated Object Manufacturing (LOM):

Paper is placed on a build table from a roll, a laser cuts out the desired contour, and the next layer is positioned and adhered to the previous sheet. Excess material is diced for easy removal after the part is complete. After removal, the part and excess material varnishing prevents delamination of the layers. (Gebhardt, 2012. pg. 52)

SDL - Paper Lamination:

Similar to LOM manufacturing but utilizes colour inkjet printing and a razor blade to cut the desired contour with full colour. Full-colour parts can be produced with this method. See Figure 04.23. (Gebhardt, 2012. pg. 54)

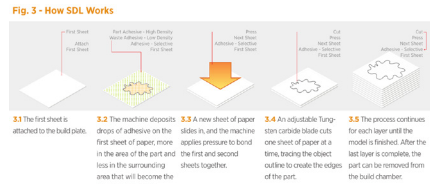


Figure 04.23 • SDL

Plastic Laminate Printers:

Similar process but utilizes solid plastic. See Figure 04.24. (Gebhardt, 2012. pg. 54)

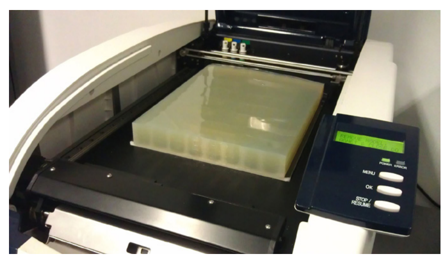


Figure 04.24 • Solido

LLM for metal:

Sheets are milled/cut and joined by either welding, soldering, or mechanically with bolts. These are not typical AM processes but additive and layer oriented. (Gebhardt, 2012. pg. 55)

Ultrasonic Consolidation:

Uses a traditional milling machine with an integrated ultrasonic welding device that joins thin aluminum strips on top of a semi-finished part. After each layer is applied, the piece is milled, and a new layer added. Various metallic types can be used in this process creating dense metallic parts. Multiple materials may be joined in this process to produce unique material properties. (Gebhardt, 2012. pg. 56)

Figure 04.25 • Large Scale Examples
(a) D-Shape (b) DUS Architecture (c) WASP (d) Winsun

o4.3 Advancements/Developments

Additive Manufacturing is continuously under development in today's industry. With size limitations being conquered and new material adaption, the possibilities are ever changing. Adjustments to size limitations affect the application of AM to many industries, Architecture included. Material limitations both effect speed of current production, but also material properties such as strength, durability, and cost.

o4.3.1 Large Scale Applications

Many of these processes have been adopted for large-scale applications. Large-scale requires a volume of print that is large enough to be occupied. The smallest of the following case studies has a print area around 2m x 2m x 6m or larger.

D-Shape:

A large-scale variation of the binder jet process. The printer uses a polymer binder applied to natural stone powder to create a solid stone-like material. The printer established the earliest architectural structures at the scale of a person with a printing area of at least 6mx6mx6m. They went on to explore the benefits of using the technology to rehabilitate the ocean sea-bottom. [See Figure o4.25 (a)]

Kamermaker:

A large-scale variation of fused deposition modelling processes. The printer existing within a large shipping container stood on end with a print area is 2mx2mx8m and uses recycled plastic. The architects prototype various components of a house and have created a temporary house. [See Figure o4.25 (b)]

Wasp:

An ink writing printer which focused on extruding clay. The printer uses a lightweight steel frame to allow for a massive print area. Natural materials such as straw are included to help reinforce the clay layers. [See Figure o4.25 (c)]

WinSun:

An ink writing printer which focused on extruding a patented concrete material. The printer utilizes a massive print area to produce prefabricated architectural components. These are packaged and shipped to site for assembly on-site. They have successfully implemented projects in China, Taiwan, and Dubai. [See Figure o4.25 (d)]

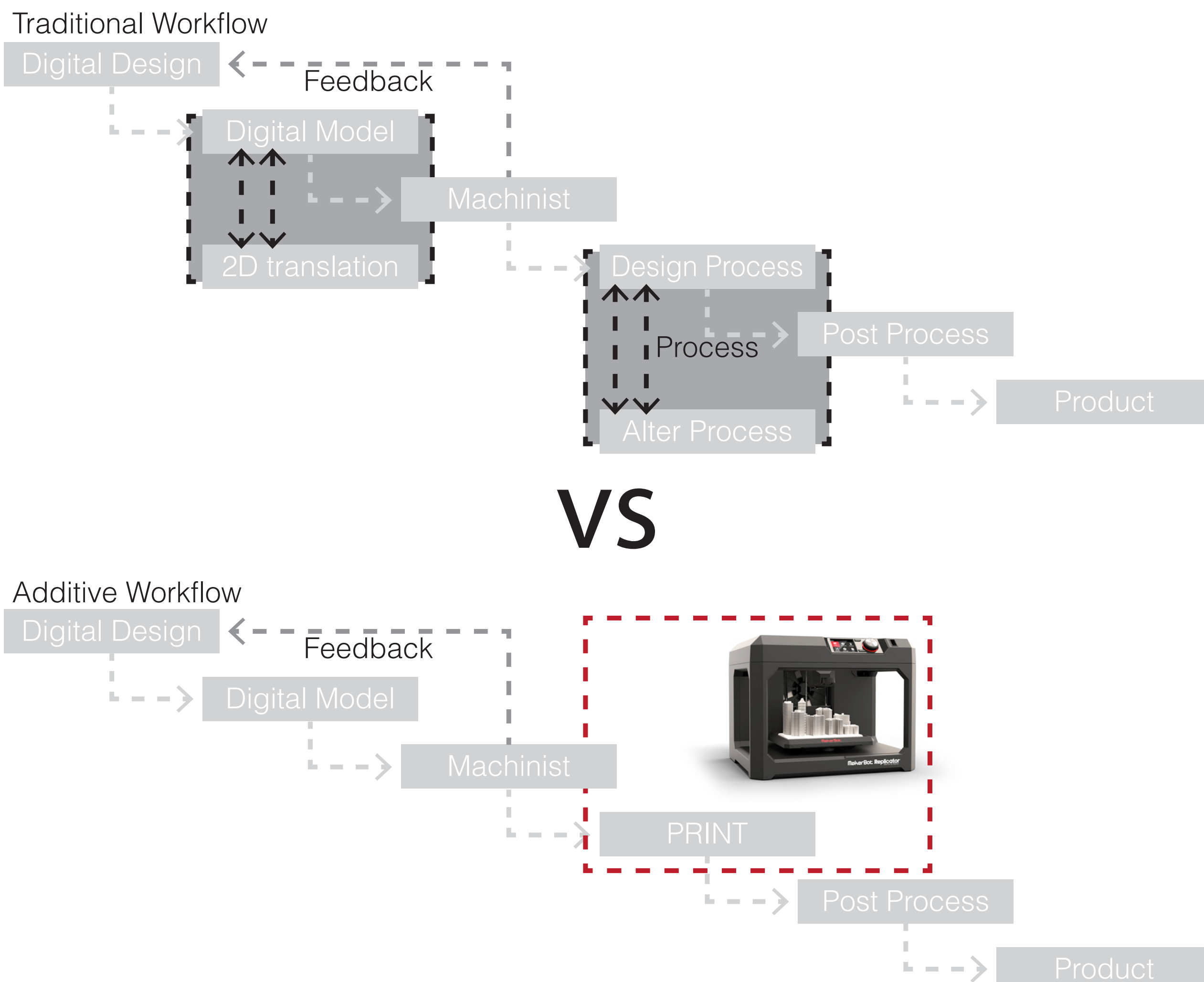


Figure 04.26 • Workflow diagram

o4.4 Advantage/Challenges

"Each time the architectural production technology changes, then architecture changes as well" Conrad Wachsmann (Digital Manufacturing in design and architecture – Asterios Agkathidis) The advent of Additive manufacturing allows us to review how we produce items as it puts forth certain freedoms and limitations. Two things which are strikingly different from traditional manufacturing are: its ability to be a process of universal production and the ability to utilize the computational power of a computer (similar to the roboticization of other industries.) These differences bring with it the potential to integrate production directly into the design workflow. Significant advantages of 3D printing are: the ability to create objects with immense complexity, its wide range of material processes developed, and the workflow of physical object creation from start to finish.

o4.4.1 Formal complexity

Many processes can handle formal complexity, but many come with constraints which set 3D Printing apart. For example, a product made with injection moulding would require knowledge of a materials workability, the ability to turn the material semi-solid, a prebuilt mould of the desired shape, knowledge of the materials expected shrinkage, and knowledge that the material in the desired shape will retain the desired physical properties.

The production of the negative is one of the physically demanding elements and would need to be produced first to create the positive (the final product). The cost of producing moulds is then incorporated into the cost of every product produced thereafter, lending to the methodology that with more products produced the cheaper the mould is per object. With a single product, the cost for the mould plays a significant role in the cost fo the final product but with the production of thousands of products the cost per mould is relatively smaller.

Material limits affect the ability of a material able to achieve a form in two manners, through the physical properties and how they can be shaped. Physical properties such as strength, hardness and bending require different processes to achieve similar shapes. Plastic may bend to any shape, but if incorrectly done doesn't retain its strength, metal can be bent in many ways, but it bent to much becomes brittle and breaks. Bending Limits require consideration when sheets are being bent and pressed. Shear strength effects the ability to punch holes or objects out of

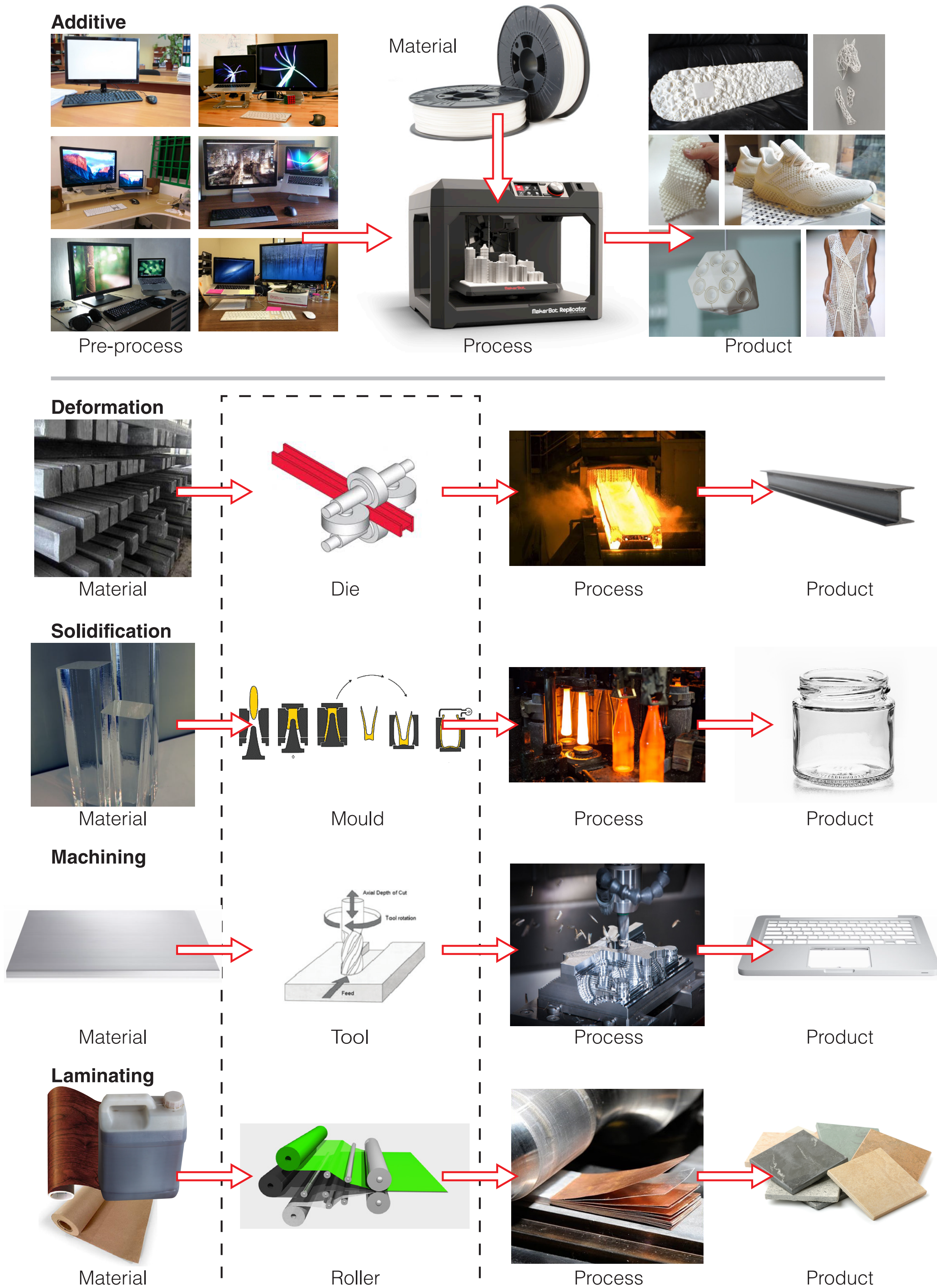


Figure 04.27 • Comparison of process flow

sheets. Support for semisolid materials is required in the moulding of materials and dies for the forming of others.

With various 3DP techniques, objects are supported in a bed of loose material or with supports both of which can be removed at a later stage. Allowing free-form mechanical creation of an object without “effort” or “skill.” A new product does not require tweaking, altering or creating a new process to make it. This has been coined as a platform capable of Universal production.

o4.4.2 Material Use

Three Dimensional Printing can use a wide variety of materials. The most considerable advantage of its use of material is that it can disregard material processes within the production of an object. While making an object, one does not need to rely on the way a material will react (e.g. ductility for extruding) as forming because most processes use a base of powdered, liquid, or spooled materials. In regards to individual 3D printing - the processes are highly differentiated per materials. This differs from other processes in that -3dP metal does not utilize its ductility (extruding), malleability (hammering), molten state (as liquid injection) but does utilize its ability to conduct heat and melt at extreme temperatures. Ceramics are printed as resin onto a powder which gets solidified through heat. Concretes are made less viscous so that they maintain shape when poured. Plastics are heated to a semi-liquid state and cooled in place. This freedom of specific materials constraints allows one to by-pass specific material knowledge in order to attain the final product.

This has two potential effects: the ability to make objects with far superior performance with the same materials, or the ability to make one-off objects in a much more complex geometric form. 3DP restricts materials to that which can be printed. For some materials, this is a performance reduction. For others, it can take full advantage of material properties.

An example of new objects created with The first could be equated to Boeing’s new turbo injector for their plane engines. Due to increased complexity, it can only be 3dP – but it brings improved engine performance and high-quality build. The second could be seen as the typical desktop consumer use – a one-off item which if mass produced would be done so much better with injection moulding – trinkets etc. also due to availability it is easier for the average person not specialized training to access a 3dp than injection moulding fabricator. (injection moulding dies are

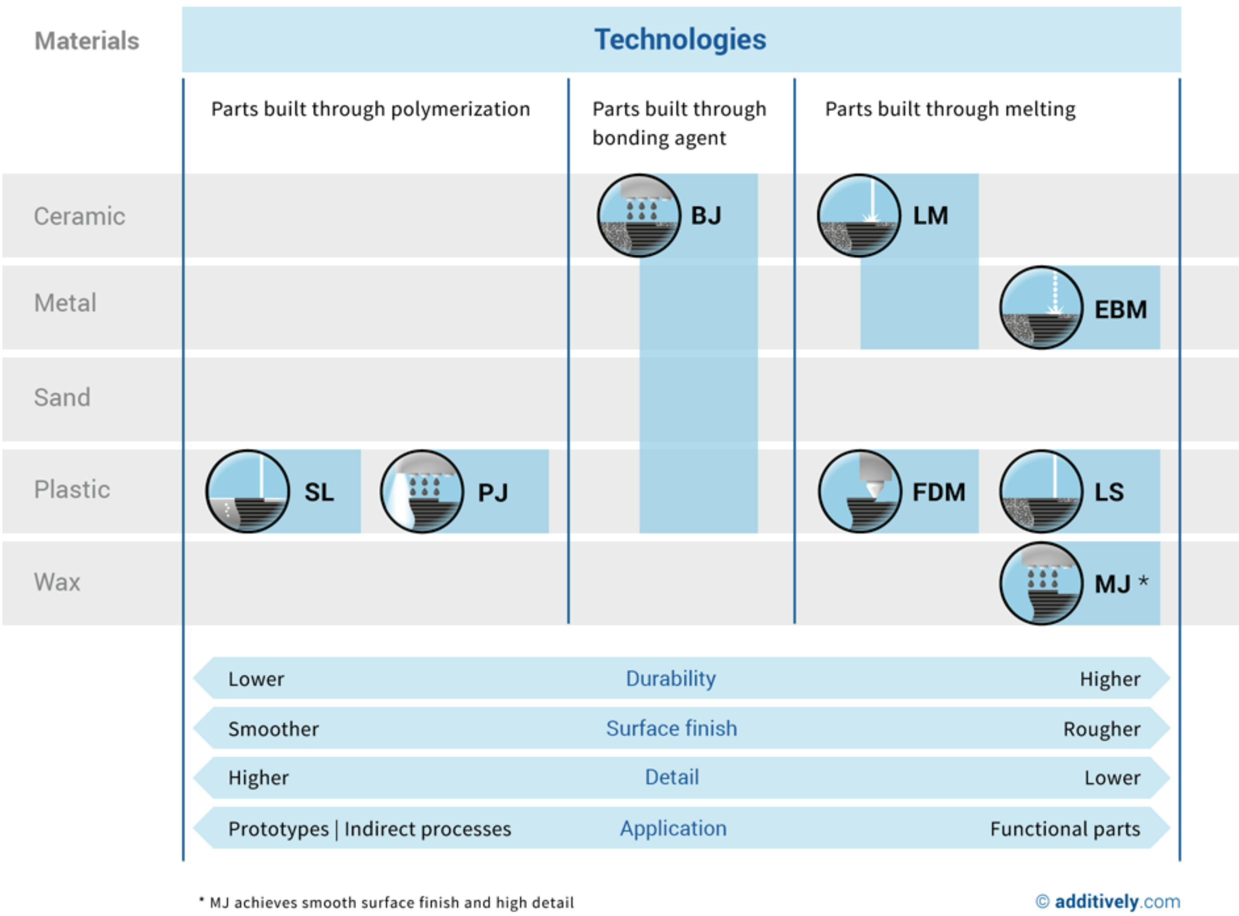


Figure 04.28 • Comparison of AM Processes

expensive, e.g. $5-50k and hence can only be justified for high production runs.)

3DP has imprinted itself on the general population as the new tool of creation. Not just in the manufacturing of parts that are impossible to make, but also as an on delivery method of production. Lending itself to the efficient creation of one-off's and highly unique, dynamic, complex forms, it has also broken into industrial use for production and rapid prototypes - granting the ability for any 3D form to quickly and efficiently be converted from a series of electronic bits into a physical form.

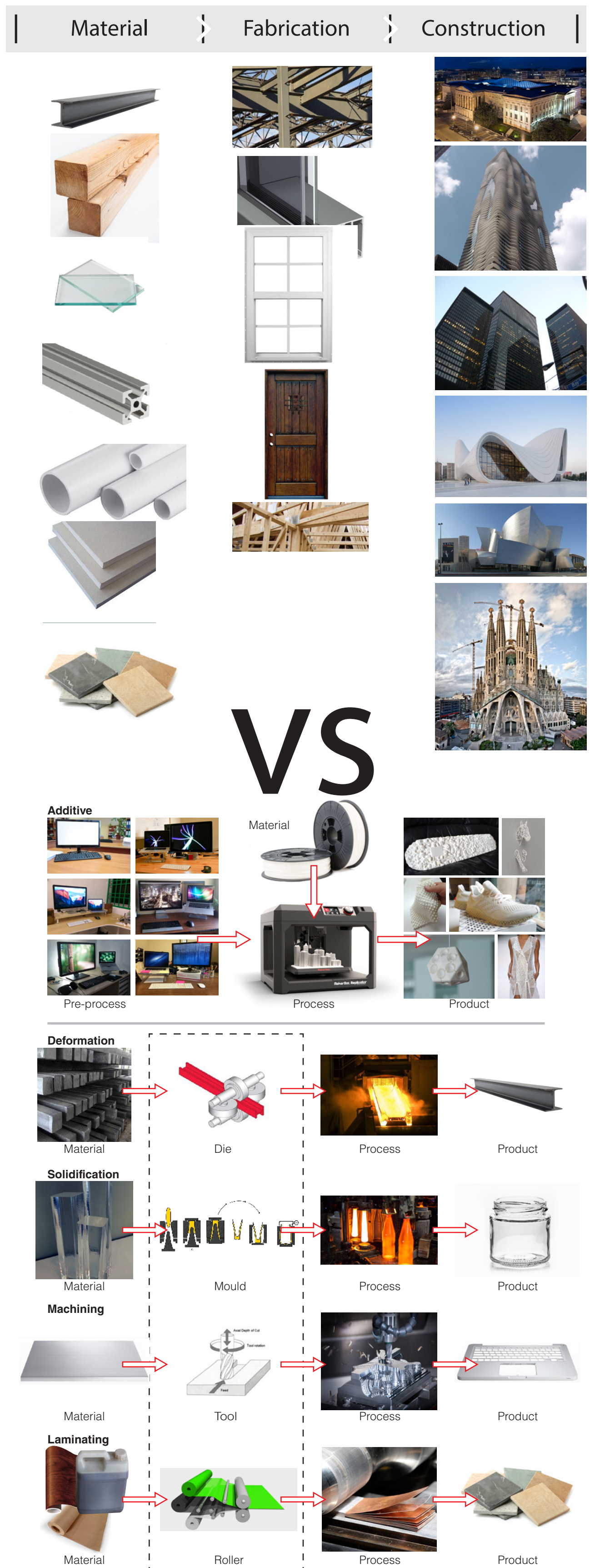
Machines have taken various forms to enable the process of 3D printing – from free-standing robotic-arms to large structures crafted from heavy steel – each attempts to communicate a straightforward thing, a location in space. With fused deposition modelling the form the machine takes on plays a direct limit to build area and volume, formal limitations derive from the structural material properties. A plethora of adaptation is possible; material can be deposited in a dense solid, as geometric patterns, or in thin, elegant shapes. This possibility of a gradient in the system opens opportunities to create a wall that ranges from strong and thick to thin and translucent. With the utilization of 3D printing, we gain control of creating a gradient through the form and control the systems which occupy the poché..

o4.4.3 Product Design

With additive manufacturing, the design of a product has the initial potential to be freed from all previous constraints. [Un]Fortunatly the designers' mind come imprinted with a whole series of biases which inform the design of an object. Designers may initially lend the formation of a 3D-object with the production of available sheets of steel, or the ability to be cast. Whiles these traits are a conditional and trained reaction to the working mind, additive manufacturing has yet to become broad-stream enough to free many designers of these biased constraints. The apparent benefit is that young designers may find it easier to flow into the mindset of production geared around additive maturation. Exhibited in the ARUP's research and development for the printed node, Galjaard commented that focus would be given to later iterations to thoroughly remove the bias of construction from the design of the 2nd generation components, with the goal of allowing the materiality and process performance to their highest potential.

Making Architecture

05


Material
Fabrication
Construction
VS
Additive
Material
Pre-process
Process
Product
Deformation
Material
Die
Process
Product
Solidification
Material
Mould
Process
Product
Machining
Material
Tool
Process
Product
Laminating
Material
Roller
Process
Product

o5: Making Architecture

o5.1 Manufacturing Architecture

As identified in the first section of this thesis, architecture is built from the combination and arrangement of many smaller individual pieces. These pieces range in size and material, with many possible solutions to solve a problem. Choices are influenced by factors not necessarily based on performance but aesthetics, culture, and personal ego. Through the years, movements have focused on optimizing construction to allow for its production to flow in a manner similar to that of manufacturing. As these new technologies develop, they slowly find their way into architecture. Ideals were borrowed to reduce architecture to a simple assembly of prefabricated parts; now with additive manufacturing, there is a new technology looking for its ability to fit and transform how we produce architecture. The case studies show the possibility of producing complex forms which are digitally created, in a seamless manner from the digital file. Production of technically complex forms no longer correlates with skilled craftsmen or increased labour, as the part has the potential to be produced as quickly as a geometrically simple part - through a machine, with the push of a button.

The second section walked through the different classification of materials, how they are chosen, and what performance criteria they best perform. Based upon the material chosen there are typically a number of production choices that are available to shape it. Secondly, the expected end performance of an object can also assist in the manufacturing choice. Materials in architecture are chosen specifically for the physical performance they are expected to withstand. Materials used on the outside of a building must resist the impacts of nature while also achieving an aesthetic value.

The formal complexity of an object typically limits the material choice as well as the effective shaping process. Shaping operations can take large volumes and remove material, flat sheets or semi-liquids and force a form, or use the addition of materials and binders to create. The goal of manufacturing is to transform raw material into a processed part through the addition of machinery, tooling, energy, and labour. The ability to create many objects within a set tolerance allows for the easy assembly of these items later. A significant difference between manufacturing and architecture is the range of tolerances acceptable. Within manufacturing, the tolerance of any given product is typically sub-millimetre measurements. However, in architecture, the tolerance of adjacent components is typically set in the range of 5-15mm.

The third section highlights the production of objects. The production of one item varies drastically with the production of many items. From the manual labour required for the treatment and flow of parts coming together to form a final object, to the way definitive decisions can be delayed to allow for the appearance of choice. Architecture, as a building, is generally produced as a high variety/low quantity item, every building being slightly

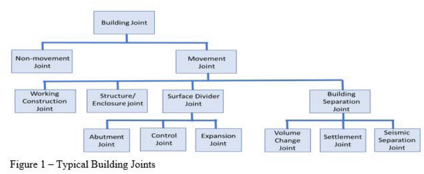


Figure 05.1 • Building Joints

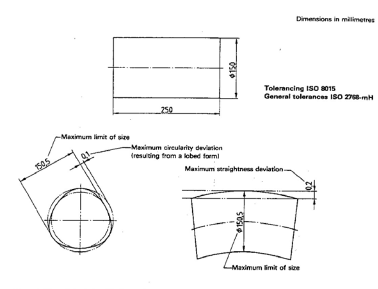


Figure 05.2 • Tolerances

Figure 05.3 • Comparison of Construction to Manufacturing

Figure 05.4 • Use of 3D Printing in Architectural Design

to remarkably different. Multiple factors contribute to this. The industry is comprised of many stakeholders contributing to a project thus creating the need for standardized methodologies to be established to maintain a level of quality. Similar to the progress of standardization undertaken within manufacturing, from the industrial revolution to the present day. As these technologies transform the way we make items, there are possibilities to affect the production of architecture.

Section four provided an in-depth examination of Additive Manufacturing. The technology is relatively old, and as it has been around since the early 1980s, various methodologies have emerged managing to additively produce objects with materials from each classification. Challenges of Additive Manufacturing pertain to material consistency as well as the dimensional accuracy of objects. As with other manufacturing processes AM will be considered a primary shaping process, requiring finish operations to follow. Potentials of AM within manufacturing concentrate on the ability to reduce labour and material used for the production of parts; demonstrated through its ability to by-pass steps required within other processes (such as moulds) or place material exactly where required (as with ARUP's nodes). The union between additive manufacturing allows for a carryover of these potentials to meet challenges within architecture. This section provides an exploration of the potentials of the production of architectural components. Followed by a summary of the remaining challenges. The section concludes with a look to future potentials of fully integrated production..

o5.2 3D printing and Architecture: Potential

There is much potential using 3D printing for the production of Architecture, with greatest gains within the areas of complex forms, digital design, and the creation of unique components. 3D printing creates advantages for architecture in its ability to create complex forms, reduce parts, integrate easily into digital workflows, and allow fine grain details.

3D printing has uniquely allowed for the ability of products to break geometric constraints far easier than other forms of manufacturing. Formative processes, as a rule, require malleable volumes of materials to be placed into or onto a mould. Formative endeavours require the production of a mould, an endeavour of time and expense. Subtractive processes are often wasteful due to the removal of excess material (though potentially recyclable). Complex forms require the implementation of an additional axis of articulation to adequately shape. Depending on the machine, the processes can be adaptable to new forms, but many machines will be fixed to the production of a particular form, and changes require time and expertise.

The processes of 3D printing can efficiently produce unique or complex forms continuously without changes to the to the machine or requiring new physical implements such as a mould. 3D printing places material only where it is instructed, reducing any waste of excess material, even when printed in a bed of powder, where excess material can be used in future

Figure 05.5 • Guggenheim Bilbao - Gehry: Complexity

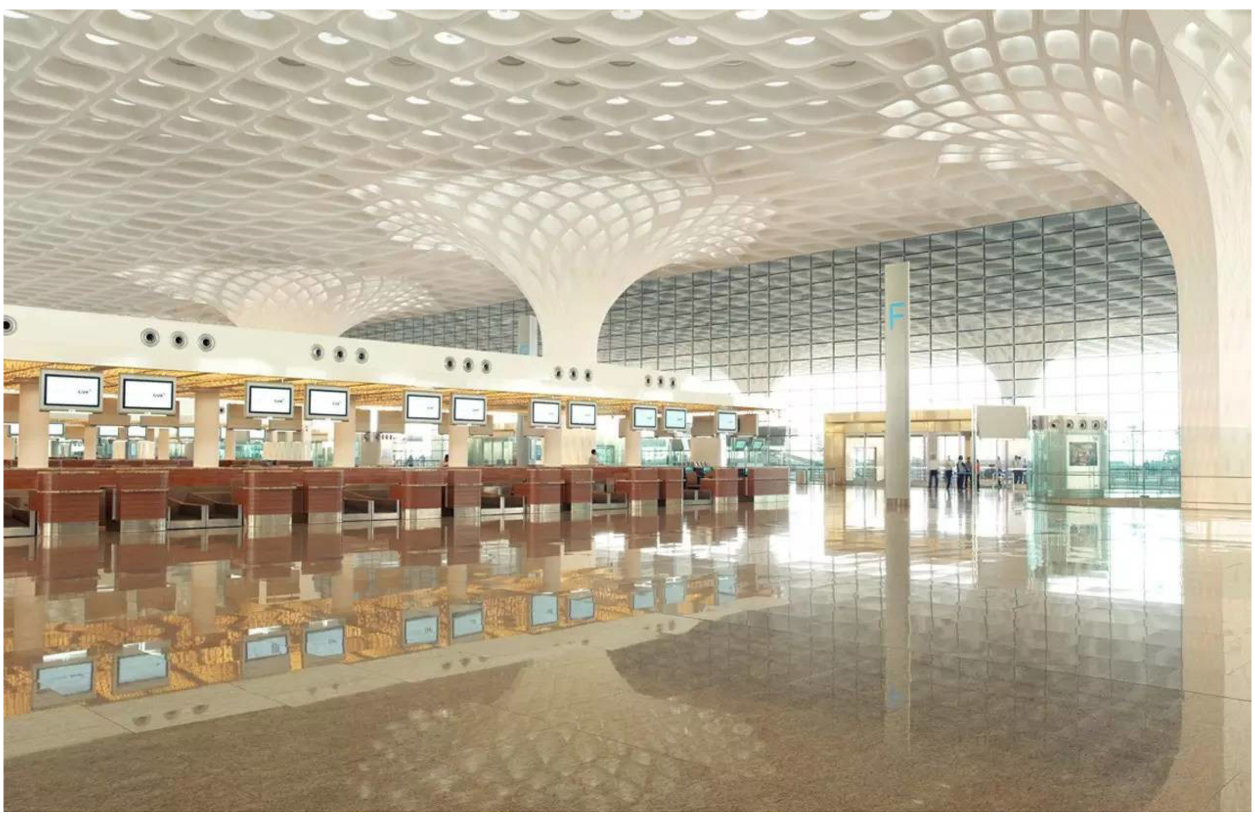


Figure 05.6 • International Airport - SOM: Complexity

prints. 3D printing incrementally builds up in layers which allows the production of complex forms without the machine constraining the physical geometry of the object.

Currently, complex geometry is achieved by subdividing the form into producible parts and joining them post-process. Resulting in simultaneous aspects of one component moving forward at the same time, then assembled later, potentially using more labour in the production of a part.

With the ability to produce parts with less limit due to geometric constraints, complex parts can be simplified from many pieces to one piece. Avoiding logistic issues of part handling and production. With the incremental production of parts, architectural pieces are freed of the aesthetic and formal constraints of traditional manufacturing. Meaning articulation of a surface will not substantially hinder a part's production. Fine articulation within a mould could make the part impossible to release, or not transfer adequately from the mould to the final part. 3D printers can easily print to a thickness of 100 microns, if not finer on specialty machines, and can bring to life the most minute of details. After completion of a part, the next piece can be entirely unique from the previous one without any tinkering or physical changes to the machine. The next set of instructions can be sent and executed immediately. With nesting functions, the volume of printing beds can be filled with multiple parts, so unique pieces come off the line at the exact same time. With architecture in the digital age, many projects are exploring geometric conditions resulting in many unique or sequentially produced parts, where each nodal condition is unique. Manufacturing constraints often hinder these.

A process such as 3D printing simplifies the unnecessary steps of producing 2D instructions (plans, elevations, sections) and allows the part to transfer from designer to fabricator in an entirely digital environment. A secondary advantage of this is that production times could be dramatically sped up on complex parts, as one could potentially begin printing almost immediately from digital representation.

With the loss of craftsmen and the specialization and skill of labourers in the past, the detail of ornamentation present in older projects is difficult to match today. Digital processes have gotten to the point where existing detail can be digitally scanned and archived. However, digital replicas or replacements can be produced to match the existing form or altered more easily to suit new conditions, providing opportunities for renovation, or imitation of classical and existing ornamentation produced by contemporary methods. As with the construction of Sagrada Familia in Barcelona, a cathedral of very complex geometries. Individual blocks were prototyped with 3D prints before being translated into a crafted piece. 3D printing allowed for the production of pieces at a faster rate, shortening the construction period of this elaborate monument. 3D printing even exceeds traditionally skilled craftsmen by allowing for new surficial explorations. The articulation of surfaces can become new significant elements to design when the designer is involved with production choices. The range of flamed, blasted, smooth, or

	TAB LENGTH (OD)	BEND ANGLE	BEND DIRECTION
A	2.25"	89.86°	UP
B	2.25"	89.98°	UP
C	2.25"	90.094°	UP
D	2.25"	92.12°	UP
E	2.25"	90.267°	UP
F	2.25"	92.487°	UP
G	–	132.685°	UP
H	–	104.918°	UP

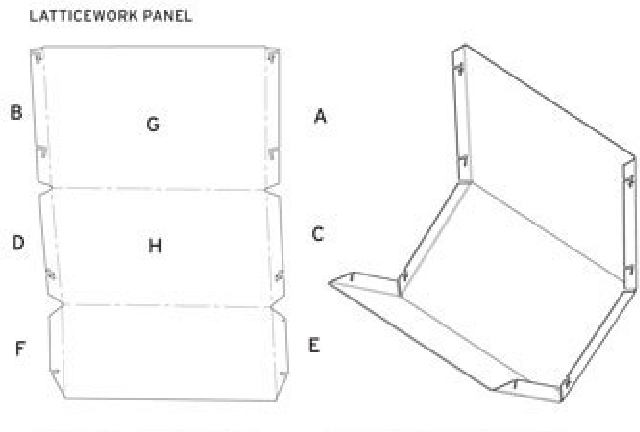


Figure 05.7 • Barclays Center - SHoP: Mass Customization

Figure 05.8 • Salginatobel Bridge: Material Limits

polished finishes can be pushed to new possibilities. It can be specifically patterned or treated, or even produced with the intent of being part of a more substantial creation within a space.

Architectural construction can also utilize digital design tools to control the flow of information between all parties involved in the process of building. This digital workflow is driven by the promise of producing design documentation quicker and to a fuller extent than previous methods. This digital environment is becoming increasingly "smarter" to allow for direct control over the physical implementation, such as automatic generation of schedules for doors, windows, finishes, etc. or more easily quantifiable kit of parts for construction. With this integrated nature, links between the digital and physical world are getting stronger. The workflow between programs is becoming easier to navigate, and digital production is a natural extension of this process. Digital elements can be defined in one program, refined (detailed) for production in another, and sent to the fabricator directly. The removal of translating design intent between mediums has the potential to shortcut extraneous labour involved in the communication of a part.

Digital design has also led to the creation of architectural styles that push the boundaries of what is possible. Moving away from an era which simplifies design components for buildability to one which favours complexity of form through surfaces, formal constraints are being quickly surpassed, through those of parametric design algorithms as seen in Gehry's work (see Figure 5.5). These designs rely upon unique parts to create complex forms. With many unique parts, traditional production struggles to keep fabrication cost low due to the skilled labour involved to produce each part to the desired specifications. Additionally, reliance on labour-based manufacturing can often force parts to be reworked and repeatedly prototyped to achieve digital tolerances.

Digital workflows have also helped to alleviate the overwhelming volume of managing multitudes of unique objects on site, such as the construction of Barclays Centre in Brooklyn that used a custom app to manage façade elements. The ability to handle and organize a multitude of unique parts is a pre-requisite to implementing a process which if allowed would only produce unique parts, as installers need to be able to place units together in the correct order on site.

As digital design combines with 3D printing manufacturing to more easily create unique elements, this may produce a wave of structure and façade explorations which are unprecedented, in much the same way that the exploration of reinforced concrete had on architecture in the twentieth century. There is the potential to be more freedom in the production of parts, and a system in place which will allow these unique parts to be installed within an ordered system.

Additionally, this freedom may not result in the reinvention of the lost art of craft. Elements both historical, and yet imagined which are complicated to build now, or instead elements which we have distilled down to a simple, minimal element that is difficult to manufacture, could be reborn with life, elaborate ornamentation,

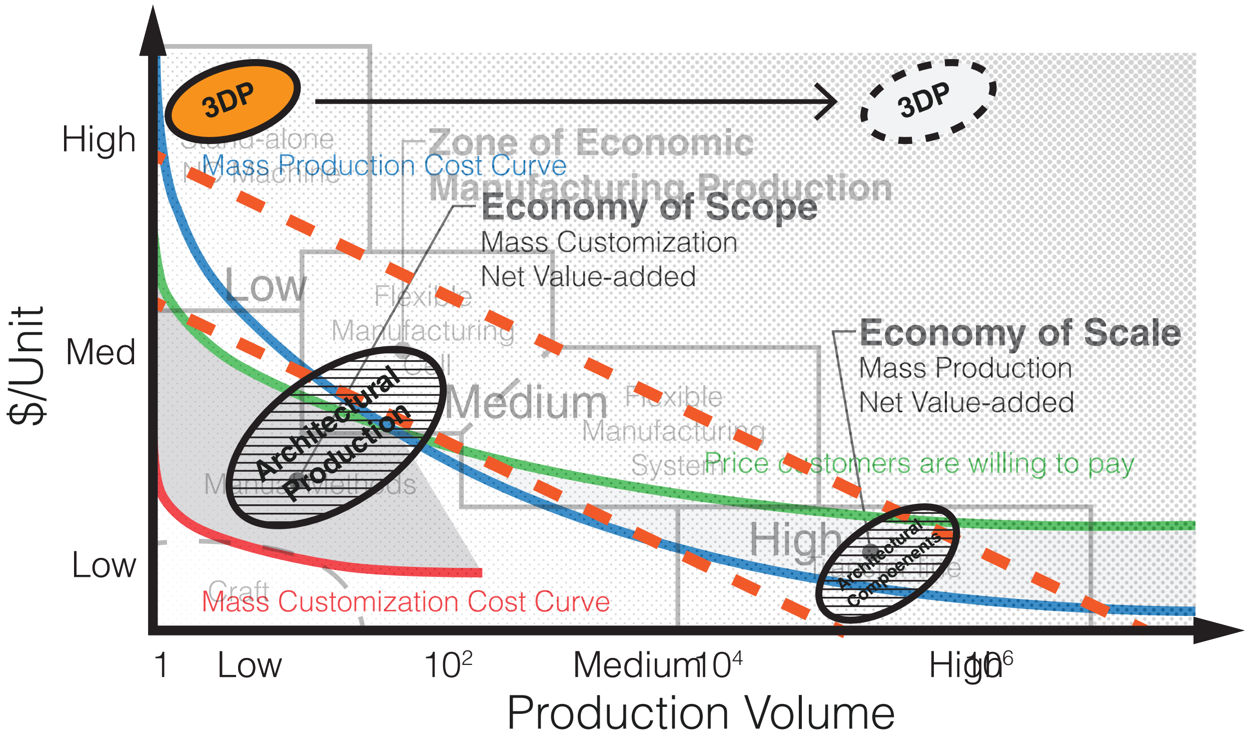


Figure 05.9 • Overlay of Production Scales and 3DP

and of any scale. This increased detail may find its place as a recollection of lost style, or it can adapt and push the envelope into the next style of architecture.

Beyond overall formal and process advantages, 3D printing has the potential with Architecture to find its niche in complex structural connections, façade elements, or other surface treatments, small individualized hardware items, transitions, coves, bricks or other modularized elements, and even panelized systems. These components could be uniquely designed printed and installed and be implemented on projects in tandem with traditional components. Items could be one-hundred percent unique or iterative from project to project, and reprints of pieces are possible where a client wants an exact copy of an existing piece or previous 3D printing element.

o5.3 Challenges for 3D Printing in Architecture

Architectural components are typically produced in large quantities. Though individual projects differ quite a lot, the market is significant, and the same component can be sold across a vast and often Global market base. Within this market, some components are produced effectively with existing methods. For example, the manufacturing of bricks, hot rolled steel, and extruded aluminum need not be replaced by 3D printing as it would not have the ability to produce the same product at the same volume. This logic will also apply to many existing architectural components that would not benefit from the technology or efficiency. Tall, straight, glass-covered buildings made out of rolled steel, extruded aluminum, and floated glass do not need 3D printing as they rely on regularized parts and connections which can be produced in volume, a feat not suited to the strengths of 3D printing.

Batch and large volume production absorb the costs of standardized testing, material grading, design time, and machine time within their large output capacity. Mass-produced items can have one of the thousand identical products tested, certifying the rest of the line. 3D printed components that are required to conform to a quality or safety standard would need to be assessed and passed individually. Design time for a brick, hot rolled steel section, an extruded aluminum channel, or a poured precast panel is incorporated into the batch of products. With custom production, design time is a large part of the final item, which, though assisted by the direct-translation form digital to fabrication may still be less efficient. The machine time or time that a product is within the manufacturing process is evident with custom pieces. Off the shelf or quick-ship items have allowed architects and customers to become used to and expect short lead times. Custom solutions incorporated late can have the impact of longer lead times and delay or extend construction times. 3D printing can be produced at any time, in any place, but it can only be produced as demanded. 3D printing is appropriate at the intersection of variety and unique needs supporting low to medium production quantities.

The physical performance of 3D printing is the final hurdle

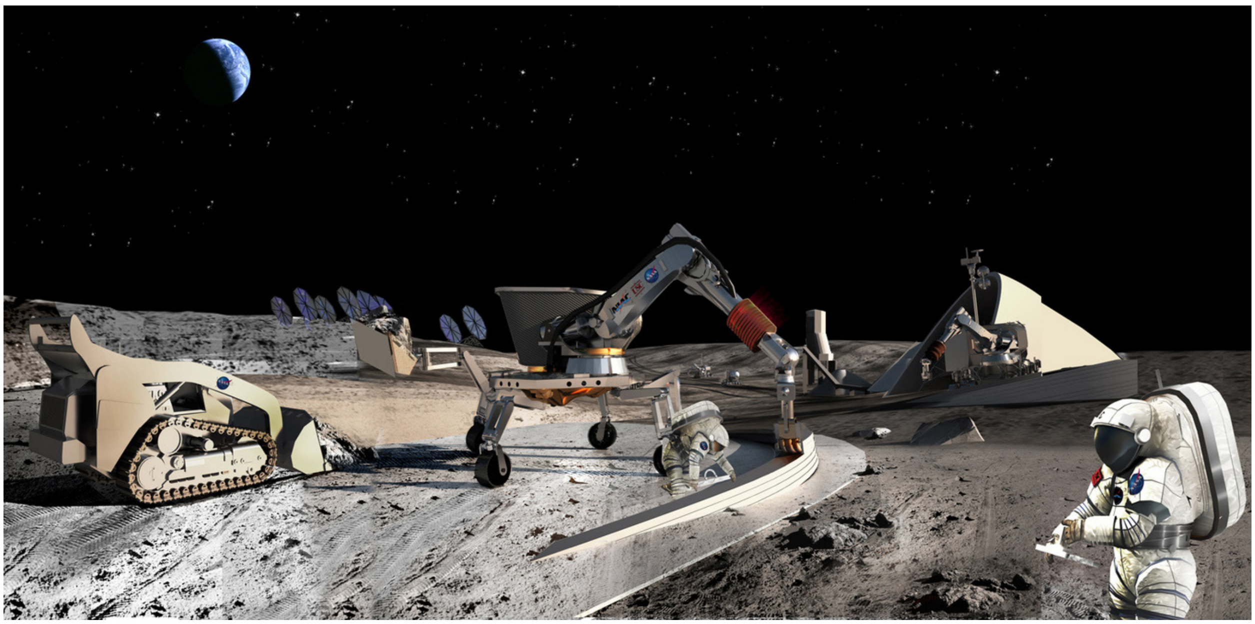


Figure 05.10 • Contour Crafting: Lunar Studies

to mass implementation. Material properties of metal pieces have been tested to be on target with design estimates. Ceramic pieces have been tested and approved for aviation use. Plastics have entered the market for consumer wearables such as shoes. However the performance of 3D printed surfaces parts in different world climates of freeze/thaw, UV, earthquake, etc., all have yet to be thoroughly examined and tested. As a result, there is currently a gap for 3D printed parts to effectively enter the market in areas other than steel connections or interior decoration.

o5.4 Future of 3D Printing for Architecture

There is a direct application for 3D printing in areas where labour is not available, or the cost of getting labour to a site is high. 3D printing could allow for the production of parts on site, or for pre-assembled unique pieces to be shipped to the site for more natural erection. The extreme end of this spectrum could be where human labour is non-existent such as lunar or martian construction. 3D printing could allow for construction in remote locations as long as surrounding materials could be used.

The cost of existing 3D printing processes will continue to decrease as demand increases for these services. With 3D printing, at a consumer level becoming increasingly popular, the excitement surrounding this technology continues to grow. The technology continues to develop, driving down cost, and increased knowledge of its existence will also give it a place to become known for its production capacity. Beyond the consumer hobby market, medical and dental adoption of the technology is becoming widespread though architectural applications are only now emerging, the shift is inevitable.

Hybrid processes may lead to the broadest practical implementation of 3D printing. In some applications, 3D printing is used for the production of moulds used for investment casting. Reducing labour of material casts and decreases turnaround time. Alternate to this are applications where 3D printing is used to print a base from which parts then are milled to final dimensions and tolerances. Reducing the overall waste of milling processes and produced parts which have established finished or tolerances desired in the marketplace. Within Architecture this hybrid approach seems the most realistic application for 3D printing technology, where builders would utilize tried and true components for building far most of the bulk and utilize 3D printing technology where its benefits for complex forms or the translation of digital components to reality are most beneficial. As reviewed in section o1, new avenues continue to be prototyped and explained, and future usage of 3D printing technology may widen with time.

Conclusion

06

Figure 6.1 • Re-imagination of Construction
The complete 3D printing of a building can be imagined with many techniques. This image explores the possibility of converting construction cranes into the frame work of a large scale printing apparatus.

Conclusion

Architecture is a large-scale sophisticated craft, requiring communication between many different people to transform an idea into a physical construct. As a profession, we are continuously refining and revising the process to make better buildings in a shorter timespan. This refinement has led the field of architecture towards a digital era, where designs can be explored and communicated with increasing depth and precision. With the rise of manufacturing turning digital through 3D technology we find ourselves at the potential union of two worlds, the digital and physical. This union brings with it the opportunity to quickly move from the digital concept to physical reality; translating our models and drawings into real artifacts more readily than in the past. Additive manufacturing is the newest addition to the collection of other digital fabrication tools such as CNC machines, laser cutters, plasma cutters, mills, and routers that are currently used. The freedom of 3D printing comes from its ability to build an object up, shaping the item through the direct placement of material.

Three dimensional printing is a powerful tool which excels to create complex shapes with ease and produce unique artifacts on demand, unlike traditional manufacturing processes which excel at producing long continuous elements, or repeat pieces in continuous production. Rolled steel processes effectively create beams of consistent cross-section, thickness and weight. Wood is milled, shaped and plied into consistent parts such as dimensional lumber or engineered products. Buildings are made of numerous pieces, many of which are produced as a repetitive standard element; typically off the shelf components are fashioned into unique parts, or dimensions. Steel beams and columns are cut to a given dimension, with connection or bearing plates manually welded to suit the final application. This is an economical solution to construction as standardized parts come cheaply and quickly regardless that material waste is generated when modifying off the shelf elements to suit. The custom portion of architecture happens at a very fine-scale and a very large-scale. 3D printing has the capacity at the moment to address the fine-scale, but in order to print large-scale structures the hurdles of site construction and economic constraints need to be met. The production of large volumes with modern construction techniques is logically quicker and cheaper at the moment then erecting a machine large enough to print a unique shell on site. Steel frame construction can typically be erected quickly on-site. Concrete structures require on-site moulds and temporary support structure to account for curing time to reach 80% strength capacity. Off-site fabrication has made the greatest strides in shortening construction with a variety of structural materials. 3D Printing has an avenue to infiltrate this market with prefabrication modules ready for on-site installation. Apart from the structure of a building, the largest challenge is fitting the various mechanical, electrical and building envelope elements within the finished skins. With technical progression of 3D Printing technology - the printing of various materials from a single machine is possible. This can translate into the direct embedding of conduits and chase ways into printed structural components. At the moment

Figure 6.2 • Production *en masse*
Production facilities geared towards independent production, this image imagines an abandoned shoe factory into a high tech laboratory.

structures or structural elements can be printed effectively as well as facade and interior surfaces. The interior services of a building are seemingly constrained to the status quo of being physically assembled 3D Printed components.

There will undoubtedly be on-site 3D printed buildings in the future beyond the proof of concepts we see today due to cultural shifts, sustainability goals, and advancing construction techniques. The direction of our throw-away society with their desire for unique possessions is moving manufacturing methods down more flexible avenues; these flexible manufacturing processes allow for customization and bespoke items. 3D Printing excels in the production of bespoke items and easily continues to expand this market. With the growing concern over sustainable living, advanced manufacturing methods as it has the ability to use material more effectively reducing construction waste through amount of materials required in construction. Structural designs can utilize material properties in direct structural pathways and optimize pieces based on loads rather than ability to manufacture a specific shape. Reduction of material will impact weight and therein the concrete foundations and footings required. Additionally, reducing the amount of material for a building and required to be shipped to site will lessen the environmental impact of the built form. The most realistic applications of 3D printing needs to be found with combination of already existing and growing manufacturing processes. Current practices of building will provide the larger pieces that are easily manufactured on main while 3D printing has a place contributing to the unique components needed to make a project work. The potentials of this technology give it traction in the creation of unique connection points, complex surfaces, or decorative panels for the interior and exterior.

3D printing has entered the market with many unique strengths but not that single it out as solution to a problem. Yet, it is regarded as a technology which may change the very nature of how we manufacture products. These beliefs founded on the technologies ability to create complex, detailed shapes and surfaces. Designers will find ever more complicated forms to try and bring technology slowly into the mainstream. Although 3D printing may not seem to be directly applicable to a large object like architecture at this point in time, other digital technologies such as CNC milling are currently use. 3D printing gives the illusion that the wall between designer and fabricator is gone, the reality is that divide still exists. Utilizing 3D printing in today's industry is almost impossible unless the industry changes how it produces buildings, as the architect and contractor would require a greater deal of integration and a blurring of responsibility.

In today's market, the word custom brings about many preconceived ideas about expense and difficulty. At the same time there is a large place for customization in our current manufacturing practices. The desire for custom is prominent with both the client and architect. Professionally but there exists a divide in knowledge to which tools are available for production. This seems to stem from the fact that some building elements are assembled on-site where as others are produced separate and

Figure 6.3 • Producing Uniqueness
Production facilities geared towards independent production, this image imagines an abandoned shoe factory into a high tech laboratory.

delivered to site for installation. It is easy to customize the shape of a curtain wall but a hassle to modify a stocked window from the hardware store. Having intimate workings of digital production tools will allow architects to be confident with unique designs and effectively collaborate with fabricators for optimized unique items which can be competitively built. 3D printing allows an avenue to constructability which may become cheaper then alternative methods. Cost for production via 3D printing quite is quite costly compared to other production methods. Within architecture, the prevalent production methods allow for the cost to be spread over many items. High production cost of a single item does have application in other fields, such as aviation and biomedical. In aviation a more costly part which optimizes fuel use will easily offset its production cost. In the biomedical industry unique elements can be produced specifically for individuals where unique items are already being produced at high cost (because batch production is not utilized) 3D printing offers a more direct pathway.

Through a better understanding of manufacturing processes the potential for a hybrid between new and old technology will allow for never before imagined architectural forms to be explored. In the future, sending a digital model, one which can be created at the push of a button, will bypass the need to communicate about design intent, structural capacity, or surface treatment. We will send an unchallengeable object which will be produced as is; here’s hoping we send the right file.

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Glossary

Additive Manufacturing – the shaping of an object through the addition of volume to the base material.

additive manufacturing (AM), n – a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication. [ASTM, F2792-12a, http://www.astm.org. 2012]

binder jetting, n – an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials. [ASTM, F2792-12a, http://www.astm.org. 2012]

CAD, n – Computer-Aided Design. The use of computers for the design of real or virtual objects. [ASTM, F2792-12a, http://www.astm.org. 2012]

CAD/CAM – (Computer Assisted Drawing/Manufacturing) – through the use of employing machines to assist in the drawing of projects, designers can create more comprehensive virtual representations of their creations. CAD files can then be interpolated by programs to create directions for machines. Such as a CNC (Computer Numerical Control) router, mill, extruder. This allows for a direct translation of the virtual to the physical.

CAM, n – Computer-Aided Manufacturing. Typically refers to systems that use surface data to drive CNC machines, such as digitally-driven mills and lathes, to produce parts, molds, and dies. [ASTM, F2792-12a, http://www.astm.org. 2012]

CNC, n – Computer Numerical Control. Computerized control of machines for manufacturing. [ASTM, F2792-12a, http://www.astm.org. 2012]

Digital Fabrication – the action or process of manufacturing or inventing something through means of computer aid design and manufacturing

directed energy deposition, n – an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. [ASTM, F2792-12a, http://www.astm.org. 2012]

Division of labour – division of the total work into tasks and having individual workers each become specialized at performing only one task. (Groover p.2)

Economy of Scale – the cost advantage achieved through production efficiency where the production volume is increased while lowering production costs as the money going into the product is spread over a larger quantity of good. This can effect both fixed and variable costs. <https://www.investopedia.com/terms/e/economiesofscale.asp>

Economy of Scope – a situation where the production of one good reduces the cost of producing another related good. The long-run average and marginal cost associated with the production of the goods decreases for the company due to the production of a complementary good or service. < https://www.investopedia.com/terms/e/economiesofscope.asp>

Fabrication vs Manufacturing – fabrication in general refers to the production of a small batch of unique items. Manufacturing refers to the production of many items at a time. Many manufacturing shops will have fabrication centers contained within – for pieces which are unique or the production of machine parts.

Factory system – the use of machines and the principles of division of labour for the manufacturing of objects. (Groover p.3)

Formative Manufacturing – the reshaping of an object of material from base material to the desired shape utilizing a given volume.

Machine Mentality – as defined by David Noble, "understandable perhaps but nevertheless self-serving belief that whatever the problem, a machine is the solution. This manifests itself in a preference for, and tireless promotion of, capital-intensive methods and in the widespread but mistaken belief that the more capital intensive the process of production, the higher the productivity." (Moe, pg 162 Fabricating Architecture)

Manufacturing – is the transformation of a material into a product through the application of physical and chemical processes by way of machinery, tooling, energy and labour. There are three categories of shaping objects; formative, subtractive, and additive. Manufacturing also includes the post processing of objects, these are finishing and assembly. < Groover, Mikell P., 1939-. Fundamentals of Modern Manufacturing : Materials, Processes, and Systems. 5th ed. ed. Hoboken, NJ: John Wiley & Sons, Inc, 2013. pg. 3.>

Mass Customization – the manufacturing technique which allows for the flexibility and personalization of a "custom-made" product with the low-cost attributed to mass production.<http://www.investopedia.com/terms/m/masscustomization.asp>

Mass production – The manufacture of large quantities of standardized products, frequently utilizing assembly line technology. Mass production refers to the process of creating large numbers of similar products efficiently. Mass production is typically characterized by some type of mechanization, as with an assembly line, to achieve high volume, the detailed organization of materials flow, careful control of quality standards and division of labor. < http://www.investopedia.com/terms/m/mass-production.asp>

material extrusion, n – an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice. [ASTM, F2792-12a, http://www.astm.org. 2012]

material jetting, n – an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. [ASTM, F2792-12a, http://www.astm.org. 2012]

powder bed fusion, n – an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. [ASTM, F2792-12a, http://www.astm.org. 2012]

Pre-Fabrication – The act of preemptively manufacturing elements to be constructed or assembled into a whole at a later time and or place.

rapid prototyping, n – additive manufacturing of a design, often iterative, for form, fit, or functional testing, or combination thereof. [ASTM, F2792-12a, http://www.astm.org. 2012]

sheet lamination, n – a additive manufacturing process in which sheets of material are bonded to form an object. [ASTM, F2792-12a, http://www.astm.org. 2012]

STL, n – in additive manufacturing, file format for 3D model data used by machines to build physical parts; STL, is the de facto standard interface for additive manufacturing systems. STL originated from the term stereolithography. The STL format, in binary and ASCII forms, uses triangular facets to approximate the shape of an object. The format lists the vertices, ordered by the right-hand rule, and unit normal of the triangles, and excludes CAD model attributes. [ASTM, F2792-12a, http://www.astm.org. 2012] (Current edition approved March 1, 2012. Published March 2012. Originally approved in 2009. Last previous edition approved in 2012 as F2792–12. DOI: 10.1520/F2792-12A.)

Subtractive Manufacturing – the shaping of an object through the removal of volume from the base material.

Systems of manufacturing – the way of organizing people and equipment so that production can be performed more efficiently. (Groover p.2)

tool, tooling, n – a mold, die, or other device used in various manufacturing and fabrication processes such as plastic injection molding, thermoforming, blow molding, vacuum casting, die casting, sheet metal stamping, hydroforming, forging, composite lay-up tools, machining and assembly fixtures, etc. [ASTM, F2792-12a, http://www.astm.org. 2012]

vat photopolymerization, n – an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization. [ASTM, F2792-12a, http://www.astm.org. 2012]