3D PRINTING WITH BIOMATERIALS

TOWARDS A SUSTAINABLE AND CIRCULAR ECONOMY

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THE VISION

3D Printing with Biomaterials, towards a sustainable and circular economy

JIP, my robotic assistant, wakes me up. While we discuss the day ahead, the 3D-printer is printing my breakfast, adding an integrated supplement of potassium and calcium - apparently my values are too low. Nowadays, we are living a fully sustainable and circular life - thanks to excellent resource management, a sustainable energy supply for everyone and the use of Additive Manufacturing Facilities (AMF).

JIP informs me he had a new camera printed for my glasses. As he hands it to me, I see the lens had been broken: good timing! Isn't it great to have it repaired without any outside intervention, just by design? The old camera is directly disposed in the material-digester to be broken down for complete re-use on a molecular level. From my window I enjoy the view of our urban landscape: a vast, intelligent, fully automatic megacity of 28,679,936 inhabitants; projected in my glasses the number counts up as new habitants are registered. It all may seem overwhelmingly complex, but thanks to the food revolution and AMFs the logistics are actually quite simple.

Our car is on its way from the Car Park Power Plant. It notifies me that a new door panel from bio-plastic, reinforced with natural fibers, was printed overnight and replaced by the AMF at the Car Park Power Plant. While 30% lighter, it is even slightly stronger than the previous one!

My wife and I have a safe trip to the clinic – we are expecting our first baby shortly. We refused to have a prenatal model of our baby printed in 3D, which is a very unusual choice – and a disappointment to my parents and grandparents. But I think that some things are meant to remain a blissful surprise, just like the future!

This view into the future is not science fiction – it will become reality due to the developments in 3D printing. 3D printing – or Additive Manufacturing – is a group of manufacturing techniques defined as the process of joining materials layer upon layer to make objects from 3D-model data. It is a rapidly developing manufacturing technology which makes it possible to produce, repair or replace products everywhere; in a shop, in the hospital, at the office, at school or even at home. A product design is simply downloaded and then printed. One may copy, modify or personalize the product before it is printed. It will also be possible to make a 3D scan of something existing - and then print it. This will fundamentally change our world. We can create, design and manufacture whatever we want, wherever we want. Additive Manufacturing will create a revolution in manufacturing; a paradigm change already called the third industrial revolution.

The advantages of 3D printing are design freedom, faster product development cycles, low startup costs for production, local production and on-demand manufacturing. It offers the promise of a simple, efficient and low-cost supply chain, with no need for mass production in factories, nor for global logistics of both raw materials and products. Only requiring *local* logistics of raw materials (preferably locally produced) and 3D printers in your neighborhood or at home.

3D printing offers the promise of manufacturing with less waste and less energy. We can print metals, ceramics, sand, food, plastics and even living organic cells. But what is the environmental impact of these input materials for 3D printing? Production of plastics for instance is based on fossil fuels, which has a serious impact on the environment, especially greenhouse gas emissions. But here too a paradigm change is occurring. Instead of using fossil fuels, plastics can be produced from renewable resources such as biomass. And some biomaterials seem to offer unique material characteristics in combination with 3D printing! A wealth of new and innovate products are emerging when these two paradigm changes are being combined: 3D printing with biomaterials. The combination of 3D printing with biomaterials provides the opportunity to realize a truly sustainable and circular economy.

SUSTAINABLE AND CIRCULAR

	PROMISES
3D PRINTING OR ADDITIVE MANUFACTURING	Design freedom Cloud- and community-based personalized design Faster product development cycle Low startup costs for production On-demand production Less transport and logistics
BIOMATERIALS	Material from biological origin instead of fossil fuels No CO_2 (short cycle) emissions Feedstock can grow everywhere Every plastic can be produced Specific and unique material characteristics for 3D printing
3D PRINTING WITH BIOMATERIALS	Local production of both biomaterials and products Zero greenhouse gas emissions Unique, innovative, new and sustainable products The realization of a sustainable and circular economy

3D PRINTING

3D Printing manufacturing will drastically change our production system. It is also called the third industrial revolution. But how does it work, what products may be printed and how will it change the world?

HOW DOES IT WORK?

In essence, 3D printing or Additive Manufacturing (the industrial term) is a computer-controlled production technique that builds a product layer by layer. Although there are different techniques available, the three basic requirements are: the digital design, the 3D print technology and the material used. (1) (2) (3) (4) (5)

DIGITAL DESIGN

The 3D printer needs an instruction on what to print. This instruction is created by a 3D modeling program and is called a Computer Aided Design (CAD) file. Such a file can be designed from scratch, from an existing file or it can be created by a 3D scanner. The design of an object is sliced in thousands of horizontal layers and then sent to the 3D printer via a command file that directs the printing process.

The product design will increasingly be community- and cloud-based. Community members will upload their designs for others to use, improve, change or integrate in their own product design. For a specific product, one can pick a design, personalize it and print it. (6) (7) Communities in the cloud are able to develop, improve and share new product designs very rapidly and anyone can be involved in it. Intellectual property and design protection (in its current form) may become obsolete, certainly affecting the design world.

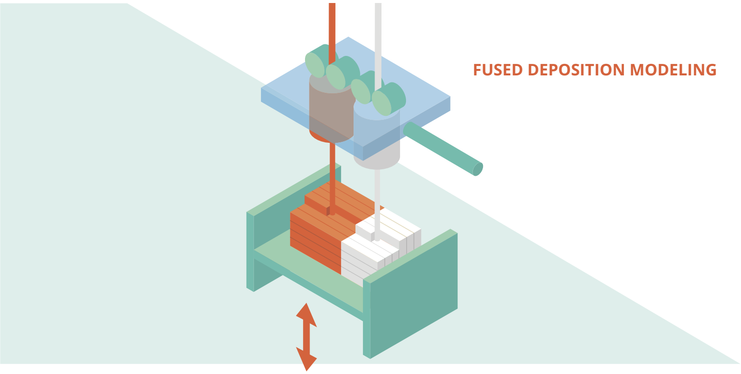
3D PRINTING TECHNOLOGIES

Additive Manufacturing, or 3D printing in popular terms, is not just one technology. Currently there are several technologies (and -variations) that cover the term 3D printing. It is called additive manufacturing because new material is continually added to the object. Material is only added where it is wanted, layer by layer, which is very material-efficient. There are many types of 3D printers, but no matter the technology involved, all are additive and build the object layer by layer. The additive manufacturing or 3D printing technologies can be divided in several classes and within these classes there are different variations: (5) (1) (2) (8) (9) (3)

- **Extrusion,** extrusion of molten material;
- **Direct energy deposition,** melting with high energy power source;
- **Solidification of powder,** fusion or joining of particles;
- **Photopolymerization,** solidification of a liquid polymer;
- **Sheet lamination,** bonding of sheets.

EXTRUSION

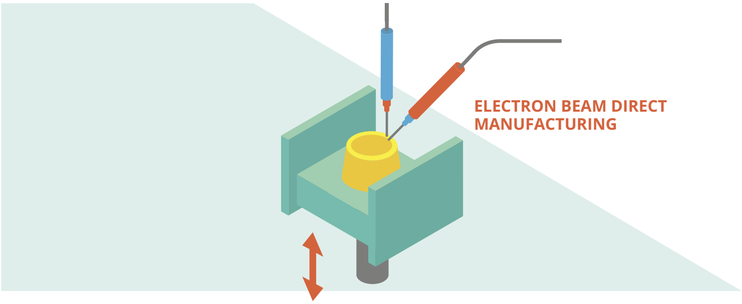
A molten material - plastic, clay, cement, silicone, ink, or even chocolate or cheese - is extruded and becomes solid after it emerges from the printer head. Designs are built up layer by layer until the final product is complete. There are several variations within this technology.



One of these technologies based on extrusion principle is **Fused Deposition Modeling**. With Fused Deposition Modeling, thermoplastic material is extruded. The molten material is printed layer by layer, on top of the previous layer and fuses when the material hardens, almost instantly after leaving the printing nozzle. Every time a layer is fully printed, the printer platform is lowered a fraction. A supporting material can be printed by a different printing nozzle. The FDM method is one of the cheapest 3D printing methods and most often used in 3D printers at home. At present the most common materials used are ABS (common plastic, oil based plastic) and PLA (polylactic acid, a bio-based plastic). (1) (2) (3) (5) (8)

DIRECT ENERGY DEPOSITION

Direct Energy Deposition is a process that melts metal wire or powder to form an object layer by layer, using a high energy power source such as an electron beam, a plasma welding torch or a laser. This 3D printing technology is specifically used to produce metal objects.

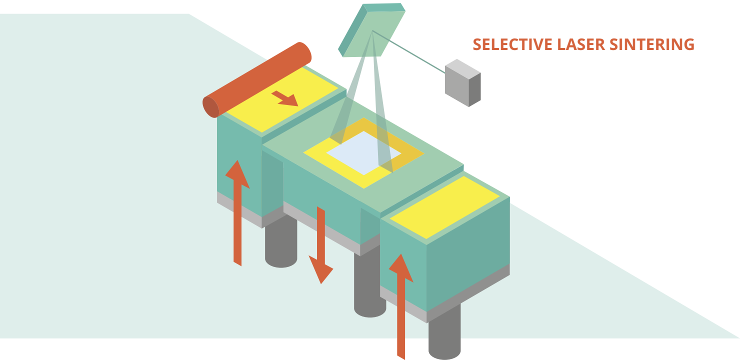


Electron Beam Direct Manufacturing (EDBM) is one of these techniques. An electron beam gun provides the energy source for melting metal, typically a metal wire. Using electromagnetic coils, this electron beam can be both precisely focused or deflected. A computer controls the electron beam and the movable table, to build up the object layer by layer. The process is conducted in a high-vacuum environment, preventing contaminations. EBDM can produce very large objects rather quickly. (1) (2) (3) (5) (8)

SOLIDIFICATION OF POWDER

Powder-based 3D print techniques are based on fusing or hardening (sintering) of powders. The most important solidification of powder techniques are Selective Laser Sintering (SLS) and 3D Printing (3DP).

Selective Laser Sintering is a powder-based 3D print technique. The powder of a thermoplastic polymer, metal or ceramic is hardened (sintered) with a CO_2 laser. The platform lowers and another layer of powder is applied and sintered. This process is repeated until the object is finished. The un-sintered powder functions as a support structure for the product. This powder can be re-used for the next printing, so there is no residual waste. Resolution restraints are caused by the minimum size of the powder particles of around 100μm. Powdered materials such as polystyrene, ceramics, glass, nylon, and metals including steel, titanium, aluminum, and silver can be used in SLS.



3D Printing is a technique to bond powder by a binding material, distributed by a movable inkjet unit. The platform lowers and another layer of powder is applied and sintered the same way. Also in this case, the un-sintered powder functions as a support structure for the product, and can be re-used for the next printing. (1) (2) (3) (5) (8)

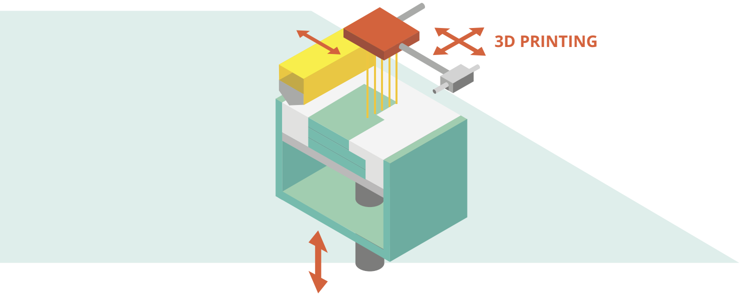
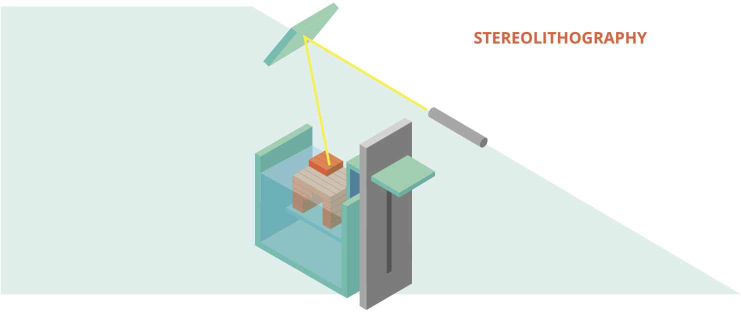
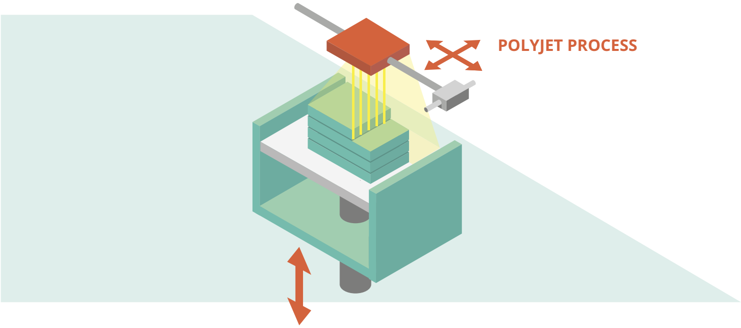


PHOTO-POLYMERIZATION

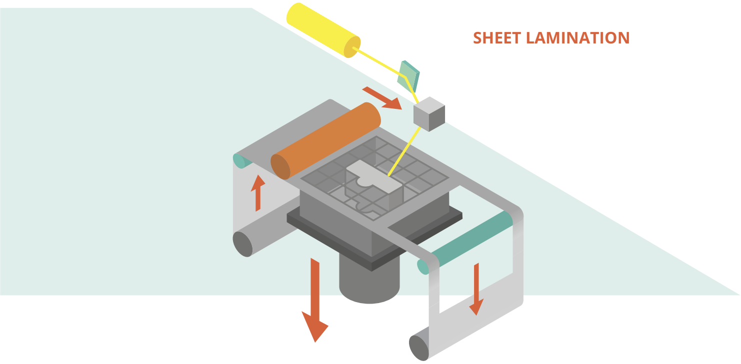
Photo-polymerization-based 3D printing techniques are based on layer by layer hardening of liquid photo-curable resins by UV-light. The most important photo-polymerization techniques are Stereo-Lithography (SLA) and the PolyJet process.



A **stereolithography** system (SLA) contains a vat or container filled with a liquid photopolymerizable resin. The platform lowers and a sweeper evenly distributes a layer of the photopolymerizable resin. The resin is hardened with UV-lasers. This process is repeated until the object is created. The first commercially available 3D printer (not called a 3D printer at that time) used the stereolithography (SLA) method. When the UV-light is applied for the whole layer at once via a Digital Light Processing projector, this is called the Digital Light Processing (DLP) technique. The projector beams the UV-light through a mask, which will expose the whole layer with UV-light at once.



The photopolymerization group also comprises the **polyjet process** because this process contains the hardening of a low viscous photopolymerizable resin. Instead of a vat with resin, the resin is dropped by a multi-nozzle ink-jet head and instantly hardened by UV-light that is integrated in the ink-jet head. The building platform lowers and the process will be repeated. The supporting material is a gel, that gets flushed away when the object is finished. (1) (2) (3) (5) (8)



SHEET LAMINATION

This 3D printing technique builds objects by trimming sheets of material and binding them together layer by layer. Laminated Object Manufacturing (LOM) is one of these sheet lamination techniques. Layers of adhesive-coated paper, plastic, or metal laminates are successively glued together and cut to shape with a knife or laser cutter. (1) (2) (3) (5) (10)

TECHNOLOGY OVERVIEW

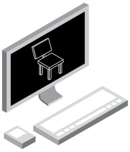
There are many different additive manufacturing or 3D printing technologies. And different classifications of these technologies are in use. We have divided the technologies in five process categories and described a few technology examples. The American Society for Testing and Materials (ASTM) (11) (9) have divided the additive manufacturing technologies in 7 process categories, which are shown in the table between brackets.

3D PRINTING TECHNOLOGIES PROCESSES (3) (9) (12)

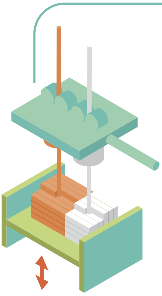
PROCESS (ASTM PROCESS)	TECHNOLOGY (SOME EXAMPLES)
EXTRUSION	Fused Deposition Modelling (FDM)
(MATERIAL EXTRUSION)	A material is melted and extruded in layers, one upon the other *(This technique is normally used in 3D printers at home)*
DIRECT ENERGY DEPOSITION	Electron Beam Direct Manufacturing (EBDM)
(DIRECT ENERGY DEPOSITION)	An electron beam melts a metal wire to form an object layer by layer
SOLIDIFICATION OF POWDER	Selective Laser Sintering (SLS)
(POWDER BED FUSION)	A bed of powder material is “sintered” (hardened) by a laser, layer upon layer until a model is pulled out of it
SOLIDIFICATION OF POWDER	3D Printing
(BINDER JETTING)	Powder is bond by a binding material distributed by a movable inkjet unit layer by layer
PHOTO-POLYMERIZATION	Stereolithography (SLA)
(VAT PHOTO-POLYMERIZATION)	Concentrating a beam of ultraviolet light focused onto the surface of a vat filled with liquid photo curable resin. The UV laser beam hardening slice by slice as the light hits the resin. When a projector beams the UV-light through a mask onto the resin it is called Digital light processing (DLP)
PHOTO-POLYMERIZATION	Polyjet Process
(MATERIAL JETTING)	A photopolymer liquid is precisely jetted out and then hardened with a UV light. The layers are stacked successively
SHEET LAMINATION	Laminated Object Manufacturing (LOM)
(SHEET LAMINATION)	Layers of adhesive-coated paper, plastic, or metal laminates are glued together and cut to shape with a knife or laser cutter

3D PRINTING

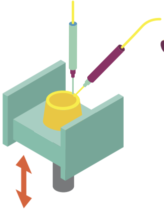
DESIGN FILE



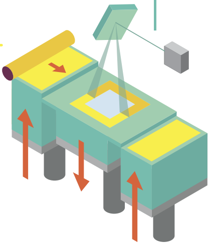
3D PRINTING TECHNOLOGIES



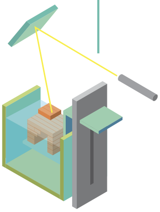
EXTRUSION
OF MOLTEN MATERIALS



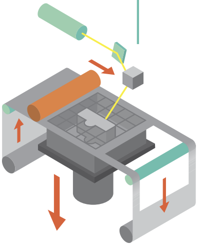
DIRECT ENERGY DEPOSITION
MELTS METAL WITH A HIGH ENERGY POWER SOURCE



SOLIDIFICATION OF POWDER
FUSION OR JOINING OF PARTICLES



PHOTOPOLYMERIZATION
SOLIDIFICATION OF A LIQUID POLYMER



SHEET LAMINATION
BONDING OF SHEETS

MATERIALS

POLYMERS

BIOBASED PLASTICS
PLA, PLL, PLGA, TPC,
TPS, PA-11,...

METALS

METALS, CERAMICS
POLYMERS

BIOBASED PLASTICS
PA-11, PLA, PLGA, PHBV,...

POLYMERS
PHOTOCURABLE
RESINS

HYBRIDS,
PAPER, METALS
CERAMICS

3D PRINTING MATERIALS

In principle, all kind of materials can be used for manufacturing with 3D printing techniques; from sand to metals, ceramics, food, living cells and plastics. Especially plastics are used in the 3D printers at home (extrusion process) and may have their origin from either a fossil fuel or a bio-based feedstock (see next chapter for an overview).

In relation to 3D printing a whole range of (bio) plastics is under development combined with (bio) additives to create special properties. For 3D printing, the main characteristics of interest are melting temperatures, melting viscosity and coagulation time.

WHAT CAN BE MANUFACTURED?

EVERYTHING CAN BE 3D PRINTED

“Additive manufacturing techniques can produce essentially everything”, explains Siert Wijnia (5); from clothes to houses and bridges, from tea cups to bikes and cars, from medical prostheses to living tissues and organs, from jewelry to food. Currently, additive manufacturing technologies are used for rapid prototyping, for tooling and for manufacturing parts of a product. Industrial designers and architects make use of 3D printing techniques to produce prototypes, to make a model of a building or to preview the design. Additive manufacturing is used to test newly designed parts or products before they are mass-produced. For example, injection molding with 3D printing is used to produce the molds much faster and cheaper (13) (14). And 3D printing is already used for the production of spare parts, personalized products and complex devices.

At present, the main manufacturing applications of additive manufacturing are the production of product parts or special-design products. In the dental sector, 3D printing is used to make dental bridges and crowns that are uniquely designed for one's jaw. The fashion industry uses 3D printing to make jewelry or extravagant dresses. Additive manufacturing is applied industrially to produce engine parts for aircrafts, to reproduce parts of old-timers that are not manufactured anymore or to make spare parts locally. Top restaurants apply 3D printing to create a nice looking desert or even a complete meal.

It may well be possible to manufacture complete complex products in the future, such as bikes, cars, washing machines or even houses. The first 3D printed examples of these complex products are already being manufactured by researchers, artist and hobbyists. These products get a lot of attention in the news, such as the first 3D printed bike, gun or hamburger. The additive manufacturing techniques promise fast, unique and personalized manufacturing of all kinds of products. Even products that cannot be imagined now. Certainly in the near future, products with the following features will by manufactured by 3D printing;

- Products produced in small quantities
- Products that need to be produced fast
- Products with a large market-volume uncertainty
- Products with a short life cycle
- Products with many variations, sizes and colors
- Complex and customized products.

A brief overview of present and future applications is given in the table below. For future applications this list is certainly not limitative. One's imaginations and dreams may be realized one day by using 3D printing techniques.

3D PRINTING APPLICATIONS

SECTOR	PRESENT APPLICATIONS	FUTURE APPLICATIONS
INDUSTRY	Product components, spare parts, reproduction of parts	Complete and complex products, washing machines, mobile phones, guns, drones
HEALTH	Dental bridges and crowns, prostheses	Living tissues and organs, bionic ears, eyes
FASHION	Jewelry, special designed clothes	Clothes, shoes, accessories - personalized for your posture and taste
FOOD	Nice looking deserts, appetizers	Producing food (hamburgers, potatoes) personalized to your diet, calories and taste.
BUILDING	No applications yet	Building parts and complete buildings with a high degree of freedom of design and future changes
AT HOME	Special designed gadgets, simple products	Order products and print at home, repair products, design and produce personalized products
OTHERS	Building in space	Chemistry: building molecules Pharmacy: building personalized medicine

3D PRINT YOUR HOUSE

The process of manufacturing buildings has not changed a lot over the past decades. First a design is made, the construction and installations are engineered and then the building is manufactured on site. We build our houses, schools, offices from wood, concrete, steel, glass, bricks, clay and all kind of other materials. However, the building process is rather complex, in many cases unique and therefore labor intensive with a high probability of mistakes.

3D Printing technology potentially offers some interesting benefits in manufacturing products that are complex, unique or made in small series. Especially buildings have these characteristics. 3D Printing makes it possible to create unique shapes, adapt the building to the personal preferences without additional cost and with a low probability to make mistakes. 3D Printing has the potential to reduce material use (especially concrete) and to avoid building and demolition waste, thus lowering environmental emissions during construction. Additional to these advantages, it creates new possibilities, new architecture, new building-physics engineering, new day lighting options and other things not even yet imagined. (15) (16) (14)

In the past decade, a couple of pioneers have tried to develop a building process based on 3D printing techniques. Enrico Dini developed a 3D printing technique to create buildings and structures through sintering of sand (17). At the University of Southern California, Behrokh Khoshnevis is developing a 3D printing technique, called contour crafting, to print walls and structures with a carbon fiber cement mixture (18). Neri Oxman, architect and artist at the mediated matter group at MIT, demonstrates the design freedom for large objects of 3D printing with different materials and techniques (19). DUS architects are creating a 3D printed canal house in Amsterdam using the “Kamermaker”, a large-scale home printer. They print each room separately and build it together as large Lego-type blocks. The rooms are connected to the outside façade, which is printed in one piece. The envelope of a wall in particular is 3D printed from plastics, leaving space for infrastructure. (20)

Many architects, designers and researchers around the world are developing new technologies and processes to manufacture buildings with 3D printing technologies. The general concept is to print the envelope and internal structure of the walls using plastics. The structure is filled with weight (sand, concrete), isolation material and the infrastructure and other elements are also integrated into this structure. Such designs are built with less material use, and ample freedom in form and flexibility. 3D Printers and robots are used on site to print and assemble the building.

Bram van den Haspel (16) has presented a step-by-step scenario towards 3D printed buildings that require one printing run on location, using different materials. The first step is based on printing small building blocks in plastic. The second step allows printing complex molds to make certain bigger parts of a building with a certain level of integrated functionalities. In the third step, complex building parts with integrated isolation, ventilation and tubes are being printed. Followed by printing the whole building in parts at the manufacturing site. The final step is printing the total building in one printing run on location or in a nearby production facility. How soon a building can be realized with 3D printing on location, depends on the development of the 3D printing technology, robot technology, construction design for 3D printing and material development. With present 3D printing technology it would cost about a year to print a simple town house with 20 printers (one printer head each). But if speed, precision and design of 3D printer technology develops as fast as the 2D printer technology, a simple town house may be printed in less than a day within 10 years from now.

According to Oxman, 3D printing of houses will happen in the near future already. In the far future, buildings may be constructed by swarms of tiny robots that use a combination of printing and weaving techniques. Today's material limitations can be overcome by printing with responsive materials. Gantry limitations can be overcome by printing with multiple interactive robot-printers. Process limitations can be overcome by moving from layering to weaving in 3D space, using a robotic arm. (21)

WHAT DOES THE FUTURE BRING?

HISTORY OF 3D PRINTING

Although it was already proposed in the 19th century to produce topographical maps layer by layer, the first real attempts to produce objects that way were made in the 1980's. In 1981 Hideo Kodama of Nagoya Municipal Industrial Research Institute published the first account of a working photopolymer rapid prototyping system. Charles (Chuck) Hull, one of the co-founders of 3D Systems, developed the first working 3D printer based on the StereoLitographic process (SLA) in 1984. In 1992 3D Systems delivered the first SLA 3D printer machine.

Stratasys made the world's first Fused Deposition Modelling (FDM) machine in 1991. This technology uses plastic and an extruder to deposit layers on a print bed. It is the predecessor of the 3D home printing machines that we can buy today.

Many new 3D printing techniques were developed at that time, such as Selective Laser Sintering (SLS) by DTM in 1992. This machine technology is similar to SLA but uses a powder (and laser) instead of a liquid. Model Maker's wax printer was released in 1994 and in 1997 Aeromet invented laser additive manufacturing. In 2000, Object Geometries produced the first 3D inkjet printer and the first multicolor 3D printer was made by Z Corp, now part of Stratasys. The first desktop 3D printer was made by Solidimension in 2001. And nowadays one can buy 3D home printers from over 100 companies.

The objects, products and things that can be produced with 3D printing techniques grew accordingly. It started with simple products, prototypes and complicated structures. But nowadays almost any complex product can be made.

3D Printing techniques are also being used for medical applications. In 1999, scientists managed to grow organs from patient's cells while using a 3D printed scaffold to support them. A miniature kidney was 3D printed in 2002 already. The first 3D artificial leg was produced in 2008, with all parts (knee, foot, socket, etc.) printed in one complex structure without assembly. Bioprinting company Organovo produced the first 3D printed blood vessel in 2009. In 2012, the infected jawbone of a 83 year old woman was successfully replaced with an artificial 3D printed titanium replacement, fabricated by LayerWise. And in the Netherlands in 2014, a complete new skull for a woman was 3D printed and implemented successfully.

Complex products have been produced by 3D printing techniques in other industrial sectors. In 2011 the world's first 3D printed robotic aircraft was made by engineers at the University of Southampton, in 7 days. In 2011 also the first 3D printed car was produced: the Urbee by Kor Ecologic. And Cody Wilson of Defense Distributed released his designs for 3D printing a gun in 2013. And in 2014 DUS architects started to 3D print a canal house in Amsterdam. (22)

Art has already changed forever due to 3D printing. Digital artists are creating magnificent pieces of jewelry, clothes and sculptures that would have been seemingly impossible to make with traditional methods. Beautiful objects, from sculptures to light fixtures, no longer need to be handcrafted but just only designed on a computer.

The next step in the development of 3D printing was open-source production and -design. It started in 2005 when the Reprap project was founded by Dr Adrian Bowyer at the University of Bath. The project was intended as a democratization of 3D printing technology.

The Reprap Darwin 3D Printer (2008) can produce many of its own parts. In the same year Shapeways launched a website market for 3D models and Makerbot's Thingiverse (7) launched a website for free file sharing of 3D (and other) models. In 2009 Makerbot introduced a Do-It-Yourself kit, based on Reprap, which allows buyers to make their own 3D printers and products. With 3D laser scanners today we can copy, change and create every digitized design, upload it to an open-source 3D printing community and 3D print our own designs or someone else's. (23) (24) (12) (25)

HOW DOES IT CHANGE THE WORLD?

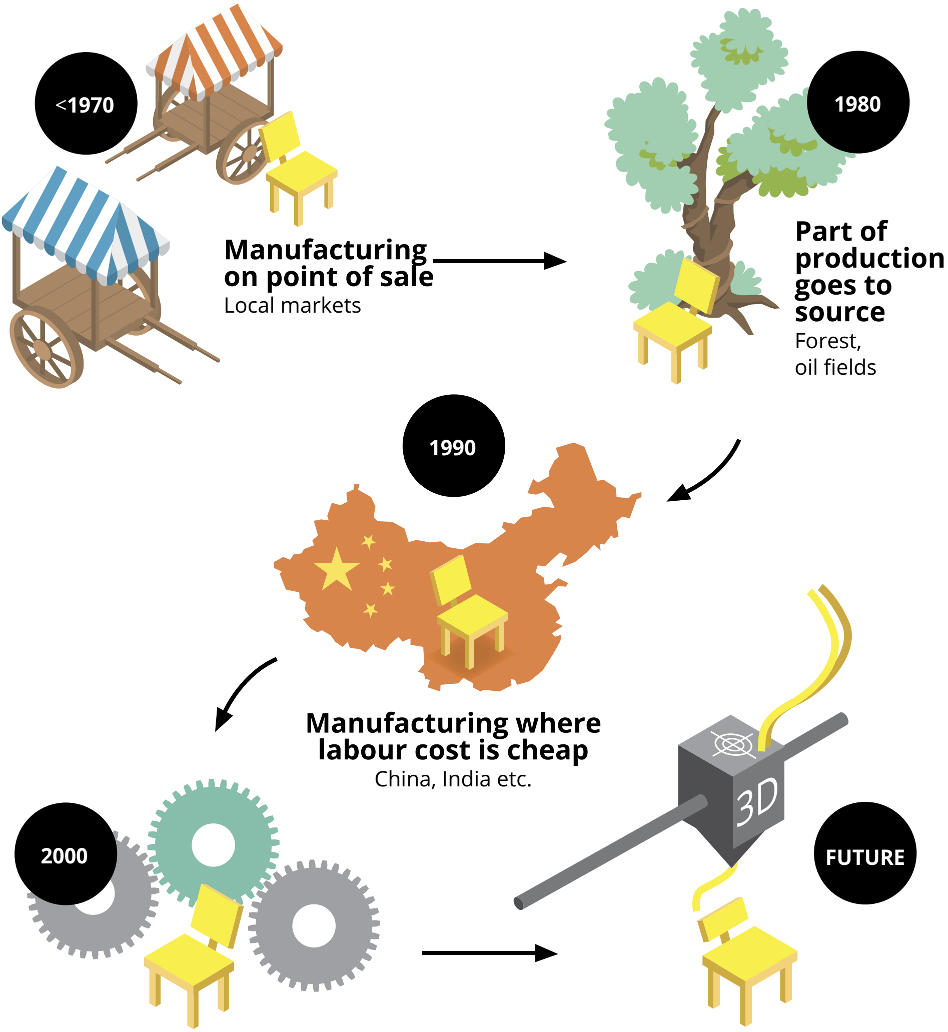
3D Printing is claimed to trigger a third industrial revolution because the technology presents new and expanding technical, economic and social impact (26) (27) (12). It will drastically affect existing manufacturing processes, like relocating manufacturing to the location of demand. It will not be based on a small number of centralized manufacturing sites with high investment costs, but rather on a large number of small investments in distributed manufacturing locations.

Distributed 3D printing manufacturing offers also the promise of lower working capital, eliminating the need for large stocks of raw materials, semi-manufactured parts and labor costs. Manufacturing near the point of demand makes the supply chain and logistics very simple and much more efficient. Only raw materials need to be transported. The required amount of feedstock material will be less, because there is virtually no production waste and we only produce what we need. In many cases, the development and design of a product will become an open-source process to which many people can contribute. The final design will be available on the Internet and can be reproduced everywhere in the world. Ton Runneboom presented an overview on how manufacturing has changed over time. He concluded that although such a paradigm shift in manufacturing will take some time, it will inevitably occur in the end because it will be cheaper. (28)

MANUFACTURING DEVELOPMENTS IN TIME (28)

MATERIAL COST	< 1970	Some manufacturing moves to raw-material locations
	1970	Low material cost, low yields compensated by low material cost
	1980	Geopolitics and resource limits become important, high raw material cost (oil)
	> 1980	Yield improvement becomes important to reduce material cost
		3D PRINTING FUTURE
		EFFICIENT MATERIAL USE AND RE-USE POSSIBLE
FIXED INVESTMENT	1970	Large fixed investment cost for manufacturing installations
	1980	Some cheap labor countries have also cheap investment money
	> 1980	More and more industry cluster investments
		3D PRINTING FUTURE
		MANY SMALL AND INDIVIDUAL FIXED INVESTMENTS
LABOR	< 1970	Labor goes to manufacturing sites
	1980	Low material cost, low yields compensated by low material cost
	> 1990	Automation significantly reduces labor time
		3D PRINTING FUTURE
		HARDLY ANY LABOR TIME
WORKING CAPITAL	1980	High working capital needed to produce on stock
	1990	Increase of working capital because of larger production sites
	> 2000	Financial crisis has reduced working capital
		3D PRINTING FUTURE
		WORKING CAPITAL NEED IS LOW
LOGISTICS	1970	Larger airplanes make larger markets possible
	1980	Containerization makes transport of goods cheaper
	> 1990	Larger ships make transport of goods and raw materials cheaper and cheaper
		3D PRINTING FUTURE
		ONLY RAW MATERIALS TRANSPORT NECESSARY
SUPPLY CHAIN	1980	First supply chain concepts and -systems come to market
	1990	Fully developed supply chain management
	> 2000	Automation and ICT makes just in time delivery possible
		3D PRINTING FUTURE
		SUPPLY CHAIN WILL BECOME VIRTUAL AND FULLY DIGITAL
MANUFACTURING	< 1970	Manufacturing close to market or resource
	1970	Manufacturing moves to raw material resource locations
	1980	Manufacturing moves to low labor cost countries
	> 1990	Automation, moving some manufacturing back to market
		3D PRINTING FUTURE
		MANUFACTURING BACK TO LOCAL MARKETS

MANUFACTURING IN TIME



<1970

Manufacturing on point of sale

Local markets

1980

Part of production goes to source

Forest,
oil fields

1990

Manufacturing where labour cost is cheap

China, India etc.

2000

Automation, less labour

Part goes back to
local markets

FUTURE

3D printing manufacturing at home

Personalized

Additional to a drastic change of the manufacturing process, 3D printing holds the promise of unique customization of our products. Before the industrial revolution, products were unique and custom-made. Furniture, clothes, houses and machines were tailor-designed and made by skilled crafts people. It took a long time to manufacture these products. Since the rise of mass production in the early 20th century, consumers' demands have been met by producing large quantities of goods in significantly less time. Products have become cheaper and available for everybody. 3D Printing however offers customers options again to personalize the products and goods they are purchasing or producing. Therefore 3D printing does not only hold the promise of cheap manufacturing, but also the promise of mass customization. (12)

The first big implication of increasing applications and price drops of 3D printing, is that more products will be manufactured at or close to their location of purchase or consumption. This might even mean production of products or replacement of parts on household level. Many products that have relied on the efficiencies of large-scale, will be produced locally with centralized manufacturing. Even if the per-unit production cost is higher, it will be more than offset by the elimination of shipping and buffer inventories. For example, whereas just a few hundred factories around the world make cars today, they might one day be made in every metropolitan area. Parts could be made at dealerships and repair shops, and assembly plants could eliminate the need for supply chain management by making components when needed. So 3D printing holds the promise to produce locally. (29)

Finally, 3D printing will create a new way to develop and design existing and revolutionary new products. It starts at the design process. Products may be developed in open-source co-creation communities on the Internet. The resulting digital design files can directly control 3D printers to produce the products. A digital design can also be made by 3D scanning of a model or an existing object or product. After such a 3D digital scan the design can be adjusted and changed digitally to get the required (customized) product. Next to this new way of designing existing products, 3D printing offers the promise to create completely new products. There is much more freedom in creating complex structures and shapes. The material properties can be adjusted on a very small scale, which gives the opportunity to create products with new characteristics and functions that are currently unimaginable. Additionally, even living tissue and organisms can be 3D printed, which opens a range of new personalized medicines, surgery and regenerative medicine. 3D printing holds the promise to (co-)create revolutionary new products, systems and applications. (26) (30) (12)

HOW DOES IT CHANGE THE WORLD?

CHEAPER MANUFACTURING	Relocate manufacturing to the point of need (market) Large number of small investments instead of small number of large investments in manufacturing capacity Lower working capital, less stock, semi-manufactured products and labor Supply chain and logistics will be simple and more efficient Less raw material required, produce what is needed, no waste
MASS CUSTOMIZATION	Every product can be adjusted to personal preferences; colors, size, design Clothes can be adjusted to personal size, shapes and preferences Furniture can be adjusted to size, number, personal style Teeth, prosthesis, medicines, etc. can be adjusted to personal conditions
LOCAL PRODUCTION	Production can take place near demand, at home or in local 3D print shops Unit production cost can be higher, will be offset by less shipping cost Spare parts and replacements parts can be produced locally Materials can be recycled and used for production locally
NEW PRODUCTS, SYSTEMS, APPLICATIONS	3D Printing technology development towards faster, more detailed and complex manufacturing Develop products in open-source co-creating communities 3D scanning of objects and adjustment of design More freedom in creating complex structures and shapes Possibility to adjust material properties on a very small scale Living tissues and organism can be 3D printed

THE 3D PRINTING MARKET

The market for 3D printing is growing rapidly. Many business analysts, consultancy companies and financial institutes have discovered the 3D printing industry and market. They follow and analyze this market and make forecasts (31) (27) (12) (32) (31) (33). Politicians have also recognized the potential of 3D printing. In his State of the Union 2013, president Obama highlighted 3D printing as something that could generate new high-tech jobs in the United States.

There is a fast-growing market for 3D printed products that drives the so-called primary market, which includes equipment, materials, software, design and services. In 2012 the primary market for 3D printing was about 2.2 billion dollar, an increase of 29% from 2011. Market growth in the past 3 to 4 years was around 30% per year. Projected growth of this primary 3D printer market for the next couple of years is estimated at 40% to 50% per year. (34) (27) (26)

According to Deloitte (27), most of the revenue in the 3D printing sector will be generated by commercial users, as equipment makers experience continued price pressure and 3D printers become more affordable. In the past, only large organizations such as 3M, Ford and Microsoft had sufficient capital to invest in 3D printers and explore new business models or product lifecycles. Smaller organizations are now increasingly joining in the exploration of applications, thanks to more affordable costs. Some are even purchasing 3D printers without a pre-defined use and setting up small labs to explore opportunities for efficiencies or new business.

Another key driver to growth is the increasing number of available materials for 3D printing. Materials are equally important as the

3D printers themselves: feedstock materials account for 40% of revenue for the 3D printing sector and are expected to increase further (35). Even though polymers are the most commonly used materials, other materials such as metals, paper and even organic tissue are becoming available. The development of new composites and smart materials could allow the industry to explore new product development in new sectors such as electronics: from simple motherboards to robots or LED’s.

And obviously, the product-design process is being transformed by the rise of 3D printing. It allows companies to market and test new products, while making necessary modifications based on customer feedback. Printing small batches of a product, testing different versions and only taking the most successful one(s) into production. Instead of mass-producing one product, based on limited feedback from focus group participants, companies can now introduce five products and sell them directly to consumers, letting the market decide which one is successful enough for mass production.

Prototyping, customized products and small production runs will keep driving the commercial usage of 3D printers in the short term while new niches develop. The range of enterprise applications for 3D printing varies between sectors, but three industries are already testing or applying 3D printing. These sectors, expecting the biggest gains, are the aerospace, biomedical and consumer product industries. (12)

BIOMATERIALS

Considerable amounts of raw materials are used for the production of houses, cars and goods. In 2050, around 9 billion people will be living on earth (36) *.If we do not change our production and consumption patterns, this will lead to a steady growth in demand for resources and raw materials* (37)*.*

The earth provides us with resources in different ways. Crops, plants and trees (i.e. biomass) grow on the earth. Sand, stones and clay are around us on the earth. Iron, aluminum, copper and other metals are found in the earth. And fossil fuels, which where crops, plants and trees many years ago, are also extracted from the earth.

However, many of these resources aren't infinitely available on our planet. Especially what we delve from the earth are limited resources, like metals and fossil fuels. In contrast, biomass is a renewable resource. So if we want to fulfill the needs of future generations, we need to change to a bio-based economy.

From an economy that runs on fossil fuels to an economy that runs on biomass feedstock.

RESOURCES AND MATERIALS

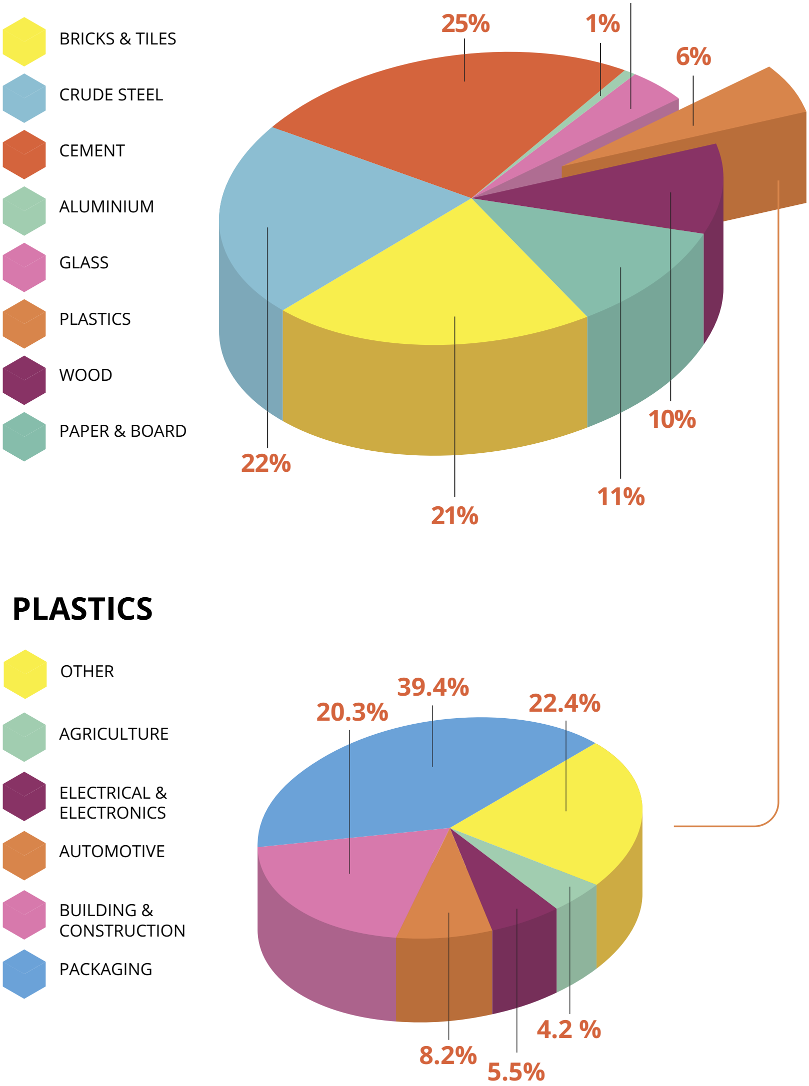
Bulk materials such as bricks and tiles, steel, cement, aluminum, glass, plastics, wood, paper and boards, account for approximately 920 million ton per year in EU-27. Cement represents 25% of the bulk material use in Europe and is responsible for the highest CO_2 emissions. Crude steel is the second largest with 22% of material use, followed by bricks and tiles with a share of 21%. Paper/board and wood account for respectively 11% and 10%. This is followed by plastics with 6%, which is followed by glass that has a share of 4%. Aluminum accounts for 1% of the bulk material use in the EU-27. (38)

In Europe, plastics represent 6% of the material use, which is around 60 million ton per year. It is used in the packaging, building and construction and automotive sectors and also applied in electronics and consumer goods. However, packaging is by far the largest application for plastics with a share of 39.4% of the total European demand in 2012. The second largest is the building and construction sector with 20.3%. The third largest is the automotive sector, accounting for 8.2% of the European plastic demand. Electrical and electronic applications and agricultural applications are responsible for 5.5% and 4.2% respectively. Other applications, such as appliances, consumer products, furniture and medical products, account for 22.4% of the European plastic demand. (38) (39)

PLASTICS

Everywhere around us, a wide variety of plastics is used. From the beginning of the 20th century, plastics have changed the world and

MARKET SHARES OF BULK MATERIALS AND PLASTICS APPLICATIONS



enabled a modern lifestyle – being applied in telephones, tablets, sporting goods, etcetera. There are even plastics with a wood, metal or leather look and plastics that function as carriers for a vaccine. The word 'plastics' comes from the Greek word *plastikós*, which means 'to mold'. This is because all plastics are soft and moldable during production, which allows for almost any object to be made out of a plastic. (40) (41)

Plastics are synthetic materials, made out of chemical building blocks. These building blocks are small organic molecules, also known as monomers, which largely contain carbon amongst other materials. During chemical reactions, long chains of monomers can form polymers. Most polymers nowadays are fossil-based; on oil derivatives such as naphtha. Alternatively, they can originate from organic materials such as corn, sugar cane and even banana peels – then being called bio-based plastics. (42)

HISTORY OF PLASTIC

Plastics haven't always been made from oil. The first plastics were actually bio-based, and were alternatives for the valuable and scarce raw materials such as ivory, horn, lapis lazuli, ebony, amber, pearls and coral. Celluloid is considered to be the very first plastic and was discovered in 1855 by the Englishman Alexander Parkes. Celluloid is made of cellulose acetate and camphor. In 1869 the first factory for the production of thermoplastic celluloid opened its doors. Celluloid was used for all kinds of applications, from billiard balls to picture graphic films and all kinds of decorative goods, such as dolls, hairpins and combs. Also the famous LEGO bricks were initially made of cellulose acetate. So celluloid exploded economically, but sometimes also literally: it was easily combustible, especially in film material when the moisture content decreased over time.

In 1923 mass production of cellophane (cellulose hydrate) started, which we still know as a transparent crispy film to wrap around flowers. At that time cellophane was the first plastic that came into direct contact with food, but it was gradually replaced with cellulose acetate in a lot of applications. (42)

Phenol formaldehyde, known as Bakelite, is a hard moldable material. It was the first synthetic plastic and a good economical alternative for celluloid. Discovered in 1907 by the Flemish chemist Leo Hendrik Arthur Baekeland during his work in New York, and was patented in 1909. Ten years later in 1919, he founded the General Bakelite Company. Because of its constant quality in mass production, non-conductivity and excellent heat resistance properties, Bakelite conquered the world. It was for instance used for telephone and radio casings and in cars and planes. Bakelite became a National Historic Chemical Landmark by the American Chemical Society in 1993. (41)

In the period between 1930-1950 the polyamides became popular, such as polystyrene, PTFE known as Teflon® and PA6.6 known as Nylon®, which was the world's first durable synthetic fiber. From 1956 onwards they were followed by today's highest volume mass-produced plastics: polyethylene (PE) and polypropylene (PP). (42)

PLASTIC MARKETS AND APPLICATIONS

From 1950-2012 the plastic industry experienced an average annual growth of 8.7%. In 2012 it was producing around 290 million tons of plastics worldwide. China is the leading plastics producer with a share of 23.9% of the world's total plastic production. The rest of the production in Asia including Japan accounts for an additional 20.7%. The European production (EU-27+2) represents 20.4% of the total production of plastics in the world, followed by North America with a share of 19.9%. (39)

GLOBAL PLASTIC PRODUCTION SHARE IN 2012 (39)

REGIONS	SHARE
CHINA	23.9%
REST OF ASIA INCLUDING JAPAN	20.7%
EUROPE	20.4%
NORTH AMERICA	19.9%
MIDDLE EAST AND AFRICA	7.2%
LATIN AMERICA	4.9%
FORMER SOVIET REPUBLIS	3.0%

In 2012, there were more than 62,000 companies in the plastic industry in the 27 members states of the European Union. These include plastic producers, converters and the plastic machinery sector. Together they account for 1.4 million jobs, with a turnover of 300 billion euro. (39)

Different plastics feature different properties and therefore have different applications. In Europe (EU-27+2) most plastic demand is for polypropylene (PP), with a share of 18.8%. PP can be used for flowerpots to car bumpers. Second comes polyethylene (PE), which is separated into low density (LD) and high density (HD) PE and represents respectively 17.5% and 12% of the European demand. This is followed by 10.7% for PVC, 7.4% for PS, 7.3% for PUR and 6.5% for PET, which is known from the soda and water bottles. Plastics like ABS, PTFE and others, account for the remaining 19.4% of the European plastic demand. (39)

PLASTIC SHARE BY RESIN TYPE IN EUROPE 2012 (39)

RESIN TYPE	SHARE	APPLICATIONS
PP	18.8%	PP flowerpots, PP car bumpers
PE-LD & PE-LLD	17.5%	PE-LD bags, PE-LLD wire cables
PE-HD	12.0%	PE-HD containers, PE-HD caps
PVC	10.7%	PVC windows, PVC rain boots
PS & PS-E	7.4%	PS yoghurt pots, PS glasses frame
PUR	7.3%	PUR sponge, PUR insulation panels
PET	6.5%	PET bottles
OTHERS	19.8%	ABS LEGO bricks, PTFE (Teflon) pan

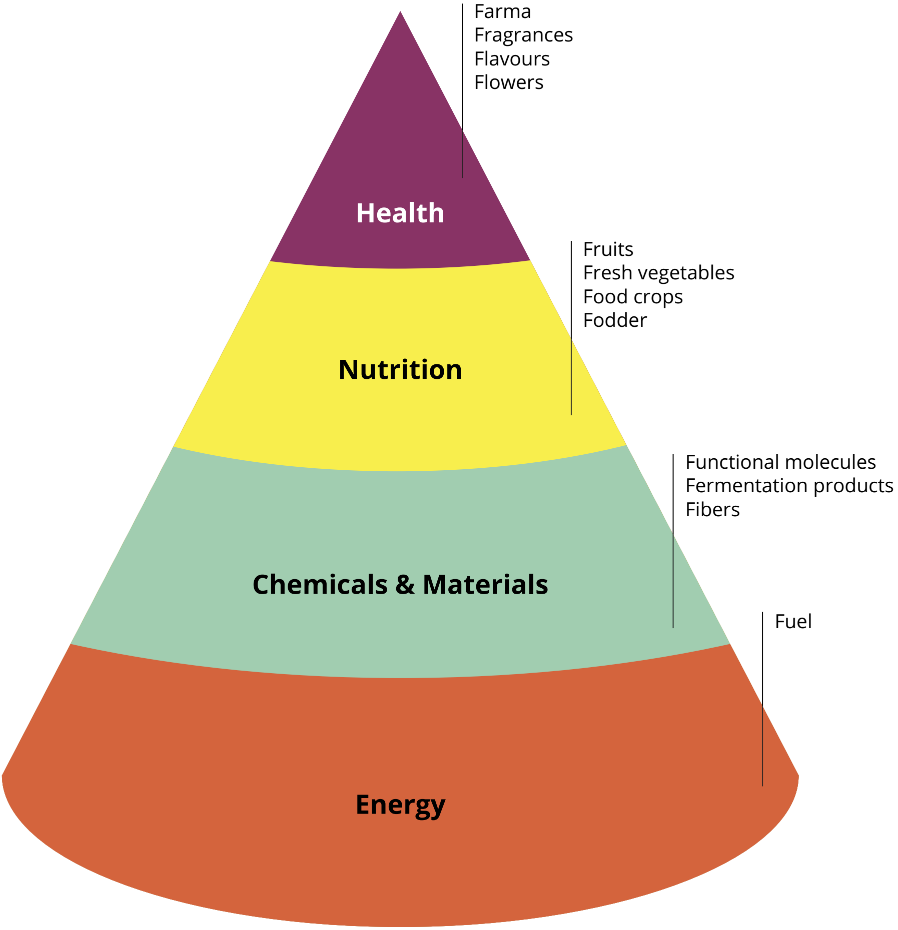
BIO-BASED PLASTICS

The world’s first plastic, celluloid, was a bio-based plastics and was used for the production of billiard balls instead of valuable ivory. More bio-based plastics followed such as cellulose acetate, which was used for the famous LEGO building bricks. Nevertheless these bio-based plastics were quickly abandoned in the era of cheap and abundant oil. Therefore most polymers are fossil-based nowadays; based on oil derivatives such as naphtha. (42)

Today, bio-based plastics represent less than 1% of about 290 million tons of plastics produced globally. The global production capacity of bio-based plastics was around 1.4 million tons in 2012 (39). Nevertheless, bio-based plastics are becoming important again. Their revival started around 1980 with plastics based on starch, caused by a relatively low price and steady availability of crops and its unique functionality of rapid biodegradability. At that time, especially the biodegradable and compostable functionalities were the focus of research and development (42). But in later years the main interest shifted towards the renewable resource aspect of the bio-based plastics, essential for a bio-based economy. (43)

In a bio-based economy, biomass is used for a variety of applications, such as pharmaceuticals, food, chemicals, materials, fuels and electricity. Biomass is preferably used firstly for high-value applications such as pharmaceuticals, food and bio-based materials, and secondly for lower-value applications, such as biofuels or electricity production (44). The value pyramid of biomass shows this hierarchy in biomass use. Low volumes with high value for pharmaceutical products at the top, and high volumes with low value for energy applications at the bottom. (45) (43)

BIOMASS VALUE PYRAMID



FROM CROPS TO BIO-BASED PLASTICS

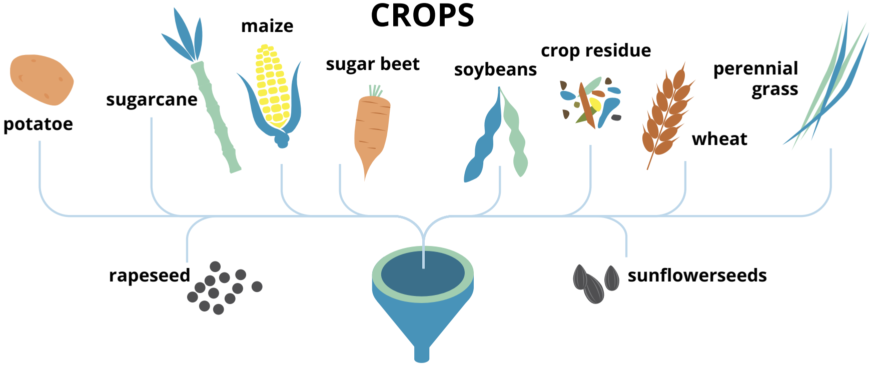
To produce a high-value application such as biomaterials, numerous types of crops can be used to extract sugars, starches, oils or lignocelluloses, ranging from sugar beet, maize, rapeseed, perennial grasses to crop residues. These crops can be converted into bio-based bulk chemicals through different conversion techniques:

1. Gasification, resulting in syngas or methanol, and subsequent conversion into materials
2. Pyrolysis, resulting in bio-oil, and subsequent conversion into materials
3. Catalytic conversion of biomass into materials e.g. furanics
4. Pulping, resulting in paper and possible lignin derivatives (cellulose)
5. Other physico-chemical synthesis of materials
6. Fermentation using micro-organisms, resulting in chemicals and intermediates (starch)
7. Enzymatic conversion, resulting in chemicals and intermediates
8. Extraction of feedstock from traditional crops, resulting in e.g. vegetable oil for lubricants
9. Extraction of materials that were produced in planta, such as PHAs

The bio-based bulk chemicals are often intermediate products and can be converted into a wide range of bio-based plastics. (37)

CROPS TO BIO-BASED PLASTICS

CROPS



CONVERSION

Gasification resulting in syngas or methanol, and subsequent conversion into materials

Pyrolysis resulting in bio-oil and subsequent conversion into materials

Catalytic conversion of bio-mass into materials e.g. furanics

Pulping resulting in paper and possibly ligning derivatives

Other physico-chemical synthesis of materials

Fermentation using micro-organisms, resulting in e.g. vegetable oil for lubricants

Enzymatic resulting in chemicals and intermediates

Extraction of feedstock from traditional crops, resulting in e.g. vegetable oil for lubricants

Extraction of materials that were produced in planta such as PHAs

BIOMATERIALS

BIOBASED PLASTICS

PLA, PHA, Bio-PE, Bio-PP, Bio-PET, TPS, etc

BIO-BASED ≠ BIODEGRADABLE

Bio-based plastics can be biodegradable or non-biodegradable but are always based on renewable resources. Biodegradable materials like bio-based plastics can be broken down by micro-organisms into naturally occurring gasses such as CO_2 and/or CH_4, water and biomass. There is a difference between home compostable or industrial compostable. With home composting, total biodegradability is possible with a compost heap in a garden. Bio-based plastics that require industrial composting do not biodegrade completely in natural environments; they need specific conditions such as higher temperatures and humidity levels to accommodate an optimum for micro-organisms. (46) (42)

It has become clear over time that biodegradability and compostability are only interesting functionalities when there is some additional value over waste disposal. Therefore the focus of research and development has shifted from biodegradability towards the bio-based content – like production of non-food raw materials and bio-based plastics from plant residues – and towards the improvement of the technical performance of different bio-based plastics. (42)

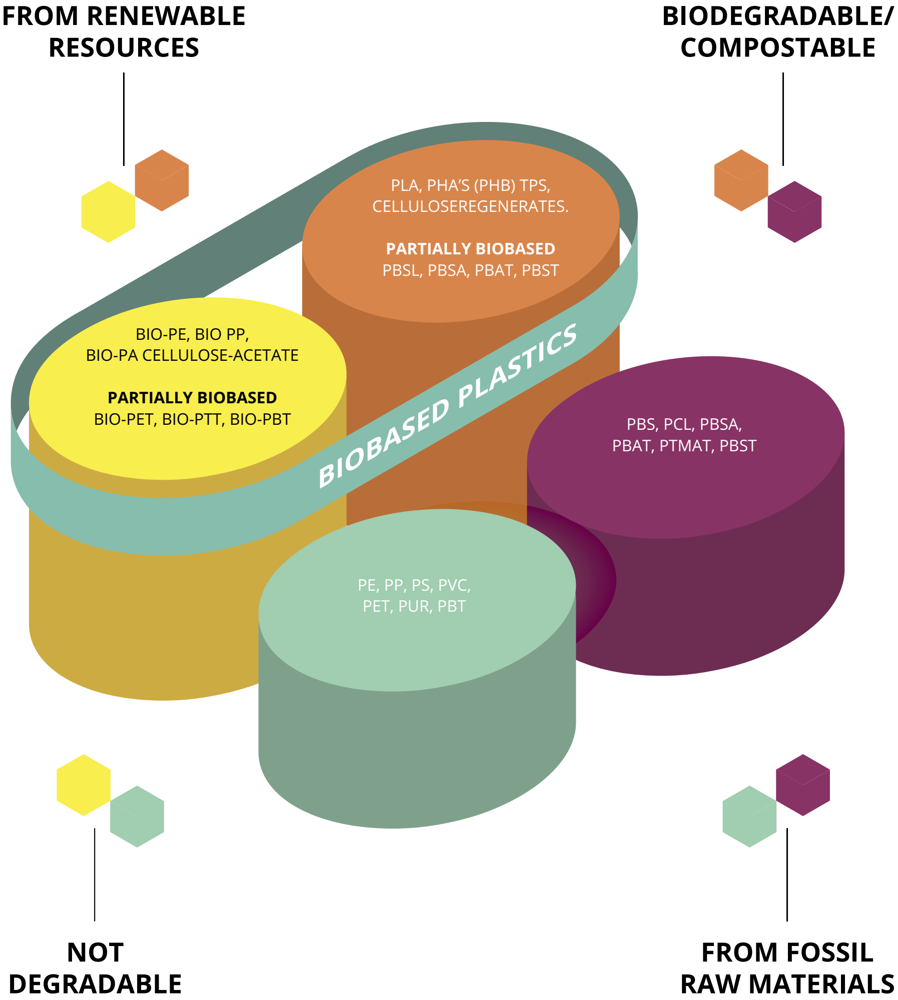
So plastics based on cellulose were the first bio-based plastics. The revival of the bio-based plastics was based on starch, and was caused by the relatively low price, steady availability of crops and its unique rapid biodegradability. By hydrolytic cracking, starch can also be converted into glucose, which again is used as a raw material in the fermentation process to produce other bio-based plastics such as PLA (Polylactic acid) and PHA (Polyhydroxy alkanoate). Sugars are also used for a lot of bio-based plastics ranging from bio-PE (Polyethylene), bio-PP (Polypropylene) and PVC (Polyvinyl chloride) to partially bio-based plastics such as PET (Polyethylene terephthalate). These latter bio-based plastics are not biodegradable while identical to their fossil-based counterparts. Because they are substitutable, these bio-based plastics are called “drop-ins” (46) (42). A mixture between fossil-based and bio-based plastics is also possible, and can range from biodegradable to non-biodegradable.

It is possible to blend bio-based plastics with other bio-based plastics, such as TPS with PLA. But it is also common to blend bio-based plastics with fossil-based plastics, for example PLA with PBAT. This blend still has its biodegradable functionality, as both the bio-based PLA and the fossil-based PBAT are compostable. However when PLA is blended with a non-biodegradable fossil-based plastic, this functionality is lost. Like adding additives, blending is another way of tweaking the mechanical, thermal and other properties (a.o. biodegradability) and is applied tailor-made for a wide range of applications. (47) (42)

BIO-BASED PLASTICS PROCESSING, ADVANTAGES AND DISADVANTAGES (48) (47)

MATERIAL	PROCESSING	ADVANTAGES	DISADVANTAGES
CELLULOSE DERIVATIVES	**PROCESSING TEMPERATURE** 190 - 240 ºC **SUITABLE FOR** injection molding, sheet extrusion (thermo forming), fiber extrusion	Good mechanical properties. Good thermal resistance. Glossy transparent appearance.	Thermal degradation possible
STARCH BASED PLASTICS	**PROCESSING TEMPERATURE** 120 - 180 ºC *No drying needed* **SUITABLE FOR** 3D printing, film blowing, injection molding, sheet extrusion (thermo forming), foam extrusion	Good mechanical properties Excellent gas barrier properties Anti-static Fast biodegradable	Humidity dependent Not completely transparent
POLYLACTIC ACID (PLA)	**PROCESSING TEMPERATURE** 170 - 210 ºC **SUITABLE FOR** 3D printing, film extrusion, thermo-forming, blow molding, injection molding, fiber extrusion	Good mechanical properties Transparent	Only compostable in industrial facilities Water sensitivity during processing Low melt strength
POLYHYDROXY ALKANOATES (PHA’S)	Harvested from micro organisms	Mechanical properties can be varied Hydrophobic Fast biodegradable	Low melt strength

BIO-BASED AND BIODEGRADABLE PLASTICS



FROM RENEWABLE RESOURCES

BIODEGRADABLE/ COMPOSTABLE

PLA, PHA'S (PHB) TPS,
CELLULOSEREGENERATES.

PARTIALLY BIOBASED
PBSL, PBSA, PBAT, PBST

BIO-PE, BIO PP,
BIO-PA CELLULOSE-ACETATE

PARTIALLY BIOBASED
BIO-PET, BIO-PTT, BIO-PBT

BIOBASED PLASTICS

PBS, PCL, PBSA,
PBAT, PTMAT, PBST

PE, PP, PS, PVC,
PET, PUR, PBT

NOT DEGRADABLE

FROM FOSSIL RAW MATERIALS

APPLICATIONS AND MARKETS

Overall the bio-based plastic market is emerging rapidly. New partnerships, pilot plants and production facilities are frequently being announced or launched. According to the European Bio-based plastics association, the worldwide bio-based plastics production capacities in 2012 were 1,4 million ton. Forecasted is that by 2017 this number will gave grown to more than 6 million ton. (39)

GLOBAL BIO-BASED PLASTIC MARKETS (39)

MARKET	2012 TONS	2017 PROGNOSIS TONS
CONSTRUCTION	2,500	12,000
PHARMACEUTICAL & MEDICAL	7,000	23,000
CONSUMER PRODUCTS	81,000	151,000
HORTICULTURE & AGRICULTURE	84,000	121,000
CATERING	101,000	181,000
TECHNICAL APPLICATIONS *INCL. AUTOMOTIVE*	130,000	663,000
BOTTLES	450,000	3,817,000
OTHER PACKAGING *INCL. CARRIER BAGS*	510,000	1,152,000
OTHERS	30,000	66,000
TOTAL	**1,395,000**	**6,185,000**

Currently, the main market for bio-based plastics is packaging: bio-PET bottles, starch or PLA based bags, foamed PLA trays and PLA pots, containers, nets, cups or bottles (39). Nevertheless the market for bio-based plastics in other applications is also increasing for numerous applications; for instance in textile (shoes, t-shirts, rugs), in agriculture and horticulture (pots, clips, ties) in consumer goods (mobile telephone housing, computer keyboards) and even in biodegradable films. As well as in various sporting goods ranging from ski boots to sunglasses, for seat covers, gear shifts, fuel connectors, accelerator pedals in the automotive industry and much more. (48) (46)

The explosive growth in bio-based plastics is first of all due to an increased production of bio-based “drop-ins” such as bio-based PET made from sugars out of corn (in US) and bio-based PE from sugars out of sugarcane (in Brazil). These plastics have exactly the same chemical composition as their fossil based counterparts and are therefore perfect one-to-one substitutes. They don’t have improved performance characteristics, and therefore compete on price, and will benefit of economies of scale. Also high growth rates are booked by bio-based plastics that have different characteristics and are therefore no substitutes for fossil-based plastics, such as PLA and PHA. Overall, the shift from biodegradable to non-biodegradable production of bio-based plastics is significant and means an increase of bio-based plastics in durable applications. (47) (42)

BIO-BASED PLASTICS FOR 3D PRINTING

There are many materials that are used for 3D printing, such as metals, ceramics and polymers. Different applications and 3D printing techniques require different materials. Thermoplastics are used for extrusion and commonly used in the 3D printing process. The two dominant thermoplastics are acrylonitrile butadiene styrene (ABS) and polylactid acid (PLA). ABS is a fossil-based plastic and PLA a bio-based plastic. (49)

GLOBAL BIO-BASED PLASTIC MARKETS (39)

PROCESS	MATERIALS	FOSSIL BASED	BIO-BASED
EXTRUSION	Polymers (thermoplastics)	ABS, ABSi, ABS-M30, ABS-M30i, ABS-plus, ABS-ESD7, PC, PC-ISO, PA, PPSF/PPSU, ULTEM-9085	PLA, PLLA, PLGA, TPC, TPS, PA-11
DIRECT ENERGY DEPOSITION	Metals		
SOLIDIFICATION OF POWDER	Metals, ceramics, polymers (thermoplastics)	PC, PS, PMMA, PA-12, HDPE, POM, PCL, PEEK, HIPS, SAN	PA-11, PLA, PLGA, PHBV
PHOTOPOLYMERIZATION	Photo-polymers (photocurable resins)	Epoxy/Acryl	
SHEET LAMINATION	Hybrids; paper, metal, ceramics		

PLA

According to Ady Jager, PLA is considered to be the most important of all bio-based polyesters on the market. PLA is generally produced from sugar (sugar beets, sugarcanes, corn). Through fermentation, with the help of micro-organisms, lactic acid is produced. This is a highly efficient process. Per sugar molecule, two molecules of lactic acid are produced, without any residual products. According to Frans Kappen, producing PLA directly from the lactic acid would result in PLA with low molecular weight and therefore bad properties. PLA with better properties is being produced from lactides. Lactic acid has two isomers; D (-) lactic acid and L (+) lactic acid, and they are each other's mirror image. Two lactic acid molecules can form one lactide molecule; a D-D-lactide, a L-L-lactide or a D-L-lactide. In the polymerization process these lactides can be mixed in order to obtain the required characteristics (47) (50). Pure poly L-lactic acid (PLLA) or pure poly D-lactic acid (PDLA) is a hard and stiff material because of high crystallinity and high melting point. Most commercially PLA grades consist of poly L-lactic acid with a small amount of D-lactic acid. When the amount of D-lactic acid increases, the material becomes less crystalline, it crystallizes slower and the melting temperature decreases. PLA that consist out of 10% D-lactic acid or more is amorphous. (48) (47)

Jan Jager added that the PLA polymer has to be adapted for specific applications. So the PLA polymer can be converted into a specific product by compounding, copolymerization or by blending with other bio-based or fossil-based plastics. With compounding, additives are added, such as color pigments, UV stabilizers, impact resistance modifiers, flame retardants, plasticizers, chain extenders, nucleating agents, etc., to optimize the properties for the planned application. (51) (47)

MODIFICATION PLA-PROPERTIES (48) (47)

CHAIN EXTENDERS FOR PLA	Increase melt strength Allow recycling Allow ‘novel’ processes
PLASTICIZERS FOR PLA	Efficiency/compatibility Volatility Safety
NUCLEATING AGENTS FOR PLA	Increase Heat Deformation Temperature Crystallization speed
PLA COMPOSITES	Natural fibers Mechanical properties Processing Degradability
IMPACT MODIFIERS FOR PLA	Injection molding Toughness in film
FLAME RETARDANTS FOR PLA	More ‘green’ additives

For PLA new additives become increasingly available and can improve properties of PLA – thereby opening new applications. However the effects of the additives are also depending on the PLA grade and the processing conditions. In addition, a careful selection is necessary as additives also have an influence on the clarity, the biodegradability/compost ability and the % of renewable resources in the product. (51) (47)

ABS VERSUS PLA

Both ABS and PLA are known as thermoplastics: they become soft and moldable when heated and return to a solid when cooled. This process can be repeated again and again. But how do these two compare in their performance for 3D printing? In the table below you can find a summary of the characteristics for ABS and PLA.

Overall ABS is preferred for its strength, flexibility, machinability and higher temperature resistance. The hot plastic smell and the fact that it’s fossil fuel based are negative qualities. The additional requirement of a heated print bed means that some printers are simply incapable of printing ABS with any reliability. PLA is preferred for its wide range of available colors and translucencies and glossy feel. It is often used for art works and small household products. Many appreciate the bio-based origin and prefer the semi-sweet smell of PLA over ABS. When properly cooled, PLA seems to have higher detail in 3D printing. Combined with low warping of parts, this makes PLA a popular plastic for home printers, hobbyists, and schools. (52) (54) (55) (53) (49)

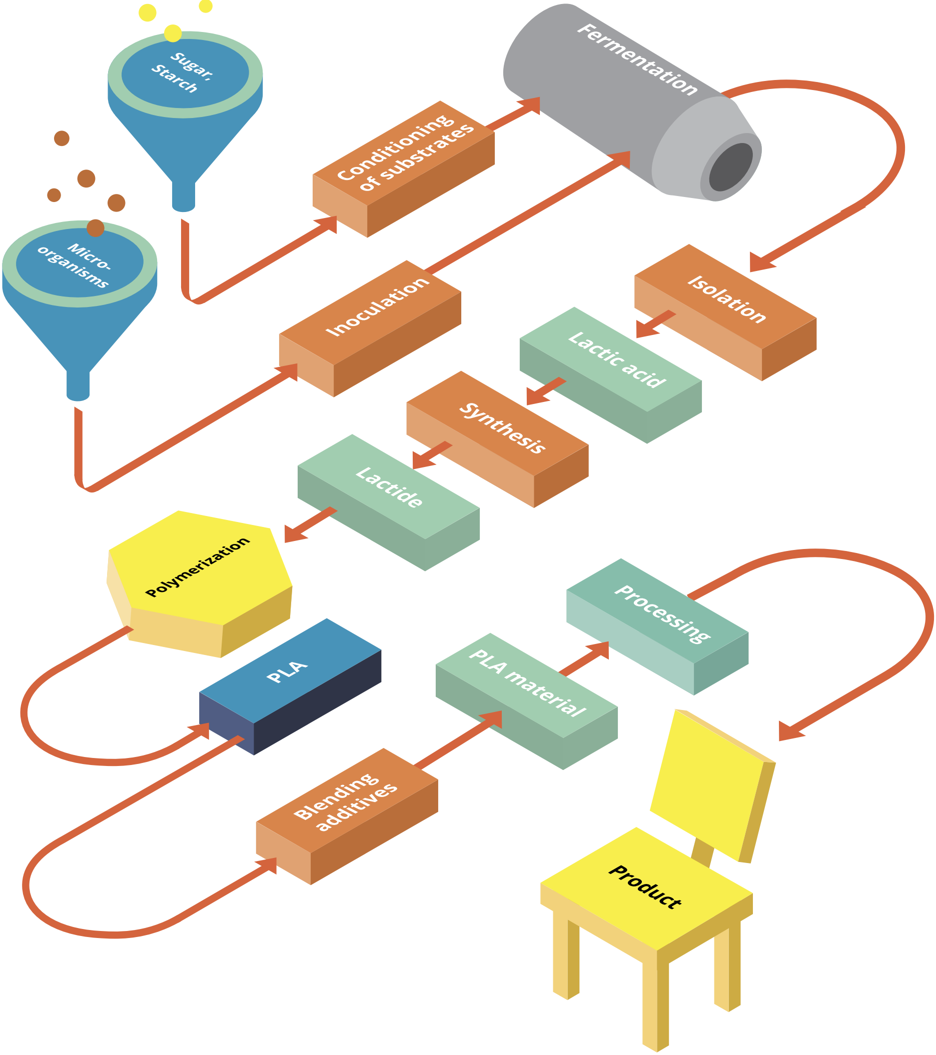
FOSSIL ABS VERSUS BIO PLA (48) (47)

	ABS	PLA
MELTING TEMP.	225 - 250 degree Celsius	190-240 degree Celsius
MOISTURE	ABS with moisture will bubble and sputter when printed, but easy to dry	PLA with moisture will bubble and sputter when printed Not easy to dry, can react with water and at high temperatures will de-polymerize
HEAT	Less deformation due to heating	Product can deform because of heat
SMELL	Plastic styrene smell	Corn like sweet smell
COLOR	Less color brightness	Bright, shiny colors and smooth appearance
HARDNESS	Very sturdy and hard	Less sturdy than ABS
FUMES	Hazardous fumes	Non-hazardous fumes
DETAIL	Higher layer height, less sharper printer corners, needs a heated printer bed for less warping	Higher max printer speed, lower layer height, sharper printed corners, less part warping
LIFETIME	Longer lifetime products	
ENVIRONMENT	Non-biodegradable Made from oil	Biodegradable Made from sugar, corn, soybeans or maize

FUTURE DEVELOPMENTS IN BIOMATERIALS FOR 3D PRINTING

The 3D printing industry is developing rapidly. Not only in the 3D printing technology but also in the materials that can be used in 3D printers. Existing (bio) plastics can be tweaked and adjusted to create the desired properties.

PLA PRODUCTION PROCESS



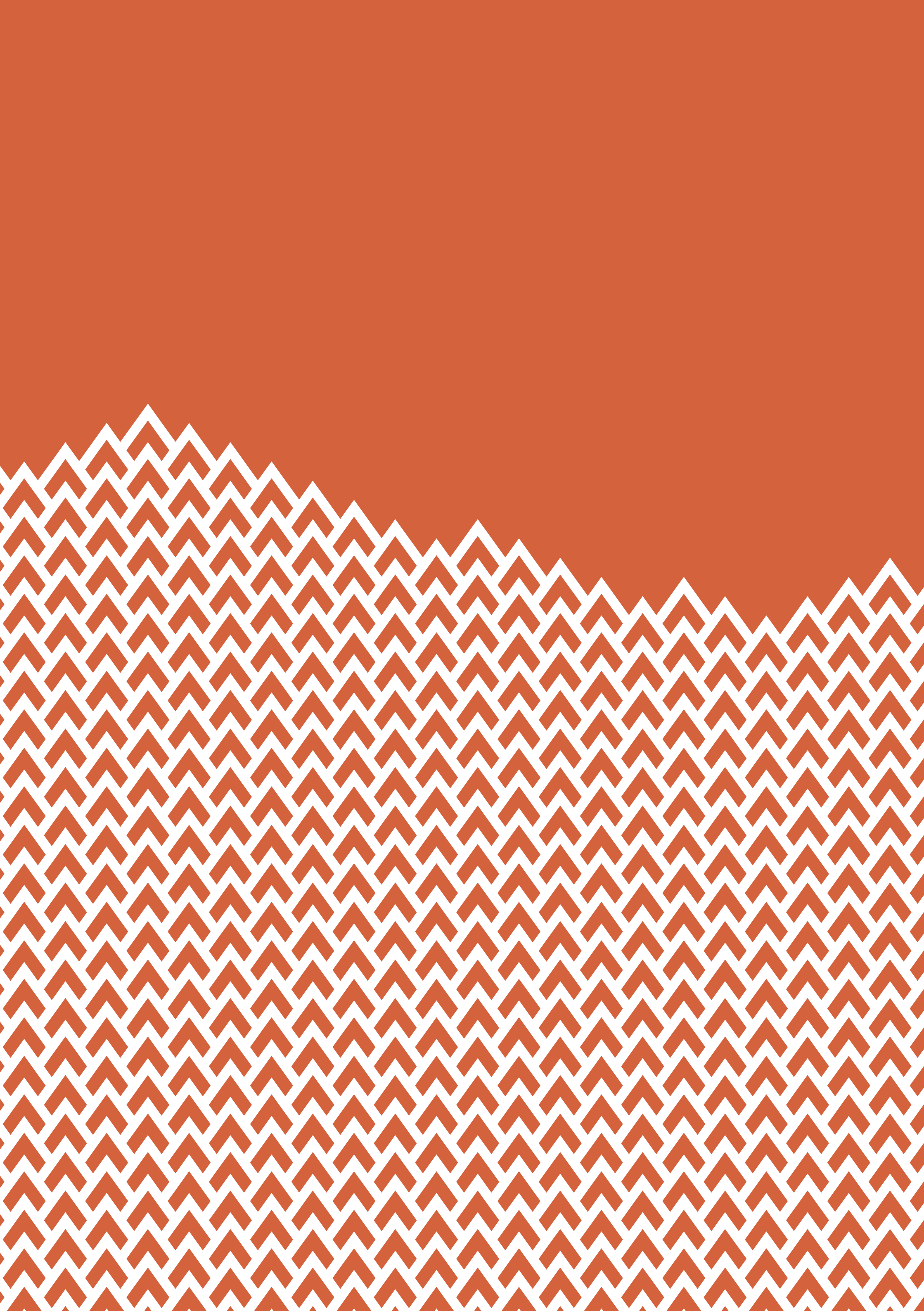
Frans Kappen has pointed at the ongoing research to mutually tune the 3D printing process and biomaterials. This will improve the range of applications; more detailed products and higher quality and stability of the products.

Developments in (bio-based) ‘smart’ materials are also ongoing. Smart materials have one or more properties that can change by external stimuli, such as pressure, temperature, light, pH, electric or magnetic fields. For example polymers that can change color or shape when the temperature increases or decreases. Or polymers that are self-healing. These smart features will lead to a whole range of new applications and products.

But especially there is a wealth of research and development into new and blended biomaterials for 3D printing. It opens up possibilities to make new, more detailed and complex products, with changing properties and a new look and feel.

(FUTURE) BIOMATERIALS FOR 3D PRINTING

	PRODUCT MATERIAL	FEATURES
THERMO CHROME PLA	Regular PLA filament with thermo chrome feature	Changes color in response to temperature changes
FLEX PLA OR SOFT PLA (59)	Regular PLA filament mixed with unknown chemical to make it soft, though and rubbery	Similar to regular PLA filament, only more flexible
NYLON 11 (59)	Polyamide 11 (PA11) or Nylon 11 from vegetable oil from castor beans	Flexible, strong and self-lubricating
BIO RUBBER (56)	TPE; thermoplastic elastomer from Rapeseed Oil	Strong, UV resistant, chemicals and temperature resistant
ARNITEL® ECO (57)	TPC; thermoplastic co-polyester made partially of rapeseed oil	Flexible, strong, C2C certified
BIOME3D (58)	Thermoplastic from plant starches	Biodegradable
STRAW BASED (59)	Straw based plastic made from rice and wheat stalks mixed with plastic and additives	Low cost material
BAMBOO BASED (60)	Filament made of finely ground bamboo	Low cost material
LAYBRICK (61)	Filament made of finely ground chalk with a polymer binder	Feel like sandstone when printed, no layered look
LAYWOOD (59)	Filament made of 40% recycled wood with a binding polymer	Wooden look and smell, can also be handled like wood



TOWARDS A SUSTAINABLE AND CIRCULAR ECONOMY

The promise of 3D printing with biomaterials is that it can create a fully sustainable and circular manufacturing process. 3D Printers will manufacture our personalized products locally and only when we need it. The printers re-use existing materials or use new biomaterials as feedstock, while running on renewable electricity.

HOW DOES 3D PRINTING FIT WITH A CIRCULAR ECONOMY?
'The circular economy is a generic term for an industrial economy that is, by design or intention, restorative and in which material

flows are of two types, biological nutrients, designed to re-enter the biosphere safely, and technical nutrients, which are designed to circulate at high quality without entering the biosphere'. (62)

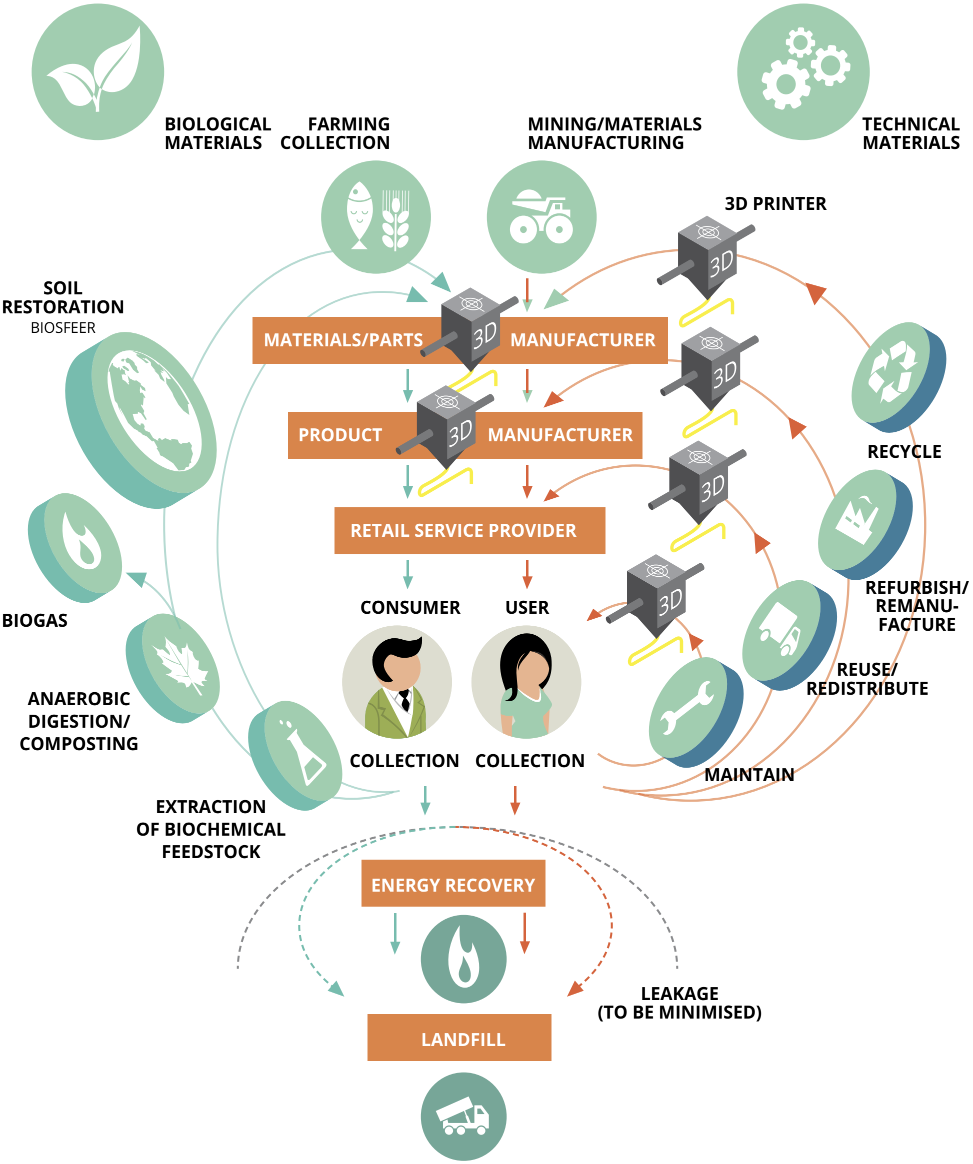
One of the influential institutions that develop the concept of the circular economy into business practice is the Ellen MacArthur Foundation (63). 'A circular economy seeks to rebuild capital, whether this is financial, manufactured, human, social or natural. This ensures enhanced flows of goods and services'. They have developed a circular economy system diagram, which illustrates the continuous flow of technical and biological materials through the 'value circle'. (63)

3D Printing can fit well in the concept of a circular economy. The 3D printing manufacturing process itself can lead to significant material savings. But 3D printing can contribute also in other parts of the circular economy system: especially in maintenance, re-use, re-manufacturing and re-cycling of products and goods. In the table below we have indicated how 3D printing could contribute to these elements in the circular economy. (64) (65) (66)

CIRCULAR ECONOMY AND 3D PRINTING

MANUFACTURING	No or less waste in manufacturing processes Less material use in products designed for 3D printing Production on demand, not for demand Production is local, requiring less transport and logistics Personalized products that fit your size, preference or style
MAINTENANCE	Print broken parts on demand, no spare parts necessary Print broken parts in situ, problem is solved immediately Print broken parts of any (old) product, lifetime of products is extended Repair can be done by yourself, any time you want, faster and cheaper
RE-USE & RE-MANUFACTURE	Products can have a second, third, etc. life by upgrading parts, replacement of old parts and/or re-design or re-styling Clothes can be adjusted to personal changes like size, shapes, preferences Furniture can be adjusted to personal circumstances, shapes, preferences Special elements could be added to the product afterwards
RE-CYCLE	Re-cycled materials can be easily used as resource for 3D printing Re-cycling can be done locally or even in situ and be used locally, less transport and logistics Plastics can be re-melted at home and directly used again in a 3D printer, no transport and logistics

CIRCULAR ECONOMY



IS 3D PRINTING SUSTAINABLE?

Although 3D printing could possibly contribute significantly to a circular economy, there are still two main aspects to cover. Firstly, plastics and other printing materials are largely produced from fossil fuels today and the production of plastics also costs energy. Secondly, current 3D printers run on electricity that is mainly produced by fossil fueled power plants.

Several Life Cycle Analyses (LCA's) have been conducted that compare the environmental impact of traditional manufacturing and additive manufacturing or 3D printing. Krieger and Pearce have performed an environmental life cycle analysis on three plastic products. The embodied energy and emissions from conventional large-scale production in, and shipping from, low-wage countries are compared to experimental measurements on a RepRap 3D printer fabricating products with acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), with and without solar photovoltaic (PV) power. The results for distributed manufacturing with existing low-cost open-source 3D printers using <25% fill PLA, indicate that the cumulative energy demand of manufacturing polymer products can be reduced by 41–64% (55–74% with PV), with concomitant emission reductions. Less pronounced positive environmental results are observed with ABS, which demands higher temperatures for the print bed and extruder. Overall, their results indicate that distributed manufacturing using open-source 3D printers with PLA has the potential to have a lower environmental impact than conventional manufacturing for a variety of products. (67)

3D Printing is not always as promising as expected. Faludi pointed out that not all 3D printing techniques produce without waste. FDM printers indeed do not produce waste, but others do: those that use material as a support structure or hardening parts of a vat with resins.

There is another important aspect aside from waste. One mass-production machine can manufacture millions identical products. Many 3D printers are needed to produce the same amount of this product. So what about all the material and energy required to produce these 3D printers? To what extent can material and energy needed to produce these 3D printers be divided among the thousands of products (68) they will be used for? Different manufacturing processes are indeed difficult to compare. But 3D printing has the promise to become the clear winner and can be an important factor in realizing a sustainable and circular economy.

PRINT YOUR HOUSE SUSTAINABLE AND CIRCULAR?

Bram van den Haspel presented a scenario towards 3D printing a house in one printing run on location. Many technological issues still have to be solved before this becomes a reality. But let's have a look into this example to 3D print a house, just to see how 3D printing can contribute to a sustainable and circular economy.

3D PRINTING YOUR HOUSE; HOUSE CHARACTERISTICS (16)

HOUSE CHARACTERISTICS	Town house with flat roof 100 m^2 floor space 110 m^2 facades + roof surface, 60 m^2 indoor walls + floor
TRADITIONAL BUILDING METHOD	50 m^3 concrete
3D PRINTING BUILDING METHOD	3 layers of 5 mm PLA in facades and roof 2 layers of 5 mm PLA in indoor walls and floor 2.25 m^3 PLA needed for layers, 2.25 m^3 PLA for internal strength 4.5 m^3 PLA needed in total Specific weight PLA is 1,200 kg/m^3 **5,400 kg PLA needed in total** + 15 m^3 concrete for weight and filling + 15 m^3 sand for weight and filling

3D PRINTING YOUR HOUSE, MATERIAL USE

Van den Haspel proposed to build a normal town house with a 3D printer. The characteristics of such a town house are a 100 m^2 floor space, flat roof, which usually needs 50 m^3 of concrete to build it. For his 3D printed house, he proposes to print layers of 5mm PLA with insulation material and concrete/sand in between. The facades and roof are printed with 3 layers PLA of 5 mm; an outside layer PLA, insulation material, layer of PLA, concrete/sand and an inside layer of PLA. The floor and indoor walls are printed with 2 layers 5mm PLA; a layer of PLA, insulation material and a layer of PLA. Connections for internal strength between the layers are also printed using PLA, using the same amount of PLA as in the layers. Overall 5,400 kg PLA is required, but the amount of concrete is reduced considerably. A rough assumption is that only 15 m^3 concrete and 15 m^3 sand are needed. (16)

3D PRINTING YOUR HOUSE, ELECTRICITY USE

The 3D printer's impact will come mostly from the electricity use of the printer itself. So let us have a look at the electricity use of a normal 3D printer, a Fused Deposition printer (FDM). The 3D printer melts a plastic filament and extrudes it in layers, one upon the other. It comprises of four main components (69):

- Electronics, computer control and cooling fans
- A heating element to melt the plastic
- Stepper motors to move the printer head
- A heated build platform to prevent curling

Clearly the heating element that has to heat up and melt the plastic will consume most of the power. The energy consumption depends on the temperature rise (about 180-200 degree Celsius), the specific heat and the melting energy of the chosen plastic. For PLA the specific heat is between 1.5 and 2.0 KJ/kg for the temperature range between 50 and

200 degree Celsius. The melting energy for PLA is 72 kJ/kg PLA. (70) Heating and melting the PLA accounts for about 66-75% of the total electricity consumption. Especially when large volumes are printed and the printer-building platform does not have to be heated up so much. The other elements of the 3D printer will consume about 25% of the total electricity consumption. (71)

In summary, heating up 1 kilo PLA requires 0.105 kWh, melting 1 kilo PLA needs 0.02 kWh and in total the electricity consumption to print 1 kilo PLA is about 0.17 kWh with present 3D printers. Energy savings however are possible when the energy for heating up and melting is re-used for heating up and melting the next part of plastic.

To build a town house that needs 5,400 kg PLA to be printed therefore requires 920 kWh. This amount of electricity is produced yearly by a 1 kWp solar system, size 8 m^2, installed in the Netherlands.

3D PRINTING YOUR HOUSE, ELECTRICITY USE (69) (70) (71)

3D PRINTER COMPONENTS THAT USE ELECTRICITY	Electronics and cooling fans A heating element to melt the plastic Stepper motors to move the printer head A heated build platform to prevent curling
PLA CHARACTERISTICS	$C_6H_{12}O_6$ sugar -> $C_6H_{13}O_5$ PLA molecular weight ratio sugar/PLA = 182/165 Specific Weight: 1.2 kg/m^3 Specific heat: 1.5-2.0 KJ/kg in T range 50-200 ºC Melting energy: 72 KJ/kg
ELECTRICITY USE PLA PRINTING	Heating up 1 kg 200ºC = 200 * 1.9/3.6 = 0.105 kWh/kg Melting 1 kg = 72/3.6 = 0.020 kWh/kg Heating and melting 1 kg PLA is 0.125 kWh Heating and melting accounts for ¾ of total electricity use Electricity use to print 1 kg PLA is 0.17 kWh/kg
ELECTRICITY USE TO PRINT A TOWN HOUSE	5,400 kg PLA needed Total electricity use **920 kWh** *= 1 year production of 1 kWp solar panels in the Netherlands*

3D PRINTING YOUR HOUSE, LAND USE

PLA can be produced from maize, corn, soy beans or sugar. Or from sugar beets, which is an efficient agricultural sector in the Netherlands. The land use to produce the amount of PLA to print your own town house can be calculated.

In the Netherlands, a hectare land produces on average 73 ton sugar beets (2013). Some areas even produce as much as 100 ton per hectare. The Dutch sugar beets contain on average in 2013 16.88% sugar, which leads to an average sugar production of 12.3 ton per hectare (72). Overall you need about 1.25 kg of sugar to produce 1 kg PLA. On average one hectare of Dutch sugar beets may provide for 10 ton PLA, or in other units 1 kg PLA per m^2.

A little over ½ a hectare of land for one year is required, to print your town house with PLA made from sugar beet.

3D PRINTING YOUR HOUSE, LAND USE (72)

DUTCH SUGAR PRODUCTION FROM SUGAR BEETS	Average Dutch sugar beet production 73 ton/ha (2013) Best locations can produce sugar beet up to 100 ton/ha Average Dutch sugar % in sugar beet is 16.88% (2013) Average Dutch sugar production per ha is 12.3 ton
PLA PRODUCTION FROM SUGAR	$C_6H_{12}O_6$ sugar -> $C_6H_{13}O_5$ PLA molecular weight ratio sugar/PLA = 182/165 85% yield to produce PLA from sugar Overall 1.25 kg sugar needed to produce 1 kg PLA Average Dutch PLA production per ha is 9.9 ton/ha
LAND USE TO PRINT A TOWN HOUSE	5,400 kg PLA needed Total land use 1 year **0.55 hectare = 5,500 m^2** PLA produced from sugar beets grown in the Netherlands

3D PRINTING YOUR HOUSE, EMBODIED ENERGY AND CO_2 EMISSIONS

The next step is to assess the environmental benefit of 3D printing a town house. Scientifically, this would require a Life Cycle Analysis on both the traditional build town house and the 3D printed town house. In a simplified way however we may compare energy use and CO_2 emissions to produce the concrete for a traditional town house with those for concrete and PLA for the 3D printed town house. Further assumption is that for building a traditional or a 3D printed town house all energy and material use are the same. And we assume that the 3D printed town house will use electricity for printing from a solar system, which has no direct CO_2 emissions.

We compare the so-called embodied energy that is needed to produce the materials from cradle to factory gate. The figures for concrete are taken from a database by Hammond et all (73). The figures for PLA are from a study by Vink et all (50).

The results are interesting. In a traditional town house considerably more concrete is used than in the 3D printed town house. While in the 3D printed town house we need PLA to print the envelop of the walls, roof and floor. Our simple calculations show that the 3D printed town house ‘consumes’ more embodied energy than the traditional town house. However, the CO_2 emissions are considerable lower for the 3D printed town house. This is due to the production process of concrete that is, by its nature, emitting carbon dioxide. And for PLA only CO_2 emissions of the production process count, not those of the crops that are used to produce PLA.

In our simple calculations the embodied energy in the traditional town house is 133 GJ, while for the 3D printed town house it is 186 GJ. The CO_2 emissions in the traditional town house are 19.2 ton of CO_2 and in the 3D printed town house it is only 7.3 ton of CO_2.

3D PRINTING YOUR HOUSE, ENERGY AND CO_2 (73) (50)

	CONCRETE	PLA
SPECIFIC WEIGHT	2,400 kg/m^3	1,200 kg/m^3
EMBODIED ENERGY	1.11 MJ/kg	27.2 MJ/kg
CO_2 EMISSION	0.159 kg CO_2/kg	0.27 kg CO_2/kg

	TRADITIONAL BUILD TOWN HOUSE	3D PRINTED TOWN HOUSE
MATERIAL USE	50 m^3 concrete = 120 ton concrete	5.4 ton PLA 15 m^3 concrete = 36 ton 15 m^3 sand
EMBODIED ENERGY	**133 GJ**	**186 GJ**
CO_2 EMISSION	**19.2 ton CO_2**	**7.3 ton CO_2**

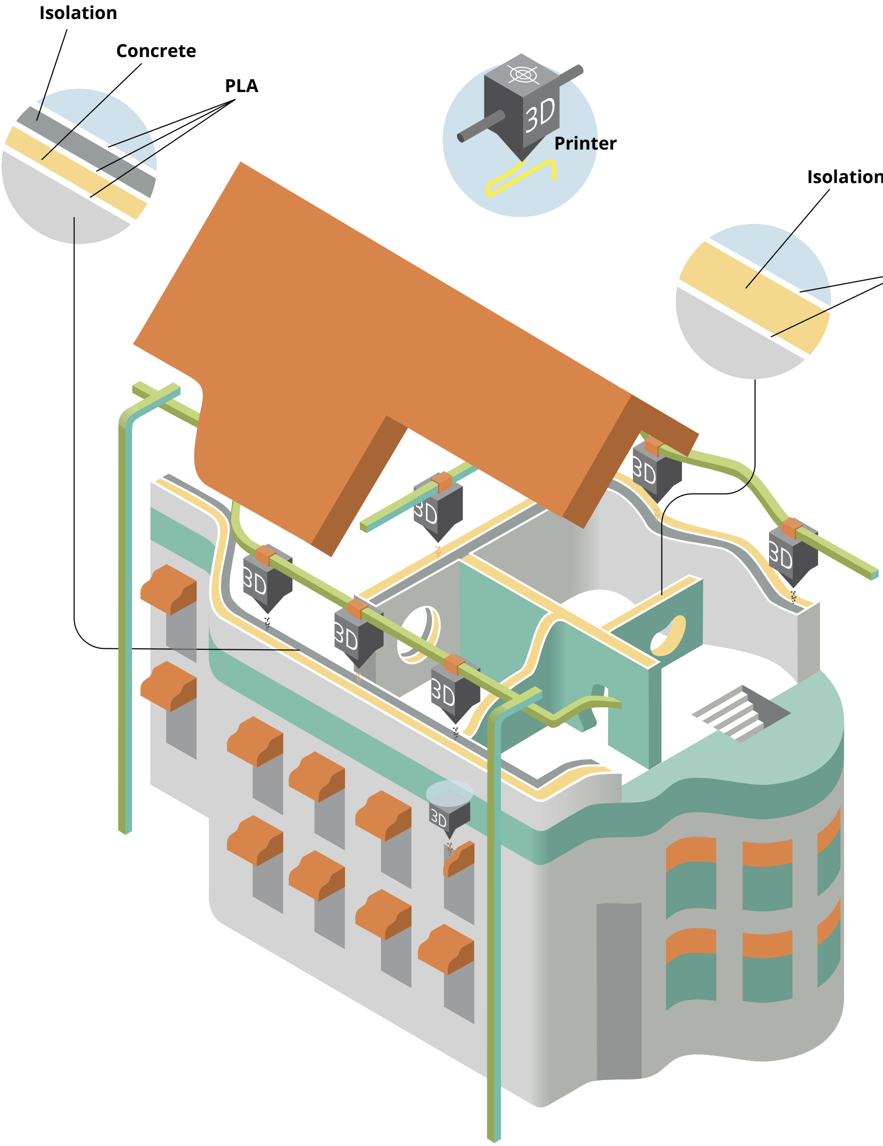
3D PRINTING YOUR HOUSE, TOWARDS CIRCULARITY

This example to 3D print a town house, shows that you need about ½ ha of sugar beet production and 1 kWp solar system to produce the PLA and electricity for 3D printing. The result is a considerable saving on CO_2 emissions in the building process.

3D Printing your own house is obviously not the holy grail of sustainability and circular economy. The example to print a town house with layers of PLA and filling it with concrete and sand shows that we still need concrete to fill the structure with weight. PLA consumes a lot of energy in the harvesting, logistics and production process. And we need electricity for 3D printing and land to grow sugar beets or corn for the production of PLA. Maybe PLA is not the appropriate biomaterial to use, because of temperature and moisture degradation.

Apart from this simple comparison there is much more to explore about 3D printing. Is it feasible and beneficial to 3D print the total building infrastructure: cables, low temperature heating, sewer, the other building structures; frames, doors, windows, isolation or

3D PRINTING A HOUSE

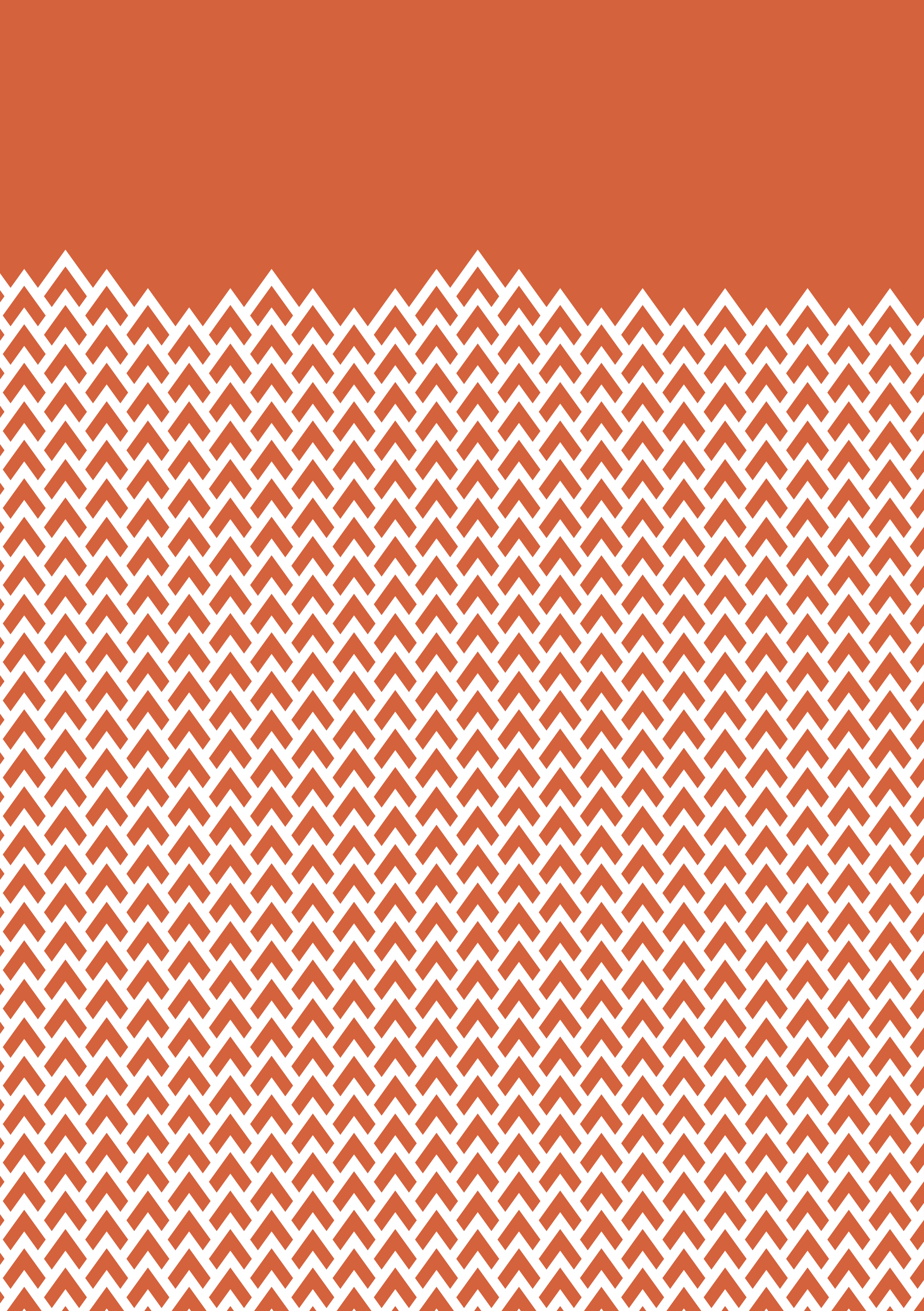


installations; heat pump, solar system, ventilation, etc.? And how can 3D printing improve the building process, building logistics, building costs or maintenance?

3D Printing a building is very promising for architects, offering more design freedom. What you can draw, you can 3D print. It also looks promising for the reduction of costs for building and maintenance. And last but not least, it can lead to a more sustainable and circular economy. But we have a long way to go! Many technological, organizational, social and other issues have to be addressed and solved, before we achieve a sustainable and circular building process with 3D printing.

3D PRINTING YOUR HOUSE, TOWARDS CIRCULARITY

	TRADITIONAL BUILD TOWN HOUSE	3D PRINTED TOWN HOUSE
FLOOR SPACE	100 m^2	100 m^2
MATERIAL USE	50 m^3 concrete	5.4 ton PLA+15 m^3 concrete + 15 m^3 sand
ELECTRICITY USE FOR 3D PRINTING		920 kWh
LAND USE FOR PLA		0.55 ha = 5,500 m^2 *(Sugar beet in the Netherlands)*
EMBODIED ENERGY	133 GJ	186 GJ
CO_2 EMISSIONS	19.2 ton CO_2	7.3 ton CO_2



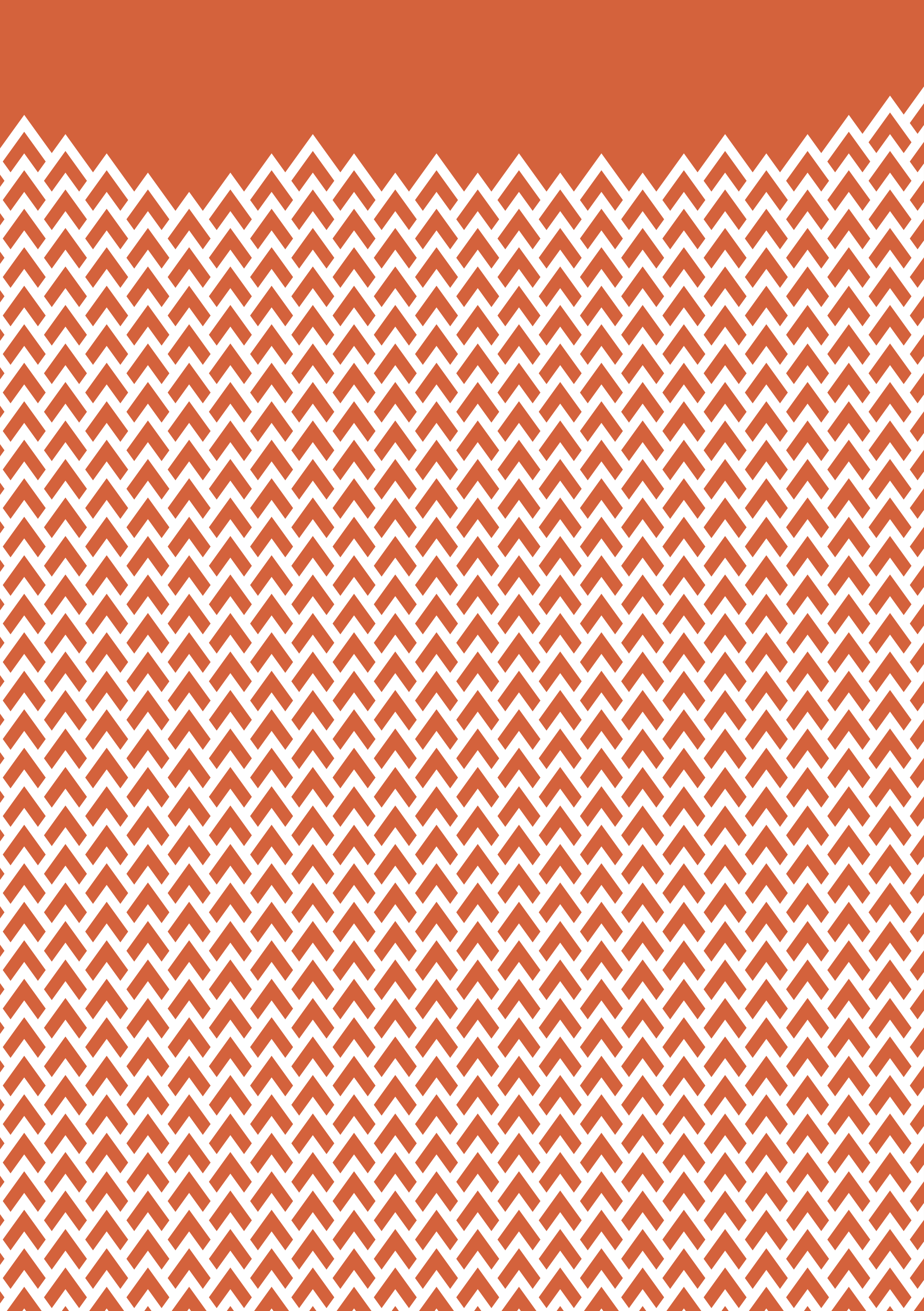
3D PRINTING

It will happen!

3D Printing or additive manufacturing will emerge inevitably. It is a paradigm-changing technology that will change the way we manufacture and use our products and systems. Not only the 3D printing technology is revolutionary, but it comes together with the internet of things, cloud computing, automated driving, solar cells, fuel cells, etc.

The characteristics of all these new technologies are that we can produce, manufacture and control products and systems by ourselves. Also 3D printing holds these promises. We can manufacture our own personalized products, when and where we need it. It does not require high upfront investments, development time, skills and knowledge. Simply download a file or make a photo, adjust it to your preferences and 3D print it. Therefore 3D printing will happen.

Will it also lead to a sustainable and circular economy? It certainly holds the promise. But to realize these promises we have to develop the right type of materials for 3D printing. In particular, several kinds of biomaterials and bio-plastics need to be developed or adjusted for 3D printer use. Furthermore, in a circular economy, re-use and re-cycling of these biomaterials on a local scale is equally important. And the electricity that is used for 3D printing must be produced by renewable energy sources, preferably locally. The development of 3D printing, biomaterials and renewable energy goes hand in hand. If this can be done for the benefit of the people and our planet, we certainly will realize a more sustainable and circular economy.



3D PRINTING WITH BIOMATERIALS

Workshop 16-12-2013

The content of this book is based on the presentations given during the workshop '3D printing with biomaterials' held on 16 December 2013 at the TU Delft, organized by The Green Village - TU Delft, The BioBased Economy and the Amsterdam University of Applied Sciences (HvA) - research program Urban Technology. The authors have used this material, the discussions, and added relevant and related information presented in this readable book. The speakers during this workshop deserve the credits for providing their knowledge, insights, information and overview. The workshop speakers are presented below. Lectures can be watched on the webiste: www.thegreenvillage.org.

The Green Village and 3D printing
Ad van Wijk
Professor Future Energy Systems, TU Delft

3D Printing; towards sustainability
Ton Runneboom
Chairman Biorenewables Business Platform

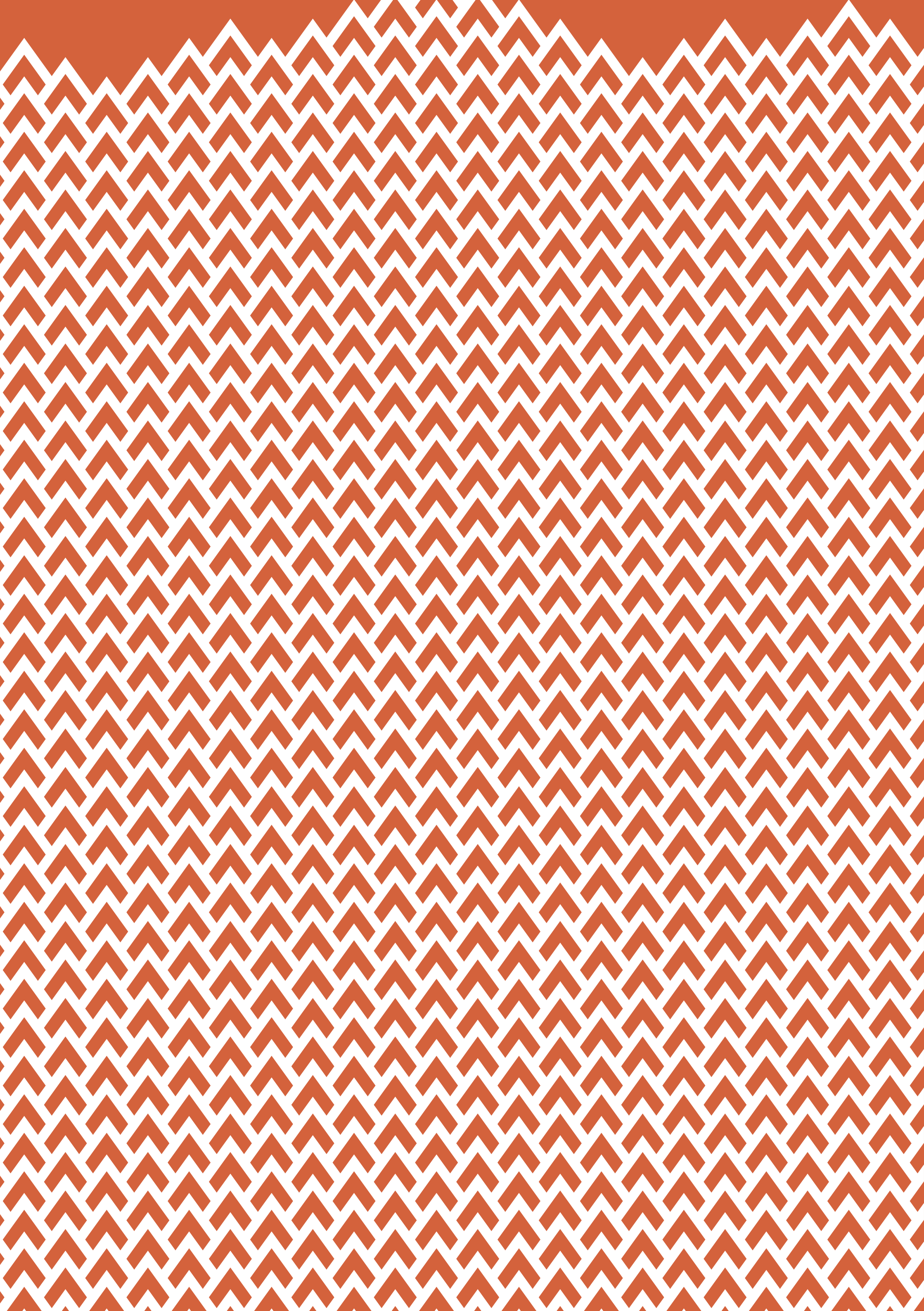
3D printing; how does it work
Siert Wijnia
Co-founder Ultimaker

3D printing with bio-based plastics
Jan Jager
Lector Stenden PRE (Polymer Research and Education) and Director R&D API Institute

PLA new product development
Ady Jager
Business Development Manager Natureworks

3D printing building
Bram van den Haspel
BRAMVANDENHASPEL innovation & design

Bio-based plastics and processing
Frans Kappen
Wageningen UR and Amsterdam University of Applied Sciences



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ABOUT THE AUTHORS

Iris van Wijk is lecturer at the Amsterdam University of Applied Sciences. Innovation and sustainability are ever returning themes in the personal and professional life of Iris. After her International Business and Management study, she worked as a consultant for OneCarbon in Chili.

As of the summer of 2010, Iris started the master ‘Environment and Resource Management’ at the Vrije Universiteit Amsterdam. She finished this with a research on the systemic obstacles to eco-innovations in the bio-based plastics sector. It was because of her research project that Iris came into contact with the bio-based plastics sector and was immediately intrigued by it.

Iris continued to work on this subject for the research program Urban Technology of the Amsterdam University of Applied Sciences (HvA). She applied for a two-year subsidy that was granted for the research project ‘Design Challenges with Bio-based Plastics’. She also initiated an ongoing joint research project with the University of Amsterdam (UvA) about the applicability of a new biomaterial into products.

In 2014 she obtained her degree of certified lecturer in higher education, and designed and lectured courses in sustainability and research methods.

Ad van Wijk is sustainable energy entrepreneur and Professor Future Energy Systems at Delft University of Technology, the Netherlands. Van Wijk started his career as scientific researcher in sustainable energy at Utrecht University.

In 1984, van Wijk founded the company Ecofys, which eventually grew into Econcern. Econcern developed many new sustainable energy products, services and projects. Examples include the 120 MW offshore wind farm Princess Amalia in the North Sea, several multi-MW solar farms in Spain and a bio-methanol plant in the Netherlands, which is the largest second-generation biomass plant in the world.

Van Wijk achieved many important prizes for excellent entrepreneurship. Amongst others he was Dutch entrepreneur of the year in 2007 and Dutch top-executive in 2008.

At TU Delft, Van Wijk will focus on the energy systems of the future such as the car as power plant. He will do research and at the same time he will realize The Green Village, where these future energy systems will be implemented, tested and researched in 'Future labs'.

Follow Ad van Wijk at twitter @advanwijk
or via his website www.profadvanwijk.com

Other books by Ad Van Wijk

- 'How to boil an egg' ISBN: 978-1-60750-989-9
- 'Welcome to the Green Village' ISBN: 978-1-61499-283-7 (print)
- 'Welcome to the Green Village' ISBN 978-1-61499-284-4 (online)
- 'Our Car as Power Plant' ISBN 978-1-61499-376-6 (print)
- 'Our Car as Power Plant' ISBN 978-1-61499-377-3 (online)

THE GREEN VILLAGE *TU Delft*

A sustainable world can only be achieved by an open collaboration between science, business and the public. That is why we create The Green Village at the TU Delft campus in the Netherlands: an innovative, lively, interactive and challenging environment where entrepreneurs, innovators, companies, artists, teachers and visitors can meet, work and play to develop, apply and experience innovative sustainable products and solutions.

In The Green Village you will find Future Labs for paradigm-shifting system research, resulting in icon projects such as the Car Park Power Plant, the Harp and the Energy Wall. The Green Village will be sustainable powered by the Engines, with ‘heart’, ‘veins’ and ‘lungs’ that supply energy and water, treat waste water and solid waste into useful new products and provide energy and transport fuels like electricity and hydrogen.

It will also house the Store, an innovative co-making shop for LED, 3D printing, apps, crowd funding and more. And it will be the stage for many sustainability events: exhibitions, shows, contests, workshops, games, challenges, conferences, etc.

The Green Village is located at the TU Delft campus, enabled by the Delft University of Technology and empowered by a lively community of scientists, entrepreneurs, companies, organizations. Its vision: ‘Creating a sustainable, lively and entrepreneurial environment where we discover, learn and show how to solve society’s urgent challenges’.

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BIOBASED ECONOMY

BioBased Economy (BBE) is about the change in our economy, based on fossil feedstock today, to an economy based on biomass as feedstock; from fossil-based to bio-based economy. The bio-based economy meant the use of biomass for non-food applications, such as chemicals, materials, transport fuels, electricity and heat. Biomass is, by its nature, suitable to replace fossil feedstock where carbon is essential, such as in chemicals, materials and transport fuels. The unique character of biomass in comparison with solar and wind is that you can produce materials such as plastics or chemicals for all kind of applications, relatively easy. Biomass and the bio-based economy is therefore not only about energy.

The transition from an economy based on fossil fuels to a bio-based economy is described as a complex system innovation in an unstable international environment. It is expected that biomass becomes increasingly important in the coming years, because of many reasons such as economic opportunities, innovation, energy independence, energy security and reducing greenhouse gases.

Especially the Netherlands has excellent conditions to make a success of the bio-based economy; excellent agricultural knowledge, good logistics and a leading chemical industry. Therefore the Ministry of Economic Affairs in the Netherlands has established the BioBased Economy community to stimulate this bio-based economy. The website features an interactive infographic that provides insight in the different biomass-to-biomaterial conversion routes.

One of the platforms within the BioBased Economy is the Biorenewables Business Platform (BBP). The Biorenewables Business Platform is to create business opportunities and to promote the sustainable development of the BioBased Economy in the Netherlands. Read more about it on www.biobasedeconomy.nl

URBAN TECHNOLOGY RESEARCH PROGRAM

Amsterdam University of Applied Sciences (HvA)

Urban Technology is a research program of the Amsterdam University of Applied Sciences (HvA), it focusses on technological solutions for a sustainable, liveable and connected city. The Urban Technology research areas of expertise are: Smart Energy Systems, Smart Urban Design, Smart Mobility and Logistics and Circular Design and Smart Production which are themes that also play an important role in the Amsterdam metropole region.

Urban Technology is part of the clusters Engineering, Logistics and Built Environment of the HvA School of Technology. It created a place where students, lecturers and companies work closely together to apply smart technologies and develop innovative and sustainable products, urban designs, logistical concepts and business models. The research projects are demand driven and resulted in a variety of successful projects. For example the e-mobility charge infrastructure database, the yearly CleanMobility competitions and the design RAAK project ‘Water in the City’. Also founded by Urban Technology and situated at the HvA, is the Software Energy Footprint Lab (SEFLab), which is a unique lab were the influence of software on the energy consumption is measured precisely. Within the Circular Design and Smart Production theme, the two-year ongoing project Design Challenges with Biobased Plastics is contributing to removing obstacles for the adaptation of biobased plastics in higher value goods.

Urban Technology is determined to speed up the application and market introduction of smart, sustainable and innovative technologies and products, and to create new tools for the urban specialists. And by doing so, at the same time, strengthening the foundational knowledge of our future engineers, logisticians and builders!

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