Diginova

Innovation for Digital Fabrication

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SEVENTH FRAMEWORK PROGRAMME

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Vision and objective of the Diginova Roadmap for Digital Fabrication

As the world is becoming ever more digital, decentralised and connected, the transition from analogue to digital technologies has a profound impact on many industries, markets, consumers and value chains. Well known and clear examples of this transition can be found in the music industry, in photography, printing and communication.

In common with many other industries, the manufacturing industry will also make the transition to the digital realm, and when it does, manufacturing will change beyond recognition. Established (analogue) fabrication methods and technologies will be replaced by Digital Fabrication technologies and solutions. This is expected to lead to a revolution in the manufacturing industry that needs to be anticipated, understood and supported.

> **´We´ve had an industrial revolution.**
> **We've had a digital revolution.**
> **Now is the time for a digital industrial revolution.´**

Although the potential of certain Digital Fabrication technologies (such as 3D printing/Additive Manufacturing, digital graphical printing and printed electronics) and associated applications is well recognized, so far there has been no coherent roadmap delineating how the benefits and the potential of the whole field and concept of Digital Fabrication should best be pursued. This document aims to fill this gap by providing the first roadmap for Digital Fabrication in Europe.

> ***Digital Fabrication*** **is defined as a new industry in which computer controlled tools and processes** ***transform digital designs directly into physical products*****.**
> **The key driving force and success factor appears to be the** ***development of well matched combinations of advanced new material deposition processes and materials.***

The overall objective of the Diginova[1] project was to assess and promote the potential of Digital Fabrication for the future of manufacturing and materials research in Europe. We have mapped the most promising application and material innovation domains, identified business drivers, key technology challenges and new business opportunities. We have also identified, connected to and involved a wide range of stakeholders across the value chain to assure wide acknowledgement and support. This roadmap and the underlying vision on Digital Fabrication are intended to provide guidance for innovation in Digital Fabrication technologies, materials and applications and to clarify how Digital Fabrication is envisioned to lead to a radical paradigm shift in manufacturing. The roadmap also indicates how and why this paradigm shift is expected to open up opportunities for significant growth for the manufacturing industry and related material developments in Europe. The work leading towards this roadmap also led to a vision statement for Digital Fabrication, which is described below.

Vision for Digital Fabrication

Within the next 10-20 years, Digital Fabrication will increasingly transform the nature of global manufacturing, with an increasing influence on many aspects of our everyday lives. Manufacturing will evolve towards a global distribution of digital design and specification files that will form the basis of local production. The economical advantage of large scale production will decrease, which makes smaller series production increasingly competitive and customised products affordable to an increasing number of consumers. The combined characteristics and possibilities of Digital Fabrication will generate new business models and new markets for new types of products and services. Transformation to Digital Fabrication will contribute to the decrease of resource consumption and resource-intensive production, targeting low-carbon and zero waste manufacturing. This paradigm shift in manufacturing opens up great opportunities for entirely new ways of production and material development in Europe.

1 The roadmap was created within the scope of the 7th Research Framework Programme of the EU in a Coordination and Support Action project called “Innovation for Digital Fabrication”, with the acronym ‘Diginova’.

Business drivers

Business drivers for the adoption and development of Digital Fabrication technologies have been found to vary depending on the intended application, status of the particular Digital Fabrication technology and industry sectors. However, the following business drivers were identified as the most important ones across multiple applications and industry segments. Digital Fabrication holds the following promises:

- Independence of economies of scale
- Product customisation, personalisation and customer involvement
- Increasing design freedom
- Supply chain consolidation and decentralisation
- Reduced raw material use and waste
- Reduction of hazardous materials use and waste
- Reduction in lead times.

Most promising opportunities

Within the scope of the Diginova project, the following nine most promising applications or application domains have been identified, researched and described.

Digital Graphical Printing

Large advertisement on a building wall. (Source: Xaar)

The conversion from analogue to digital printing technologies is fuelling growth of the digital printing industry. Digital printing enables on-demand production, zero waste, no need for stocks, high flexibility, fast-turnaround, small series, personalisation, mass customisation and very short distribution and supply chains. As one of the biggest industry sectors in the world, printing clearly offers a great opportunity, with inkjet emerging as the most promising digital printing technology. If we assume the analogue to digital conversion rate is about 50% over the next 10 to 20 years, this results in a market potential of over $250 billon (€185 billon).

Digital Textiles

Fashion application.
(Source: Shutterstock)

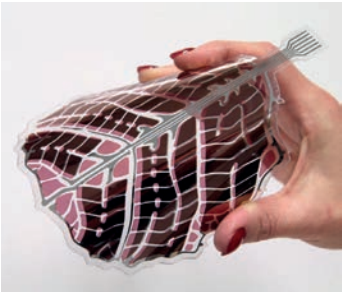
Digital textiles consist basically of two slightly different applications: digital direct-to-fabric printing and digitally fabricated garments. Digital textile printing technology supports versatility, quick delivery, short printing runs, cost effectiveness and especially the fast fashion market. Next to adding decoration to textiles, an emerging field is to add other functions, like anti-bacterial and flame retardancy properties to textiles (smart textiles). Although digital printing still only constitutes 2% of the total market for printed textiles, it is assumed to be growing fast, at a compound annual growth rate of roughly 30%.

Functional end-use parts and products

Topology optimised 3D printed end-use part.
(Source: University of Nottingham)

The manufacturing of functional end-use products and parts constitute the core purpose of all manufacturing activity. The increased utilization of Digital Fabrication technologies has been driven mainly by the ability to efficiently manufacture a) geometrically complex components and products, which exhibit comparatively higher levels of performance or b) low quantities of products, down to a single unit. The current size of the European 3D Digital Fabrication industry (2012) can be approximated at $423 million (€309 million). We assume that the potential for revenue growth is very significant and will continue in the foreseeable future.

Additively manufactured objects with embedded printed intelligence



Decorative solar cell can be used to power battery-less sensors for lighting control. (Source: VTT)

Innovative future products will integrate 'ready-assembled' multifunctional devices and structures. Integration of such functional structures will allow the incorporation of, for example, sensors, control logic, in-part health monitoring, electronic interfaces, and internal energy distribution or communication devices. This will result in a new generation of extremely capable and high value products for many different applications. As an emerging application area, the impact of such products is difficult to forecast. It is clear however, that these products embody the combination of several disciplines of science. Such combinations tend to lead to innovations that change the everyday lives of consumers.

OLED lighting and displays

Flexible display. (Source: Shutterstock)

OLED (Organic Light Emitting Diodes) technology can be applied to non-flat and bendable surfaces as an efficient, bright, lightweight and thin light source. OLEDs are used in lighting and display applications, such as smart phone screens, television screens and lighting panels. Several advantages, like lightweight, potentially flexible structures and wider viewing angles, are driving this technology forward. Currently, controlled thermal evaporation and spin coating are typically used for OLED processing. If OLEDs were digitally fabricated with, for example inkjet technology, the two most important issues for OLED production technology, i.e. price and scalability, could be overcome, while at the same time greatly enhancing freedom of design.

Smart Windows

Electrochromic Printed Electronics prototypes. (Source: CeNTI and Ynvisible)

Smart Windows can change light transmittance by applying an electrical current in response to an environmental signal such as sunlight or temperature sensed by a light/ temperature sensor. When activated, the glass changes from transparent to translucent or tinted, blocking some or all wavelengths of light. They can help to save energy in highly glazed buildings by reducing cooling or heating loads and the demand for electric lighting. The use of Digital Fabrication for glass construction potentially allows smart windows to be produced at low-cost with small runs of customised products. Different materials can be applied using the same types of equipment, and digital fabrication technologies can be envisioned opening up new design concepts to be readily produced for different applications in marketing, advertising and graphic design.

Printed Sensors

Thermocouple sensor. (Source: Wang 2010)

Sensors are needed in various applications; to control industrial processes, monitor climate and environmental conditions or simplify the procedures of everyday life, to mention just a few. The specific input could be light, heat, motion, moisture, pressure, amongst other phenomena. The sensor output is generally a signal that is converted to human-readable information. Printing enables manufacturing of cost effective large area sensor arrays on flexible substrates for various applications. However, fully printed sensors are not yet readily available on the market. Digital Fabrication is going to provide the capabilities required to produce printed sensors tailored to the specific application needs of the final consumer.

Personalised Diagnostics & Drug Delivery

Carbon nonotube based biosensor. (Fars 2013)

Personalised Medicine refers to the tailoring of medical treatment and delivery of health care to the individual characteristics of each patient, aiming to accelerate diagnostics, increase effectiveness and efficiency of prescribed medications, and reduce the incidence of side effects. Digital Fabrication technologies, like inkjet printing, will allow the automation of diagnostics and support new opportunities to print highly complex multi polymorphism assays (such as ‘organs on a chip’), containing patient tissues with a range of markers for automated computational analysis and interpretation. Printing technology could be used to generate a drug with patient specific dose and release rates as well as custom printed biosensor arrays. Personalised medicine is in its infancy, and we estimate that the timescale for delivering huge value using this new technology will be over 20 years.

Medical Microfactories

Blood haematology analyser. (Source: Shutterstock)

The concept of a microfactory is usually linked to the miniaturisation of machining and assembly elements to allow for desktop-based fabrication of small devices. Thus, medical microfactories can be understood as a standalone, dedicated manufacturing solution for a specific medical problem or condition. Medical microfactories can be desktop size fabrication points of custom made medical devices such as dental aligners, prosthetic sockets, lower and upper limb orthotics or surgical instruments as well as stations supplying on-demand biocompatible skin sections that match the patient’s specific requirements. The key reason for the adoption of additive manufacturing within medical microfactories is the ability to make personalised geometries based on digital scanning. In addition, for a range of applications it is attractive to make highly porous structures with a range of micro and macro porosities. The emergence of fully functioning medical microfactories is at least a decade away from widespread adoption, but offers a big opportunity in future.

Key Technology Challenges and barriers: recommendations for research

In order to realise the vision for Digital Fabrication a number of challenges need to be overcome in the coming years. Although many of these challenges are application- or technology specific, we have identified a number of challenges that apply to a broad group of applications and technologies. These technology challenge areas are given in the overview below. To overcome the challenges dedicated research is required, therefore for each challenge mentioned below, recommendations for research have been formulated that address it specifically.

Key technology challenges and research recommendations

Technology challenge area	Research recommendations to address challenges
Process implementation and economics	• Develop approaches to improve the reliability and repeatability of the Digital Fabrication processes • Research methodologies to reduce the amount of wasted raw materials on some Digital Fabrication processes
Core process technology	• Research on process fundamentals, process physics and chemistry • Implement programme for the improvement of core components of material deposition engines
Design systems	• Research appropriate methodologies for product design data handling, eliminating current limitations holding back the adoption of Digital Fabrication
Supporting processes	• Develop quality control methodologies tailored to the specifics of Digital Fabrication, allowing a build-up of confidence in the user base
Supply chain support	• Address the lack of commercialisation efforts by supporting near to market technology development

Technology challenge area	Research recommendations to address challenges
Education, legal and political agenda	• Develop a strategy to establish the required training for Digital Fabrication on multiple levels, including engagement in schools, professional training, and tailored courses in higher education • Research requirements for a legal framework improving user confidence in the commercial implementation of the technology.
Improvement of material properties	• Research materials matching the performance of conventionally processed polymers, metals and ceramics • Fundamental research into novel materials capable of delivering properties required by novel applications enabled by Digital Fabrication • Research into materials suitable for the Digital Fabrication of multifunctional components. • Research into novel materials resulting in fewer undesirable byproducts and less material wastage.
Material recyclability	• Establish methodologies for the recycling of end-use products manufactured via Digital Fabrication • Develop methods for the recovery of valuable raw materials from the waste streams associated with some Digital Fabrication technologies.
Biomaterials	• Research entirely novel bio-functional materials capable of supporting the use of Digital Fabrication in novel Human and diagnostic applications.

Foreword

In January 2011 a group of people from 16 organizations gathered in Amsterdam for a one day meeting to exchange views on the impact of the digital revolution on manufacturing. During this meeting we quickly found common ground and shared interests in what we defined and envisioned as a new kind of industry, called Digital Fabrication. One of the ideas arising from this meeting was to write a project proposal for a European funded CSA project, which resulted in the FP7 Diginova project of which this roadmap document is one of the main outcomes.

We established a clear vision, ambitious goals and a sound project plan in March 2011, but it was not until March 2012 before we actually started the proposed work in the Diginova project. Meanwhile the Diginova project consortium had been expanded to 20 parties spread across Europe, while still including 15 from the 16 organizations that were already present at the first visioning session described above.

Over the past two years, the Diginova project has been very inspiring and successful. We met all of our objectives and connected to a wide stakeholder community. Digital Fabrication gained a lot of attention in the media, especially on the topic of 3D printing. This reinforced our vision and beliefs regarding the relevance of our main objectives.

One of the main outcomes of our work is this roadmap document. It is the first ever roadmap for Digital Fabrication and it is my firm belief that it will serve its primary purpose in providing guidance for innovation in this field to open up growth opportunities for the 21st century manufacturing industry in Europe. As such, I also trust that the results of Diginova will find their way into existing or new initiatives and programs in the framework of Horizon 2020. The manufacturing industry is and needs to remain an important pillar for the European economy. It is also my firm belief that acquiring preemptive knowledge about emerging technologies is the best way to ensure that we have a say in the making of our future.

I would like to thank all the participants in the Diginova project for their contributions and the inspiring and fruitful collaboration during the course of the project. Furthermore I would like to thank the European Commission for funding this exciting and valuable project.

Marcel Slot
Project coordinator of Diginova

> *"Before you become too entranced with gorgeous gadgets and mesmerizing video displays, let me remind you that information is not knowledge, knowledge is not wisdom, and wisdom is not foresight. Each grows out of the other, and we need them all."* — Arthur C. Clarke

1 Introduction

This report describes a roadmap for Digital Fabrication as well as a summary of the key findings of the Diginova project.

In March 2012, a consortium consisting of twenty European companies, universities and institutes joined forces and started the Diginova project. The project name was derived as an abbreviation from the targeted field of interest and full project name: ‘InNOVAtion for DIGItal fabrication’. As a Coordination and Support Action project, Diginova received European funding under the FP7 framework.

As the world is becoming ever more digital, decentralised and connected, the transition from analogue to digital technologies has a profound impact on many industries, markets and value chains. Well known and clear examples where this transition has already happened can be found in the music industry, photography, print and communication.

Diginova originated from a joint vision of all project partners: similar to many other industries, manufacturing will change beyond recognition when it makes the transition to the digital realm. A Digital Revolution in manufacturing should therefore be anticipated, understood and supported.

Although the potential of a number of Digital Fabrication technologies (such as 3D printing) and associated applications are well recognised, there is no coherent roadmap delineating how the benefits and the potential of Digital Fabrication technologies should be best pursued. Diginova aims to fill this gap by providing clear guidance in clarifying the most promising future opportunities as well as key barriers potentially interfering with their success.

The overall objective of the Diginova project has been to assess and promote the potential of Digital Fabrication for the future of manufacturing and materials research in Europe. We have mapped the most promising applications and material innovation domains, identified business drivers, key technology challenges and new business opportunities. We have also identified, connected to and involved a wide range of stakeholders across the value chain to create a roadmap for Digital Fabrication with the potential for wide acknowledgement and support. The roadmap and the underlying vision on Digital Fabrication provides guidance for innovation in Digital Fabrication technologies, materials and applications and clarifies how Digital Fabrication is envisioned to lead to a paradigm shift in manufacturing. The Diginova findings that are summarized in this report indicate how and why this paradigm shift is expected to open up opportunities for significant growth for the manufacturing industry and related material developments in Europe.

This introduction has presented the concept of Digital Fabrication and the Diginova project. This is followed by chapter 2 which provides an overview of the Digital Fabrication field. After outlining the definition and scope of Digital Fabrication, this roadmap covers the current status of Digital Fabrication processes, materials and applications. Chapter 2 concludes with an evaluation of size, future potential and impact of Digital Fabrication within the European manufacturing industry as well as outline of our vision for Digital Fabrication in Europe, mirroring the opinions of a wide range of stakeholders. Chapter 3 describes the most promising opportunities and applications for Digital Fabrication. It addresses both the current status as well as the future outlook for each individual application. The application chapters share the same structure and are therefore easily accessible without reading the entire document. Chapter 4 identifies business drivers and key technology challenges for Digital Fabrication. In addition to key technology challenges, a range of other challenges and barriers are also described, relating to topics such as design, intellectual property, legal issues, sustainability, standardization as well as education and training. Chapter 4 ends with recommendations for future research in the field of Digital Fabrication, emanating from the identified main challenges and barriers.

2 Overview of Digital Fabrication

2.1 Introduction

> *"Imagine that you need new shoes. Instead of going to a store, you go online and buy a cool shoe design for a few dollars, or just download one for free. With a few clicks, you use a mobile phone app to scan your foot, select a few colours, and upload the design to print at a local 3D printing shop. Next you log on to a popular furniture site, browse for a while, and select an interesting metal and plastic chair, specifying a few adjustments to the size. A few hours later, on the way to the gym, you visit the 3D printing shop and try on your new shoes, which fit perfectly. Your new 3D-printed chair is delivered to your doorstep later that week.*
>
> *One might also think about one's father, who needed a knee joint replacement last year. Amazingly, the doctors were able to scan his leg and 3D print a titanium replacement that fits him perfectly. They even bioprinted replacement ligaments for his knee, using a sample of his own cells, and after rehabilitation, he's back to playing basketball with his grandkids.*" (Manyika 2013)

The above text may read as a part of a science fiction story, but we believe that in 10 to 20 years from now, mass customization, flexible and on-demand production, will have become a reality.

Today, most products are created by means of the established mass production infrastructure. Traditionally, this involves large quantities of stock, extensive manual labour inputs, vast capital investments, high energy use, long distance transportation, an 'army' of employees and the assumption of an existing sufficiently large homogeneous consumer base. Although many advanced new materials have unique functional properties that hold a great promise for innovation, they often need to meet the criteria and characteristics of this established manufacturing structure for successful application. This hampers, or at best delays, the exploitation of the huge potential residing in wholly new classes of materials. Since most existing production systems share a fundamentally rigid nature, they are suited to incremental innovation but not for paradigm shifts that could boost innovation.

The world is becoming ever more digital, decentralized and connected. The transition from analogue to digital technologies has had a profound impact in domains such as communication, computing, photography and printing. MP3 changed the music industry, digital cameras did the same for photography and digital print enabled everyone to become a publisher. As the digital age advances, we need to rethink our approach to developing and manufacturing materials and products and also to reconsider how this will affect the very products we produce. We have to acknowledge the significance of major societal trends and consumer needs such as customisation, personalisation and on-demand fulfilment. This will also affect the established manufacturing infrastructure, where fabrication and materials processing have until now remained 'disconnected' from the digital domain. Successful innovation in the digital age will require networked, flexible and open approaches. The advent of 'Digital Fabrication' will enable innovations that bypass the established manufacturing structure to an extent. It can be envisioned that ultimately people will be able to order, define or even (co)create and locally manufacture their own products in materials of their choice and will not be bound by the mass-produced selection they can find in the stores of today.

´We´ve had an industrial revolution.
We've had a digital revolution.
Now is the time for a digital industrial revolution.´

2.2 Scope and definition

Digital Fabrication can be generally defined as a new kind of industry that uses computer controlled tools and processes to transform digital designs directly into useful physical products. This includes all technologies which use digital material deposition methods to create two- or three dimensional structures, patterns or products, i.e. modern digital printing technologies (2D Digital Fabrication) and additive manufacturing, often called 3D printing technologies (3D Digital Fabrication). Next to the above mentioned technologies, laser processing and coating technology are also considered to be in the scope of this roadmap as supporting complementary technologies. In the present state-of-the-art, the development of well-matched combinations of advanced new material deposition tools and materials is emerging as a key success factor for Digital Fabrication.

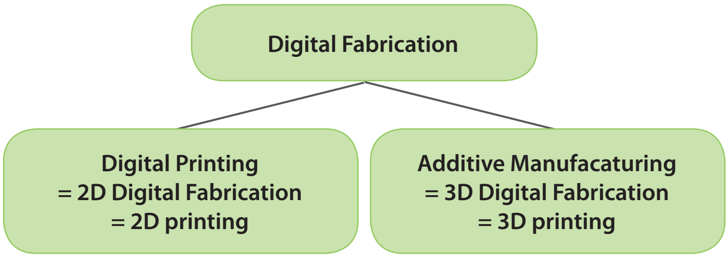


Figure 2.1. *Terminology in the field of Digital Fabrication.*

Additive Manufacturing (AM) has been specified in the ASTM F2792-12 standard as well as the ISO 17296-1 as a process of joining materials to make objects from 3D model data, as opposed to subtractive manufacturing methodologies, such as traditional machining, whereas the technical definition of 3D printing refers to the fabrication of objects through the deposition of a material using a printhead, nozzle, or another printer technology. However, due to recent media attention ”3D printing” has become the most common term used when referring to additive manufacturing. Therefore, in this roadmap, both terms are used synonymously; the term ”additive manufacturing” is predominately used when addressing these technologies from a technical perspective and the same technologies may be referred to as ”3D printing” when regarded from a business or societal perspective, if not specified differently.

Diginova scope for Digital Fabrication

- *Matching manufacturing* technology to key *new materials*
- Enabling *on-demand manufacturing* for *customised products* with *potential for short production series* (down to a ‘series-of-one’)
- *Shortening change-over times* to accommodate *flexible production*
- Using *additive manufacturing* methods to enable production of products comprising of more than one material using *minimal resources* with *no waste*
- Exploiting the *inherent freedom of design* in both geometry and material composition to produce products that are *more optimised for functional performance* and not hampered by limitations inherent in more conventional manufacturing processes.

2.3 Towards a paradigm shift in manufacturing

Over the past decades, the advance of mass manufacturing in Europe has diminished and new production philosophies and approaches have emerged. During the 20th century (Figure 2.2), productivity and efficiency were the main driving forces, and production was based on analogue technology. In the middle of the century, the first computers appeared and process control and software impacted the manufacturing industry. By the end of the 20th century digital technologies became increasingly important. Computer controlled machining and robots became commonplace, leading to a reduced need for manual labour. The advent of a digital revolution became visible in the domains of engineering and manufacturing.

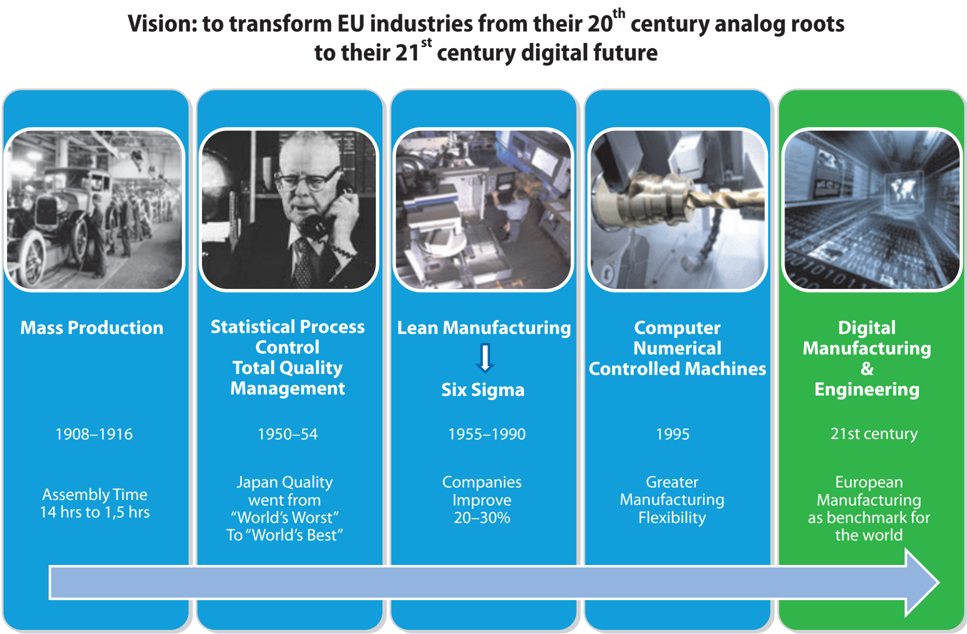


Figure 2.2. *Transformation of European industry from 20th century roots to 21st century digital future.*

We are convinced that successful innovation in Digital Fabrication can only result from a parallel, coherent and integrated development of functional materials, substrates and material deposition processes. While this may seem logical, it is not current practice. In most cases manufacturing processes are considered a given, and materials are designed around them, or at best 'tuned to fit'. It is very unfortunate to see that in this traditional approach, new and sometimes unique functional material properties are negatively affected or sometimes even lost.

We believe that Europe needs to rethink how it will stimulate cooperation in the development of new materials and new applications. The physical distances i.e. lack of personal relationships and limited chances to share and create new concepts hinder the further development of technology. In general, more active cooperation in Europe is needed. Today advances are occurring too often in isolated “silos” and in an almost disassociated way. Fundamental to some deposition processes investigated by Diginova, there is also a need to reconsider the design and production of many kinds of substrates. For example, most printed circuit boards today are made by lithography, and most of this is done in Asia. In the future, they may be printed, and combined with integrated circuits through innovative surface mount technology. The future combination of printing new substrate materials, electronics, and additive deposition technologies would contribute to the creation of many new products and could even repatriate some production activity from Asia.

Wide adoption of Digital Fabrication techniques can certainly have profound implications, of which some are characterised and envisioned below:

- **Digital Fabrication can be decentralised and it can strengthen local economies.** As Digital Fabrication technology and processes evolve, the cost of digitally manufactured products will decrease. For certain applications Digital Fabrication may even evolve to the point where it can directly compete on cost with mass production. In addition, Digital Fabrication offers huge advantages and opportunities compared to mass manufacturing in terms of flexibility, customisation, personalisation and on-demand fulfilment. When cost barriers are sufficiently lowered, it will no longer be necessary to rely on centralised large factories from which mass produced products are shipped around the world. Instead, products can be fabricated locally. Products could essentially travel most of their journey as digitally stored data. Design will be global; realisation will be local. This will greatly reduce or eliminate transportation costs and reduce carbon footprint. In shifting manufacturing (back) to local economies, Europe could lead the way in reclaiming its manufacturing heritage and recapture a share of the production volumes that have been lost to Asia in the past.

- **Digital Fabrication is flexible.** It allows for one machine or sequence of processes to fulfil many roles and reduces the use of space and resources. Industrial mass-production generally requires a different factory for every type of product, but flexible Digital Fabrication allows one set of tools and processes to be used to make many devices. Flexibility could ultimately make it worthwhile to invest in consumer fabrication tools; only industrialists invest in a tool that makes the same thing over and over again, but for certain applications a tool that can respond to one's personal needs could be a tool worth having even in your home.
- **Digital Fabrication is customisable and interactive.** The internet is revolutionising media and information services because of the ease with which users can generate their own content. Traditional media (TV, newspapers, radio etc.) are generally one-way channels that make it easy to be a consumer of information and difficult to become a producer. But with blogs, out-of-the-box websites, wikis and so forth, anyone can now broadcast information. Even funding for realisation of new innovative ideas is now commonplace through crowd-funding initiatives (such as Kickstarter). Digital Fabrication represents the same revolution whereby user-generated content can be brought to the manufacture of physical goods. With Digital Fabrication, consumers can specify, customise, design or ultimately even process materials into their own phones, their own computers, their own MP3 players or lighting fixtures. They will express their creativity in their products, rather than having to buy mass-produced ones. In fact, this is already beginning to happen, with large electronics manufacturers offering customisation on their web-sites, for example. In the next decade the current value chain with middle-men could be replaced by a simpler and short value chain, and the range of products made with new material functionality and combinations of functions could be extended. Following this reasoning, the production chain is expected to evolve more and more from a 'push' to a 'pull/on-demand' model.

- **Digital Fabrication will ultimately lower costs.** Once local economies, communities or ultimately individuals have their own fabrication equipment for small runs, they can create a car, a mobile phone, agricultural equipment or whatever product at the cost of raw materials, limited transportation and local overhead. The standard industrial supply-chain inflates the price of manufactured goods. To buy a commercially mass manufactured computer, the price has to cover the costs of mining the material, shipping the material to, for example, China, running the machines, labour, marketing, more shipping, and mark-ups by several retailers. Digital Fabrication, by producing parts or products in one step on-demand, with no waste, directly from raw materials, empowers local manufacturing, and cuts out extra costs and reduces the cost to just energy plus information plus raw materials and maybe a limited number of very special parts. Ultimately energy could be for free from the sun and information (designs) could become free from the Internet, in which case the only remaining cost would be that of raw materials.
- **Digital Fabrication contributes to a level playing field.** Means for communication, housing, medical equipment, agricultural equipment, electronics - let's assume that it would be a good thing to provide people in all countries access to these things. How are we to do it? One could say there are two ways: One is to manufacture the goods in developed and wealthy places and ship them, and the other is to manufacture them on-demand, on-site where they are needed, when they are needed, and in exactly the right quantities. Of these two solutions, only the second one creates local economic stimulus, teaches technological skills and makes communities economically more self-sufficient.
- **Digital Fabrication is evolving.** The ultimate fruit of Digital Fabrication will be the Molecular Assembler that rearranges atoms and puts them in place at great speed to build almost anything, from nano-scale robots to ham sandwiches.

Vision for Digital Fabrication

Within the next 10-20 years, Digital Fabrication will increasingly transform the nature of global manufacturing, with an increasing influence on many aspects of our everyday lives. Manufacturing will evolve towards a global distribution of digital design and specification files that will form the basis of local production. The economical advantage of large scale production will decrease, which makes smaller series production increasingly competitive and customised products affordable to an increasing number of consumers. The combined characteristics and possibilities of Digital Fabrication will generate new business models and new markets for new types of products and services. Transformation to Digital Fabrication will contribute to the decrease of resource consumption and resource-intensive production, targeting low-carbon and zero waste manufacturing. This paradigm shift in manufacturing opens up great opportunities for entirely new ways of production and material development in Europe.

2.4 Processes and materials

There are both fundamental similarities and fundamental differences between 2D and 3D Digital Fabrication technologies. Both rely on computer controlled addition of materials, but whereas 2D-printed products acquire their functionality by complex interaction between the deposited materials and substrate, or through the properties of the deposited material itself, the functionality and properties of 3D-printed products are the combined result of the type of material and the principles employed in the design and addition of that material.

Below a short overview is given of current state of the art 2D and 3D Digital Fabrication technologies.

2D Digital Fabrication

At the moment, 2D Digital Fabrication is largely based on existing digital printing methods. In graphical printing and decoration of flexible flat objects (such as paper sheets), both inkjet and toner based processes (electrophotography) are widely used, but the dominant Digital Fabrication technology in industrial applications is based on inkjet deposition techniques. Table 2.1 introduces some examples of 2D printing technologies.

Table 2.1. *Some examples of 2D Digital Fabrication technologies.*

Classification	Principle	Known Process
Inkjet, drop on demand	Only drops targeted on the substrate are generated (drop on demand). Drop formation by transducer.	Piezoelectric jetting, electrostatic jetting and thermal jetting
Inkjet, continuous jet	Drops are generated at high frequency and the wanted/unwanted drops are deflected and collected from the drop stream by a control signal from the printing system.	Binary deflection jetting and multideflection jetting
Electrophotography	Toner transfer from the photoconductor surface onto the substrate where it is fused.	Dry toner electrophotography and Liquid toner electrophotography
Aerosoljet	The material stream is aerodynamically focused using a flow guidance deposition head, which creates an annular flow of sheath gas to collimate the aerosol.	Aerosol jetting

In the most common 2D digital printing methods, inkjet and toner based methods, the printed materials typically consist of colorant, carrier (liquid), binder, and various additives. Traditionally, the materials have been developed with graphics applications and printing processes in mind. Typically the carrier is evaporated into air, absorbed into the substrate or cured on the top of the substrate. The binder remains as a part of the printed image, contributing to the visual appearance as well as the mechanical print robustness. The additives in the materials to be printed are used to ensure trouble-free operation of the printing system, for example in inkjet printheads or toner print engines.

For the production of functionality by 2D Digital Fabrication, the use of metal nanoparticle fluids, conductive and semi-conductive polymers in solution, dielectrics in solution, and etch/plating resist fluids is expected to increase in the near future. Dispensing of biomaterials and drugs in jettable form can become important in the long term as well. Other promising materials include ingestible fluids, nanoparticle dispersions (metals, ceramics), photopolymers, hybrids and various biomaterials including DNA, peptides and lipids. In order to use these new materials successfully, there is need for a better understanding of droplet formation in the present printheads and possibly completely new printhead concepts need to be developed.

3D Digital Fabrication

In 3D Digital Fabrication processes, the successive addition of material means that units of material feedstock are brought together and joined (e.g. fused or bonded), most commonly layer by layer to build a part. A layered approach to the additive building of parts may also cause directional dependence in the material properties of that part. Therefore, material properties may be dependent on that part's orientation and position in the build space during processing. Basically, the fundamental properties of 3D Digital Fabrication products are determined by:

1. Type of material (bio-based material, polymer, metal, ceramic, composite etc.) and the principle applied for fusion or bonding (melting, curing, sintering).
2. The feedstock that is used for adding the material (liquid, powder, suspension, filament, sheet) and how the feedstock is delivered to the point of fusion or bonding, i.e. the machine architecture.

Several very different technologies exist which employ different build materials and deposition/solidification techniques. They can be classified under the categories shown in the following table.

It is clear that successful innovation in Digital Fabrication can only be realised if the development of materials and material deposition processes are integrated. While this may seem a logical approach if the goal is to realise a combination of geometry and material properties, it has not been current practice in conventional manufacturing. In most cases, the manufacturing processes are considered as given, and materials are to a large extent designed to suit the designated process, or at best 'tuned to fit'. However, in Digital Fabrication the functionality of the material in the final product is also determined by the process of successive addition of material. This approach enables a higher degree of control over the design of the composition of the final material, to ensure that the material acquires the desired properties in the final product.

Table 2.2. *Technology variants of 3D Digital Fabrication.*

Classification	Principle	Known Process
Power Bed Fusion	Uses directed thermal energy such as high-temperature laser or electron beam to melt and fuse together metal, thermoplastic or ceramic powder deposited in a powder bed	Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM)
Directed Energy Deposition	The feedstock material is melted by a directed energy source, such as a laser or an electron beam, to add material to a pool of melted material on the substrate's surface for cladding and repair	Laser Engineered Net Shaping (LENS), Direct Material Deposition (DMD) and Construction Laser Additive Direct (CLAD)
Material Jetting	Using inkjet or other digital methods to deposit droplets of build material on pre-determined positions	PolyJet and Thermojet
Binder Jetting	Using inkjet or similar digital printing method to deposit a binder onto a powder bed	3D Printing (3DP)
Material Extrusion	Extrusion of material through a heated, moving nozzle to deposit it in the desired pattern on the build tray	Fused Deposition Modelling (FDM)
Vat photopoly-merisation	A liquid photo polymer is selectively cured by exposure to a light source, such as an UV-laser or a lamp with a photo mask	e.g. StereoLithography (SL or "SLA" for the apparatus)
Sheet lamination	The applied layers are subsequently cut from sheet material and bonded together to form the object	Laminated Object Manufacturing (LOM) and Ultrasonic Consolidation (UC)

2.5 Technological developments

Depending on the application, future machines may increasingly utilise hybrid technologies that take advantage of the strengths of several types of additive and subtractive processes. There are going to be new low cost and more efficient systems that will increase the affordability and ease of operation of Digital Fabrication equipment.

Larger build envelopes will enable both the manufacturing of larger parts and larger production batches. However, in order to be competitive this needs to be combined with enhanced deposition and consolidation rates.

Over the coming years there will be a focus on increasing build speed through higher deposition rates. This will lead to a trade-off between feature size and speed. There are several alternatives to increase build speed by moving from point processing to line, mask or volume based processing. A different method could be parallelisation – the use of multiple energy sources - to simultaneously build parts. There will be major challenges from a control standpoint to achieve mass parallelisation.

In-process monitoring systems are being developed. This will enable the production of parts with improved repeatability. A higher degree of quality control and quality assurance functions, such as those found in conventional machine tools, will be developed in future systems.

New developments and innovations may allow a broader range of materials to be utilised. There is on-going development of new materials that are designed with the objective of making the most out of the Digital Fabrication process instead of trying to achieve properties similar to present industrial materials. New polymers are being developed and in theory biological materials could be applied. A movement towards multiple materials can also be observed.

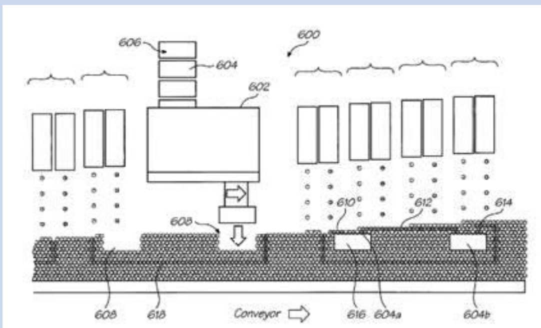
Standardisation will progress. Since 2009, the ASTM International Committee F42 is progressing in the development of industrial standards for AM technology. This initiative has been followed up by ISO, and since 2011 ISO/TC261 has also been in progress. In a unique collaboration these efforts are presently being synchronized; two joint ASTM/ISO standards have been issued and more joint working groups are being formed. This is the first time both standardisation organisations have started a collaboration of this magnitude and it is a good illustration of the importance that the industry sees in having one single set of unambiguous industrial standards to rely on.

New design and scanning tools will also be developed to fully benefit from design flexibility and to tackle the complexity of three-dimensional, multi-material, ‘freeform’ design problems within realistic constraints.

A different scenario could be a trend away from layer-based towards volume based manufacturing. Effectively, such an approach would fill the available space rather than layer materials to create a product. This would require new ways of focusing energy in a volume space instead of a point on a surface.

Long term trends

Current trends will continue and accelerate. Multiple materials will be applied in increasingly thin layers. To preserve or increase building speed, technologies like mass parallelisation are needed. Large arrays of printheads, increases in the number of print nozzles, multiple melt pools, or other build vehicles that simultaneously construct material by layers will be implemented. The option of multiple melt pools can already be found at the electron beam based powder bed fusion process developed by Arcam AB and laser based metal systems by EOS GmbH (EOS 2013). Further, mass parallelisation will require major improvements in process and control software. This scenario includes hybridisation. Different manufacturing processes including subtractive technologies will be used simultaneously.



3D object creation system employing voxels in combination with Pick & Place. Patent application Silverbrook Research (Silverbrook 2007)

Bio-inspired self-assembly and nanotechnology may be used for additive manufacturing. An abstract future concept as envisioned by Carnegie Mellon University and Intel is named Claytronics. This concept combines nano scale robotics and computer science to create individual nanometer-scale computers called Claytronic atoms, which can interact with each other to form tangible 3D objects that a user can interact with. Commonly referred to as shape-shifting programmable matter.

In the near time frame material development for Digital Fabrication will bring a much wider array of different materials to the market. To begin with, it will primarily be variations of currently available materials that have been adapted for application. The most important trend will be that the materials are going to be more generic and not necessarily tied to any specific original equipment manufacturer (OEM). The next trend will be new materials that have been specifically developed for Digital Fabrication purposes and that are designed to make the most of the processes. The analogy in this context is that most present industrial materials have been developed to perform well both in the available manufacturing process and in the intended product application. The third trend will be joint development of material and process technology that enables the freedom of designing not only complex geometries but also the material properties throughout the product.

Moreover, the principle of successive addition of material enables the creation of products with discontinuous material composition. This is a completely new technology area, but the implications are huge. Parts may contain different types of materials. This will make it possible to produce integrated products such as polymer parts with conductive patterns and integrated sensors and electronics, or products with engineered, variable and directed properties. It will be possible to create specific material combinations, like composites of metals and ceramics, and materials with characteristics that are currently not present in nature.

In the context of additive manufacturing, there are in particular two promising near future material combinations that should be mentioned. These are CerMets/-Graded materials and MetaMaterials. CerMets are material composites of ceramics and metals which combine the high abrasion resistance and hardness of ceramics with toughness derived from the metal matrix. A technically very important CerMet is the combination of tungsten carbide (WC) ceramic material in combination with cobalt (Co) as the matrix material. However, the need for the abrasion resistance and hardness of the ceramic and toughness of the metal matrix is most often variable within a product, therefore would a gradient in the material composition be highly advantageous and also enable the manufacturing of products with material properties that are not possible with present technology. MetaMaterials are a cluster of artificial materials with characteristics that are not present in nature. MetaMaterials usually gain their properties from structure rather than composition.

2.6 Industrial and socio-economic impact

The global size of the graphical commercial printing industry is \$650 billion (€480 billion). The printing industry is one of the biggest industries in the world (compare with automotive: \$650 billion and consumer electronics:

$350 billion). Of this global printing market, still only 10% of all printed volume is produced with digital printing technology. As the digital age advances, the traditional analogue printing industry is in decline (-5% per year) while at the same time the conversion from analogue to digital printing technologies is fuelling growth of the digital printing industry. Next to graphical applications, industrial printing has emerged as a new and fast growing industry with a wide range of new applications for a wide range of markets. Printing is evolving from 'printing of information' to 'printing of things'. Over the past decade, an almost unlimited number of new applications have been identified. Examples can be found in areas such as printed electronics, solar cells, displays, food and nutrition, medical diagnostics, 3D printing and even for printing of human tissue and organs.

The global market size of additive manufacturing (3D Digital Fabrication) in 2012 was $2.2 billion (€1.6 billion), and the growth rate from 2010 to 2011 as well as 2011 to 2012 was almost 29% (Wohlers 2012). Estimates for growth vary from €5 to €80 billion by the year 2020, depending on the source. The European share of the total number of systems sold is estimated to be approximately at 19% (Wohlers 2012). However, instead of looking just at the figures and the size of the AM businesses directly, it is equally important to try to understand the overall economic impact that this technology is having. Additive manufacturing is increasingly utilised in various high-value application areas; visual aids, functional models and other prototyping applications, tooling, various medical applications and increasingly for production of end-use parts, i.e. direct part production. Of these, the latter is expected to become the largest and the most significant application of AM technology. In less than ten years direct part production has grown from almost nothing to 28% of the total revenue from AM (Wohlers 2013).

Industry size and growth potential are important aspects when evaluating the relevance of industrial development initiatives. However, to get a balanced view of the topic, other criteria should be taken into account as well. It is clear that Digital Fabrication has a number of positive impacts on society and the economy, relating to e.g. the ageing population, individualisation and sustainability:

Policy related: Macro-economic European policy supports the projected benefits of Digital Fabrication because of the potential for creation of new manufacturing capabilities. This is underpinned by development of high tech educational skills, knowledge and job creation (getting manufacturing back to Europe). Although we envision that manufacturing will return to developed countries, this does not imply that manufacturing jobs will return as well. The (digital) factories of the future are thought to require a completely different workforce. Instead of workers in oily overalls on the factory floor, future manufacturing jobs will require a wider skill set. Most jobs would not be on the factory floor but in nearby offices, which would consist primarily of designers, engineers, IT specialists, logistics experts, marketing staff and other professionals. As the nature of manufacturing jobs changes, so should the labour force and an education system geared to this new Digital Fabrication paradigm.

In terms of global economical impact, McKinsey predicts that 3D printing alone could be responsible for revenues of between $230 billion (€167 billion) and $550 billion (€400 billion) per year by 2025. (Manyika 2013)

Economy: By applying digital technologies, in particular 2D and 3D Digital Fabrication, simplified supply chains become reality, which increase companies' competitiveness and improve productivity. At the same time these technologies enable mass customisation by localised on-demand manufacturing in Europe (so called mini factories, at regional level as well as retail level).

Society: Consumer requests for personalised, comfortable, safe, healthy, affordable and sustainable products are growing over a range of sectors from high technology goods to apparel, footwear and household products. Technology solutions will also need to be developed to respond to the challenges posed by an ageing population. For elderly people the development and production of bespoke products tailored to individual needs will particularly benefit from the design freedom and flexibility that Digital Fabrication offers. Examples are hearing aids, orthotics, implants, dental implants and prosthetics. Further in the future Digital Fabrication even holds the promise of being able to produce tissue and organ replacement parts.

Technology: Complex part creation with better functional properties. Digital technologies, i.e. AM, provide increased geometric complexity enabling compact lightweight design as well as making products using less parts. Multi-functionality and new forms of functionality will bring European manufacturing companies competitive advantages based on the product function instead of the manufacturing price. The knowledge added inside the product will come from the expertise of optimising the functionality through the design, the choice of the material and its manufacture.

Legal: In the case of a malfunctioning 3D printed home-made part or malfunctioning products that have been designed and traded by consumers themselves, a clear framework for safety and liability issues has still not been established.

Environmental impacts (optimal material and energy utilisation): Weight reduction, compact design and a reduction in material consumption are not only important in reducing carbon foot print, they directly influence the final price of the part. This is even more important when one of the components of the part is a rare metal. Reduced energy consumption in manufacture is crucial for the control of resources in terms of electricity, gas emissions and water.

2.7 Stakeholders' view

Stakeholders play important roles as advocates, sponsors, partners and agents of change. Understanding stakeholder expectations and needs is important because it guides their actions, interactions and eventually the strategies that are followed. Therefore a framework was developed within the Diginova project that considers the key components necessary to engage with stakeholders in order to understand their current actions, capabilities and needs. The broad aim of such engagement activities was to enable better interaction and alignment work along existing or shifting value chains and contribute to the creation of new innovation networks.

In order to understand what is required by different stakeholders to become successful players in the emerging field of Digital Fabrication, we organized dedicated workshops in conferences that attracted potential stakeholders of Digital Fabrication from relevant communities. Thus our approach in identifying the key stakeholders was to orchestrate interactive sessions on Digital Fabrication in conferences where relevant such stakeholders would be present. In addition, a questionnaire was designed and distributed to the stakeholders to better document their expectations and future vision as to where Digital Fabrication might be headed in the next 10 to 20 years.

This section provides a brief overview of all results obtained through the above mentioned activities. The following paragraphs present the results of highest importance for the context of this roadmap dealing with vision, value-chain, targets and current actions of the stakeholders in the key application fields defined by the project. The questionnaire as well as all results are structured in the categories: *General Information, Innovation, Commercialisation, and Vision of Digital Fabrication.*

Vision & targets

Looking at the Gartner hype cycle analysis (Figure 2.3), we have found that 42% of the stakeholders perceive Digital Fabrication positioned at the peak of inflated expectations. Interestingly, an approximately equal share of respondents considers Digital Fabrication to be at the stage of technological trigger (19%), while another group perceives it at the slope of enlightenment (20%). In other words, uncertainty concerning Digital Fabrication technologies is still high, with no clear consensus on the technologies' status. The Digital Fabrication roadmap will help to overcome these uncertainties.

A possible explanation for the variation of the statements might come from the industry in which the respondent are active as well as the media attention, in particular for home 3D printers. In 2013, Gartner for the first time makes a distinction between consumer 3D printing (at the top of the hype cycle), 3D bioprinting (innovation trigger) and enterprise 3D printing (slope of enlightenment).

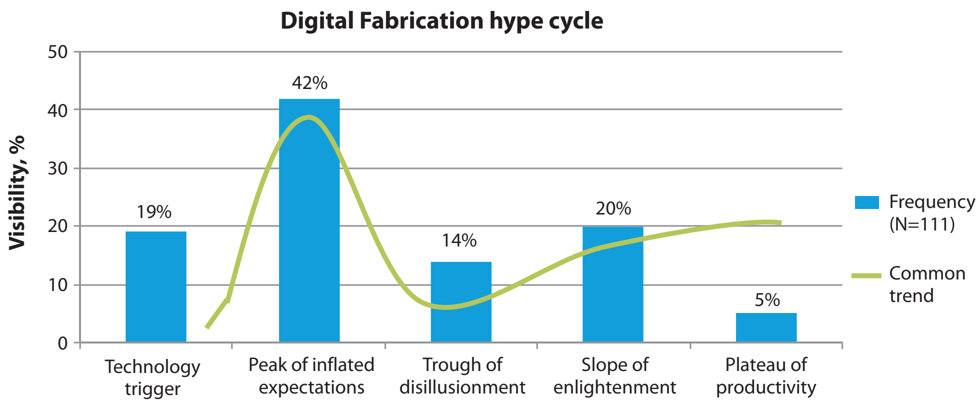


Figure 2.3. *Stakeholders' assessment of the Digital Fabrication hype cycle.*

Despite the uncertainties around the hype cycle positioning, when asked to specify the years to market of various applications, a strong consensus crystallises around a first set of projected applications and time frames. The following graphic illustrates the stakeholders' assessment of future markets showing the top ranked product domains by years to market:

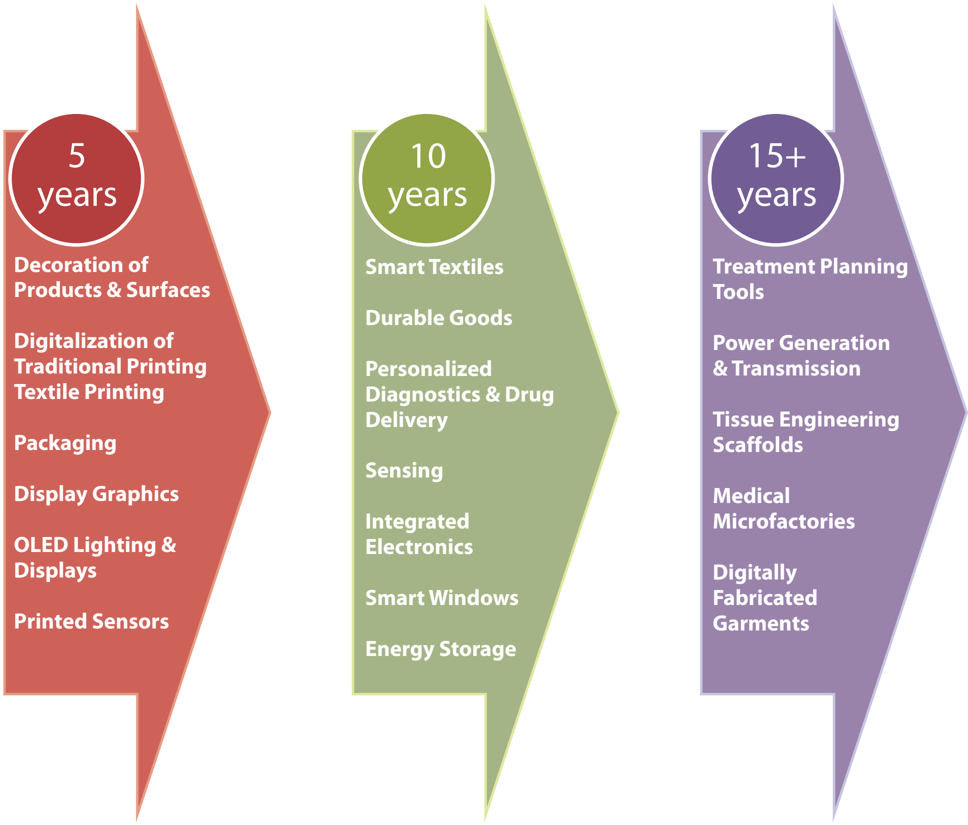


Figure 2.4. *Top future applications - years to market.*

Looking at the application categories, short-term targets involve decoration of products (78%), digitisation of the traditional printing industry (76%), textile printing (75%), packaging (71%), display graphics (66%), OLED lighting and displays (59%), and printed sensors (58%). However, in contrast, consensus on the commercialisation of mid-term applications is less strong. That being said, the probability of smart textiles (46%), durable goods (44%), personalised diagnostics and delivery (41%), sensing (40%), integrated electronics (39%), smart windows (38%), and energy storage (37%) entering the market within the next 10 years aggregates a significant percentage of respondents projections. With a 15+ -year time horizon, respondents identify the following long-term targets: treatment planning tools (64%), power generation and transmission (53%), tissue engineering scaffolds (44%), medical microfactories (39%), and digitally fabricated garments (38%).

In order to elaborate at the future vision for Digital Fabrication, stakeholders were asked to react to 5 broad vision statements about the future of Digital Fabrication. An overwhelming 85% of respondents believe Digital Fabrication is part of an ongoing industry revolution and will be supplemented by new materials and technologies. When asked whether Digital Fabrication will be an integral part of worldwide manufacturing, 74% of respondents either agree or strongly agree. A further 73% claim the applications enabled by Digital Fabrication will transcend customers' imagination. The sustainable character of these technologies in the future generates 53% of positive response as to being in strong or moderate agreement, while 57% of respondents strongly or moderately agree that Digital Fabrication paves the way to a distributed manufacturing system that enables mass production of bespoke products and solutions while securing value for innovators and restoring the manufacture of products to their geographically diversified, end-user base.

Value-chain

While the majority of respondents' activities (91%) are tool-oriented such as providing materials (21%), printing equipment (26%), functional components (17%), or integrating and manufacturing Digital Fabrication technology (27%), a significantly low number of stakeholders are in application oriented production, producing end products (9%) with Digital Fabrication technology. If not indicating a lack of commercial activity, this finding infers that a transition phase from technology to application development may be at hand. Correspondingly, creating awareness for this within the Digital Fabrication community is identified as a necessity as well as an opportunity.

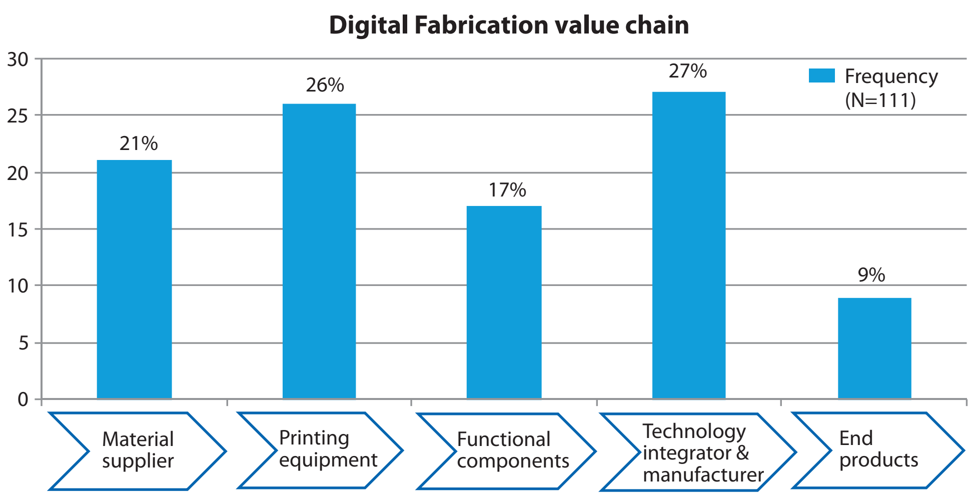


Figure 2.5. *Stakeholders' position in the Digital Fabrication value chain.*

Priorities

Whether or not support actions are already applied there is broad consensus that a wider choice of materials (89%) and improved material properties (88%) are required as business-enhancing developments for the Digital Fabrication market. Optimising accuracy (83%), repeatability (82%) and speed (80%), form a second group of issues that must be addressed. A third and final cluster of necessary developments on which respondents either strongly or moderately agree are a broadened product range (83%), standardisation (70%) and cheaper machines (69%).

What becomes clear from the questionnaire results is that the perceptions of the required business-enhancing developments as well as the support actions do perfectly match the Digital Fabrication technology barriers identified by the Diginova experts. In fact, the major barriers for 2D and 3D Digital Fabrication to overcome are related to speed, reliability and the limited range of materials. For 2D Digital Fabrication, the top priorities to address on are: prevention, prediction, detection and correction of failures in printing processes. These priorities are mainly related to the heart of the manufacturing process, the print engine, which includes the printhead architecture and operating system. The barriers for 3D Digital Fabrication are mainly related to design for additive manufacturing, reliability, predictability and scale-up of the processes as well as the absence of standards and certification.

Figure 2.6 summarises the key points that emerged as a result of deliberation between relevant stakeholders of the Digital Fabrication domain during three dedicated sessions at international conferences: Smart Lighting 2013, LOPE-C 2013 and ISFOE-2013. The X-Axis in Figure 2.6 indicates what type of stakeholders was present in the workshops according to their relevant position in the digital fabrication value chain. In Smart Lighting 2013 the end-user perspective in the lighting domain was dominant and in the workshops held in LOPE-C 2013 and ISFOE-2013 the perspective of science and industry was dominant. The Y-Axis in Figure 2.6 indicates the main topic of the discussions, i.e. opportunities and barriers inherent to the emerging process of Digital Fabrication.

A first round observation indicates that, depending on the position in the value chain, the opportunities viewed by the stakeholders may differ. It is important to note that stakeholders with an upstream position in the value chain (science and industry) point to the promises of Digital Fabrication

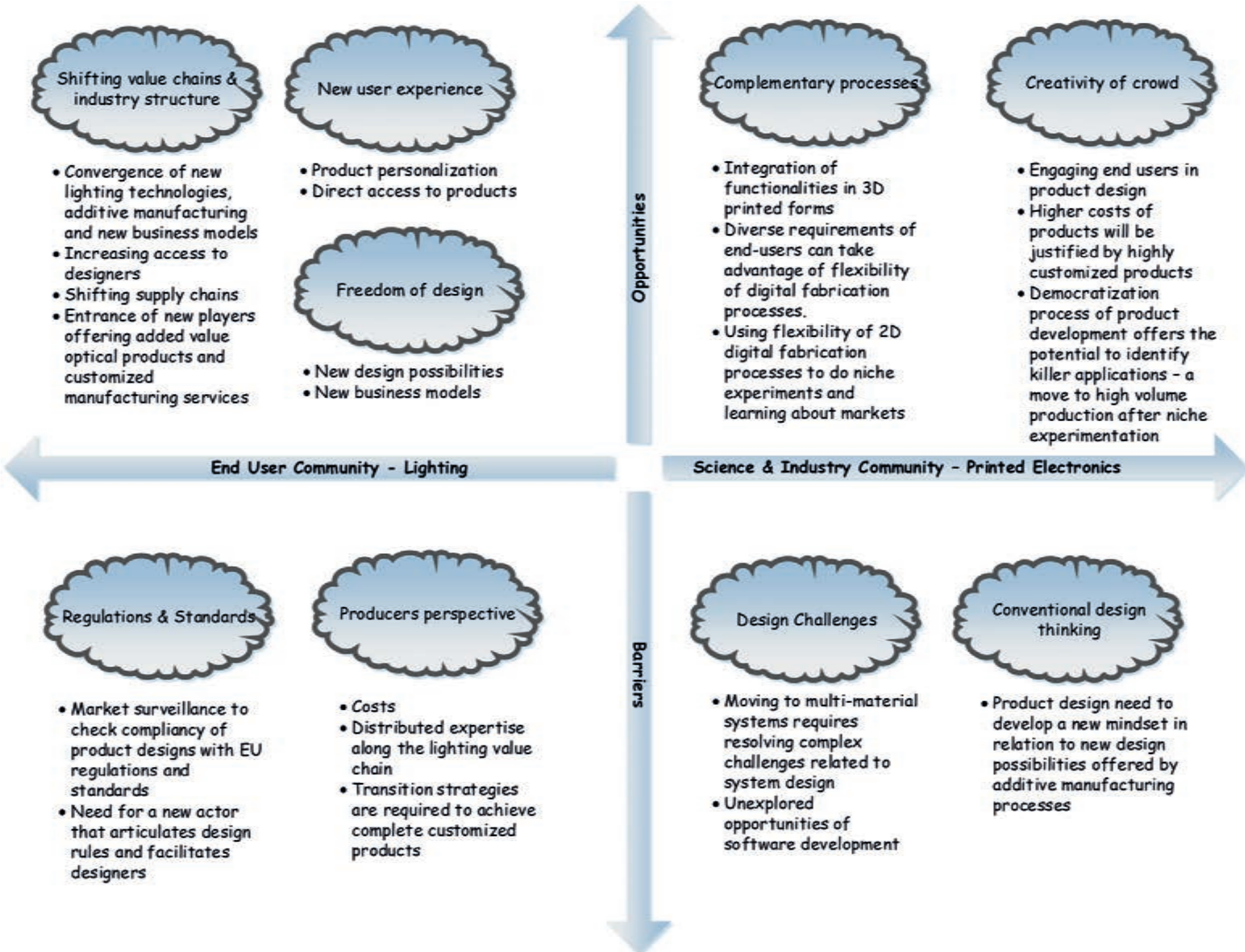


Figure 2.6. *Summary of key points that emerged during discussions in three workshops when discussing opportunities and barriers of digital fabrication.*

technologies and the wonderful possibilities they will enable for new product development. On the other hand, stakeholders with more down-stream positions point to the impact of the technological change that is being promised. The opportunities are then mainly viewed in relation to the possible shifts in value chains and industry structure. A general, yet important finding is that independent of the position of the stakeholders in the value chain, the new/changing role of end-users is viewed as a key opportunity. In short, it is expected that the democratisation process of product development enabled by the possibilities of digital fabrication technologies will help to accelerate the search process for new applications and products that are valued by the end users across different sectors.

In the same vein, stakeholders with an upstream position in the value chain (Science and industry) point to technological barriers as key challenges that have to be overcome to enact the vision of Digital Fabrication. Complex challenges related to system design and software are examples of technological barriers that were often mentioned during the workshops. In contrast, the discussions among stakeholders with a more down-stream perspective revolved around requirements that have to be met before market entry of products. For instance, while the democratisation process of product development was seen as a great opportunity, the stakeholders pointed to the importance of regulations and standards to ensure product quality assurance. It was often pointed out during the workshop discussions that creating complete customised products would require development of transition strategies ensuring that there is an actor that takes responsibility for quality assurance of products.

3 Most promising applications

Digital Fabrication will have an increasing impact on everyday life. The enabling of mass customisation would allow customers to order fully bespoke products. Within the Diginova consortium we have made a shortlist of the nine most promising opportunities or applications for Digital Fabrication in terms of impact on manufacturing and life as a whole. These nine applications were identified through assessments and discussion within the consortium in conjunction with broad stakeholder involvement. This chapter will elaborate on each of these applications, their potential, their fit with the Digital Fabrication paradigm, potential, expected lifespan (how long is an opportunity expected to have significant impact) and the related key technology challenges.

Diginova:

Most promising applications for Digital Fabrication

1. Digital graphical printing
2. Digital textiles
3. Functional end-use parts and products
4. AM objects with embedded printed intelligence
5. OLED lighting and displays
6. Smart windows
7. Printed sensors
8. Medical microfactories
9. Personalised diagnostic and drug delivery

3.1 Digital graphical printing

Advanced digital printing, as a truly digital manufacturing technology, is one of the key enabling technologies that will revolutionise many sectors in manufacturing. The first sector that it has impacted is traditional analogue graphical printing, through the replacement of analogue printing processes such as offset, screen printing and gravure. Of all digital printing technologies, inkjet is the leading and most promising technology for many applications.

One of the key driving forces for adoption of digital print technologies is the trend towards and need for decreasing run-lengths and more flexibility in print production. Customers and society in general increasingly demand more flexibility and information is changing at an ever increasing speed in our information society. Because traditional printing presses, such as offset presses, require fixed make-ready costs (plate making, machine set-up) before every print-job, the demand for smaller run-lengths puts high pressure on margins and there are limits to minimum run-lengths that are economically viable. With digital print technologies, smaller run-lengths do not impact the costs per print since there are no fixed costs. Therefore, when using digital printing, costs are completely independent of the length of a production run, enabling print production series basically down to a 'series-of-one'.

Market applications where digital graphical print has already shown a large growth and replaced significant parts of traditional analogue printing are in the printing of books and in the wide format display graphics market (posters, banners and signage).

Figure 3.1. *Wide format printed surfaces using inkjet. (Sources: Xaar and Océ)*

Fit with Digital Fabrication

Advanced digital printing, as a truly digital manufacturing technology, is one of the key enabling technologies that will revolutionise many sectors in manufacturing, starting with the conversion of the traditional graphic arts industry. Digital printing entails on-demand production, enabling zero-waste, no need for stocks, high flexibility, fast-turnaround, small series, personalisation, mass customisation and very short distribution and supply chains. The digital 'Print on Demand' paradigm means a shift from 'print-and-distribute' to 'distribute-and-print'. Designs and print jobs are sent as digital files over the internet. These designs are printed locally close to the end-users.

In terms of impact on the environment, digital print contributes to efficient use of scarce resources and minimising environmental impact (low/zero waste, lower energy and material use, shorter logistic chains). While in the traditional printing industry, between 20 to 40% of all printed material is never used and flows directly into (paper) recycling or landfill, with digital print this is reduced to virtually zero.

Potential

The global size of the graphical commercial printing industry, also known as the graphic arts industry, is $650 billion (€474 billion). This is the retail value of all printed material per year. The printing industry is one of the biggest industries in the world (compare with automotive: $650 billion and consumer electronics: $350 billion). As the digital age advances, the traditional (analogue) printing industry is in decline (-5% per year), while at the same time the conversion from analogue to digital printing technologies is fuelling growth of the digital printing industry.

Digital production printing is forecast to have a compound annual growth rate (CAGR) of 11.5% until 2018. A reasonable estimate of the analogue to digital conversion rate across all market segments in commercial printing is about 50% over the next 10 to 20 years. This results in an estimated market potential for digital production print of over $250 billion (€182 billion).

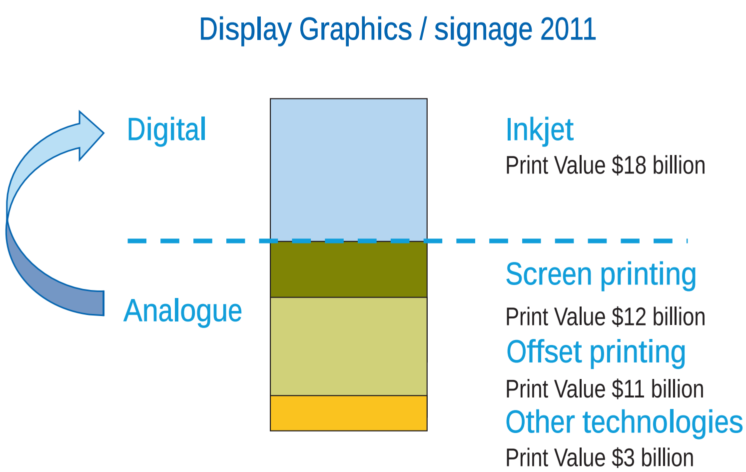


Figure 3.2. *Example of digital print transition in the Display Graphics / signage market. (Hill)*

Figure 3.2 illustrates the state of transition of analogue to digital print in 2011 for the Display Graphics market, as one of the market segments within the total commercial printing market. The main underlying mechanisms for growth in this digital manufacturing sector are the following:

1. Growth of demand (growth of digital volume itself)
   – enabled by digital capabilities such as cost-effective short-runs
   – enabled by growth of demand in developing countries
   – enabled by growth of outdoor advertising
2. General advantages as mentioned earlier for conversion of analogue to digital production volumes.

Lifespan

While the printing industry will change and needs to adapt as the digital age advances, it is not expected that print will disappear over the next few decades. Digital printing provides a viable and valuable production technology to replace traditional printing technologies. Digital printing is well suited to address the demands for sustainable production of printed products far into the future.

Technology challenges

Concerning materials, the Diginova consortium has identified challenges related to the following demands and expected trends:

- Development of low cost materials and inks to compete with traditional analogue graphical printing applications. In analogue graphical print, technology has matured over many decades and the materials used currently for inks have become commodities which are produced at very large scale with very low margins.
- Graphical applications demand good light fastness of printed output to ensure that no colour fading occurs through light or ozone. This translates into stringent demands for the light fastness and colour strength of colour pigments or dyes that are used in inks. Reducing the size of colour pigment particles can greatly contribute to colour strength, light fastness and print quality. The possibilities of producing and deploying colour pigment particles in inks with a size in the range of 10 to 50 nm hold significant promise.
- Inks should be developed with excellent performance on eco-aspects. This relates to the use of completely safe base materials, good de-inkability performance and the reduction or elimination of chemical emissions from (co-)solvents used in ink formulations.

- Formulation and production of inks using bio degradable components optimised for re-use, re-cycling and zero impact of the percentage of prints that ultimately end up in landfill.
- In a number of existing large inkjet markets (such as the wide format Display Graphics market), inkjet inks are currently based on UV curable polymers (mainly acrylates) or solvent inks (mainly for printing on vinyls). The challenge will be to develop new inks that are compatible with next generations of inkjet printheads and remain compatible with a very wide range of substrates. Promising inroads can be found with new ink designs such as water based latex inks or water based UV curable inks.

For future development of Digital Fabrication processes in the graphical printing domain, the following challenges and trends have been identified:

- Cost
  - Formation of ultra-thin layers, matching the layer thickness of ink in offset printing (<1 micrometer). Reduction of ink usage, resulting in lower cost per print as well as minimising material usage.
- Speed
  - Development of inkjet printheads that enable higher speed through higher jetting frequencies and/or by making use of printhead arrays comprising a higher number of inkjet nozzles. Key enabling factor for future generations of inkjet printheads is the use of MEMS technology for printhead manufacturing.
- Print quality
  - High speed in-line image quality inspection systems for closed-loop measurement & control
  - Compatibility of inks with very wide range of substrates. Challenges relate to ensuring good adhesion of inks on a wide range of substrates as well as flexibility of ink layers on flexible substrates.
  - Inkjet printheads should evolve to the point where stable jetting of ultra-small droplets (1 pl) is possible at very high frequencies. Today such small ink droplets are only commonly used in small and slow desktop inkjet printers, where consistency and stability are far less stringent than in high speed inkjet production systems.
- Methods for high speed fixation and drying of inks.

3.2 Digital textiles

Over the past decade, digital printing technology has been applied in the textile printing industry. Digital textile printing is by far the fastest growing sub-segment in textile printing. Digital textile printing technology supports versatility, quick delivery, short printing runs, cost effectiveness and especially suits the fast fashion market. It also benefits green manufacturing with less pollution and water usage compared to conventional textile printing processes.

Next to adding colour or graphical/decoration to textiles, a completely new field is emerging in which printing technology is used to add other functions to textiles. These include anti-bacterial and flame retardancy functions, water repellence, UV protection effects, antistatic effects, full wrinkle resistance and functionality to absorb odours.

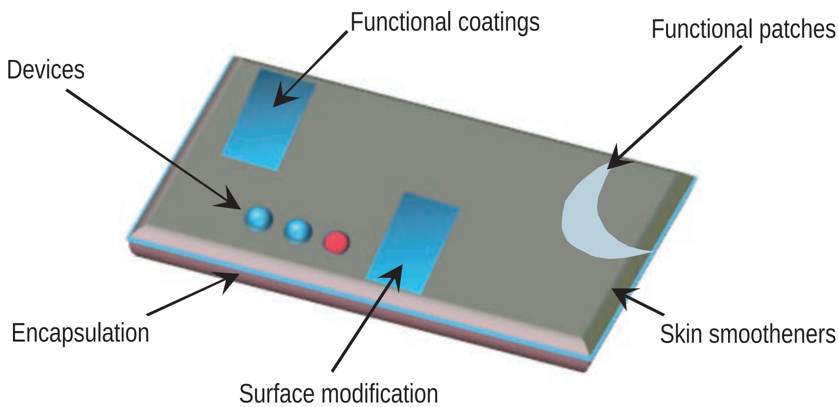


Figure 3.3. *Printed functionality, towards 'smart textiles'. (Source: Xennia Technology)*

The concept of incorporating electronics in textiles has recently emerged. There is a strong interest in lightweight, flexible, and wearable electronics to meet the technological demands of modern society. Integrated energy storage devices in textiles are a key area that is of high interest but still in its infancy. Some smart textile products are already on the market but with a low penetration, partly related to high production costs. It is expected that costs will come down as the market grows.

Another digital textile concept is to digitally fabricate the textiles or garments themselves, instead of printing colour or other functionality onto textiles. This allows the direct manufacture of items of (perfectly) fitting clothing in a single production step. Clothing manufactured in this way can be customised to conform to the user's body shape. In addition, printed clothing could also be customised on the meso/micro scale to achieve certain fabric characteristics. Further, it is possible to build functionality directly into the clothing, for example energy absorption through deforming lattices.

Figure 3.4. Printed dress.
(Source: Shutterstock)

Fit with Digital Fabrication

There are several benefits of digital textile printing compared to traditional techniques. Major factors driving change in the global textile printing market are well aligned with Digital Fabrication. They relate to the following:

Supply Chain Requirements

- Reduction of cycle time – speed to market
- Elimination of excess inventory/control of cash flow
- Greater customisation – better stand out and appeal to demand for individual expression

Globalisation

- Consistency and accuracy in global sourcing
- How new, on-demand printing technologies can disrupt established supply chains
- On-demand production enables the movement of printing closer to point of need/sale

Buyer Demands

- Faster cycle times – increase speed to market
- Individuality through personalisation and customisation
- Improved visibility and accuracy from design to delivery through workflow management software
- Reduced inventory and improved cash flow by using short run print-on-demand
- Sampling – production control of colour.

Currently digital textile printing is used for short run manufacturing. This allows jobs to be batch produced so several short runs can be seamlessly transitioned in one manufacturing run without the need to stop machines in the manufacturing process. In the future it is foreseen that production run lengths will shorten even more, costs will go down and quality will further increase. Consumers will be able to order fully bespoke textiles and garments online, to match fully their personal preference or even according to their own designs.

However, the manufacture of clothing today is a high-volume mass manufacturing industry. Therefore it is unclear how long exactly it will take Digital Fabrication processes to be able to generate products that will achieve sufficient added value to compensate for the higher per-unit cost of Digital Fabrication in textile manufacturing, which will initially be significantly higher compared to conventionally manufactured textiles and clothing.

Potential

The textiles industry is an established industry and marked by significant global trade. Increasing demand from emerging markets is currently driving industry growth. It is predicted that the industry size will increase from $662 billion (€482 billion) in 2011 to $1060 billion (€772 billion) in 2021 (Gugnani 2012). At the same time, there is a trend towards more individualised consumption patterns and, resulting from this, more fragmented markets. Although digital printing constitutes still only 2% of the total market for printed textiles, this is growing rapidly. InfoTrends estimates that revenues from digital textile equipment and ink sales will grow at a compound annual growth rate (CAGR) of 33.3% (DiMattei 2012).

Looking at the worldwide production of printed textiles, the regional mix shows that 50% of production is done in Asia, 15% in Europe and 11% in North America. Digital printing of textiles can influence this regional shift in the manufacturing of printed textiles, increasing the share of printed textile production in Europe and North America. A specific sub-segment is the production of printed home/decoration textiles. This segment amounts up to around 12 billion square metres a year, about 40% of all printed textiles.

Smart textile innovations will enable challenging and competitive applications in healthcare and relevant industries in consumer electronics, with applications that range from medical monitoring of physiological signals, assistance to emergency first-responders and commercial applications.

Smart Textiles already represents a lucrative market which is in rapid expansion.

> *"The market for smart fabrics is valued at €188.15 million in 2011 and forecast to see a CAGR of almost 23% to 2016, according to a new study by Smithers Apex. The CAGR during 2016-2021 is forecast to be just under 30%."* (Wilson 2011)

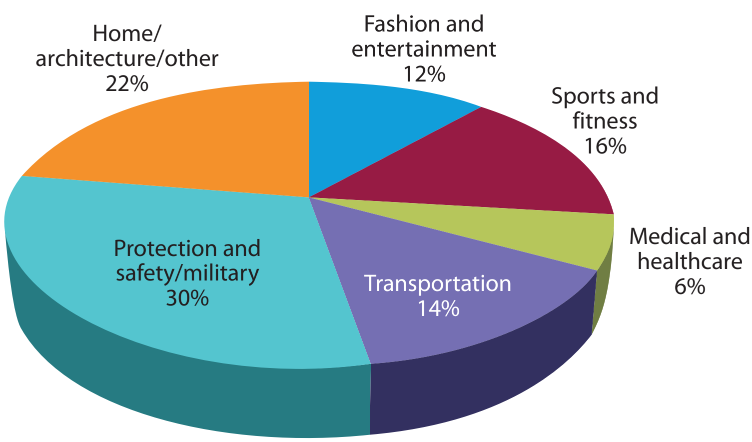


Figure 3.5. *Smart fabrics: end-use markets, 2011 (%share by value, €188.15 million). (Wilson 2011)*

Lifespan

Textiles for clothing and a wide range of other applications are not expected to become obsolete. With the growth of the world population, scarcity of resources will require reduction of waste. Waste in the textile printing industry is connected with the need for keeping stocks and over-production related to mass manufacturing. The need and market for locally produced, on-demand manufacturing of textiles in small series, ultimately in 'series-of-one', is expected to grow over the next 20 years. This can only be addressed with digital technology.

Adding new functions to textiles beyond purely colour and graphic designs is in its infancy but the prospects look very promising. This would open the way to applications and opportunities of which the lifetime cannot even be envisioned today.

The concept of digitally fabricated garments has been talked about for years, but the technology is still very new. Recently, one company, Shapeways, in partnership with Continuum Fashion, launched the first fully digitally printed garment. This was the first completely 3D printed garment, ready to wear and available to purchase. This is a great pioneering example that may lead the way in the field of digitally fabricated items of clothing.

Technology challenges

The process challenges faced in graphical printing have also been identified for the manufacture of novel digital textiles via Digital Fabrication. These include low cost inks, improved colour properties, matching inks to a wide range of 'receiving media' (in this case textile), eco-aspects and a reliable printing process in terms of speed, quality and reliability.

For the realisation of digital textiles with added smart functionally, the viability of embedding suitable electronic components is a key challenge. This requires the development of a supporting inputs market for such innovative textiles in the electronics industry. The continuous development of functional inks, suitable for digital production systems, will be instrumental in this quest, as it will provide truly flexible and inconspicuous electronic components.

Five important ink chemistries need to be (further) developed for digital textile printing to match different sorts of textile:

- Reactive inks – to print on all natural fibres
- Acid inks – to print on polyamide lycra, wool, silk

- Disperse inks – to print directly onto polyester and blends
- Sublimation inks – to print on sublimation paper to be transferred to textiles
- Pigment inks.

Materials development for functional clothing poses a challenge. The materials used must perform well in a number of dimensions. As they are worn by individuals they must be non-toxic. Further they must have attractive haptic and visual properties and they must be UV insensitive and wear resistant. However, the critical criterion for the materials is that they must be cheap enough to enable an attractive value proposition to the user/ consumer.

Table 3.1. *Limiting factors for quicker growth of digital textile printing.*

Limiting factors for a quicker growth of digital textile printing			
Factor	**Limits**	**Impact**	**Future developments**
Initial investment	Cost - performance ratio	Limits the faster spread of the technology	Prices will fall
Production speed	Slower than rotary screen printing	Limits the application to short runs	Speeds increase
Colour penetration	Drop size combined with resolution	Multiple scanning reduces process speed	Physical limits are given
Colour range	Quality of inks in use	Several colours cannot be printed digitally as e.g. fluorescent yellow, metallic	Physical limits are given
Ink cost	High price per kg	Others offered as closed systems with predefined ink supplier lead to dependencies and high cost	Increasing low cost competition from Asia will lead to falling prices
Resolution	Process speed	The printheads are the limiting factors, higher resolutions require lower speed	New printheads will offer higher speeds at high resolution
Variable dot size	Process speed with grey scale mode	High resolution with variable dot size are at most possible at reduced speed	Variable dot size will be standard
Machine, Printheads, Inks from different companies	Common strategy for development of systems	3 parties want to generate margins	Not predictable

Processes to completely (3D) print textile garments and the associated required materials need further research and development to ensure that future fully printed textiles and garments are robust, flexible and capable of producing fabric-like properties. It is unlikely designers will want to migrate to ‘digital textiles’ until they can produce something that is as good as or even better than what they can produce currently.

Printing on textile with Digital Fabrication technology also needs to match or exceed the performance of what can be achieved with conventional analogue printing. Table 3.1 above outlines some of the potential barriers of adoption and the future developments.

3.3 Functional end-use parts and products

Within the cosmos of Digital Fabrication technologies, a sub-group of processes referred to as Additive Manufacturing is particularly suitable for the general manufacture of end-use parts and products. Additive manufacturing technologies are now established as manufacturing processes which can deliver low cost parts with limited mechanical properties, or higher cost parts with structural properties. It is expected that growth of the sector as a whole can be achieved by further enhancing the processes in order to lower the cost of delivering functional products. This will be enabled by the development of both the processes and the materials for high performance low cost processes (AM Platform 2013).

The potential of additive manufacturing as an underpinning technology for distributed high value added manufacturing hinges on the acceptance of the technology among end-users and consumers. As labour expenditure can be potentially minimised by the adoption of this technology, its adoption may carry a wider social and political significance as product manufacture may be shifted back from low cost economies.

Various gateways for additively manufactured consumer products (for example, Shapeways (Shapeways 2013) or Sculpteo (Sculpteo 2013)) have already demonstrated the possibility of entirely novel supply chain configurations. For the first time it is possible, and indeed a commercial reality, that non-specialist consumers directly interact with and access industrial manufacturing technology. This has already enabled novel value chains and product design configurations. Concepts such as co-creation (offering freedom of design) can be harnessed effectively for such innovative consumer goods.

Figure 3.6. *A customised mobile phone case. (Source: 3D Printed iPhone 5 – "Sweater" Case by Shapeways, used under CC BY/ Desaturated from original)*

Fit with Digital Fabrication

The various underpinning systems for additive manufacturing have their origins in platforms designed for the automated creation of prototypes. In these settings, additive manufacturing has been extraordinarily successful and it is now the de-facto standard in the prototyping industry (Melchels 2012).

The following step in the evolution of additive manufacturing technology was the introduction of these processes into manufacturing applications for end-use products (Rudgley 2001). As evidence from high value manufacturing applications in the medical and aerospace sectors has shown, additive manufacturing is capable of delivering such products (Hopkinson 2006). A very illustrative example of the benefits of additive manufacturing is shown table 3.2.

In qualifying additive manufacturing technology adoption, however, a set of generic advantages and disadvantages associated with additive manufacturing is often cited in the literature. Table 3.3 summarises these aspects.

Table 3.2. *Case study of a joining bracket. (Baumers 2013)*

A joining bracket featuring conventional design	A topology optimised design manufactured via additive manufacturing
	
Contributing to efforts to reduce the weight of aircraft, an advanced design replacing a conventionally designed joining bracket was developed. This bracket is used for connecting carbon fibre components; the original design is manufactured from billet material using standard milling techniques. This manufacturing route results in over 80% of the billet material being machined away to scrap. The replacement design, which was created using a topological optimisation approach and manufactured by the Selective Laser Melting (SLM) process in a titanium alloy, resulted in a 40% weight saving compared to the original design.	

Table 3.3. *Generic advantages and disadvantages associated with additive manufacturing.*

Generic advantages (Tuck 2008)	Generic disadvantages (Ruffo 2006)
• Ability to efficiently manufacture geometrically complex components and products, which may exhibit comparatively higher levels of use-phase performance. • Ability to manufacture low quantities of products, down to a single unit, afforded by the absence of costs relating to tooling and changeover.	• Limited palette of build materials. • Poor dimensional accuracy compared to some non-additive processes. • Rough surface finish. • Problems with process predictability and repeatability. • Unfavourable processes economics at medium to high production volumes.

Potential

The total size of the European industry in 2012 can be approximated at $423 million (€308 million). Maintaining the current estimated annual industry growth rate of 29% (Wohlers 2013), total industry size is projected to be approximately $17 billion (€12 billion) in 2020. These estimates suggest that the potential for revenue growth is very significant. With a substantial European industrial base, growth in this area could provide a significant boost to European manufacturing.

Lifespan

The general manufacture of functional end-use products will continue in the foreseeable future. The future adoption of Digital Fabrication in this area will depend, above all, on its own trajectory of technological improvement and that of competing manufacturing processes.

Technology challenges

Materials

Virtually all types of materials can be used for additive manufacturing in the production of end-use goods. Materials which can be used for any sort of organised construction or manufacturing engineering application are known as engineering materials. These materials can be classified into the following broad groups: polymers, metals, ceramics and composites.

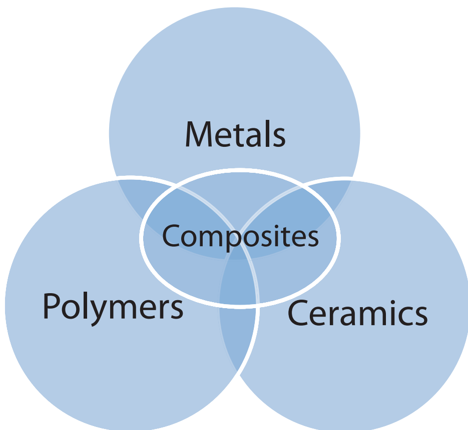


Figure 3.7. *Engineering materials.*

Although many of these engineering materials can already be processed using additive manufacturing techniques, the biggest challenge lies in matching the material properties to the production process and vice-versa in such a way that the properties of the end products are similar to, or exceed that of the products made using traditional manufacturing methods.

Polymers form the largest group of materials to be processed by additive processes. These range from photopolymerisation resin that mimics materials for plastic injection moulding to high temperature resistant ultra-polymers. It is important to note that these polymers differ significantly from the ones used for injection moulding. Even if the material is chemically identical, the resulting material and mechanical properties differ significantly. For example, material that is completely molten and injected into a tool under high pressure in a conventional process shows different properties compared to a material that is locally molten under atmospheric pressure, such as in some additive processes. Moreover, the addition of fillers such as glass, aluminium and ceramics may alter or improve mechanical properties to a certain extent.

Of particular relevance for this opportunity are the industrial grade thermoplastic polymers used in additive processes of the powder bed fusion and material deposition types, as summarised in Figure 3.8. Low cost Digital Fabrication systems aimed at consumers ('home printers') are usually not equipped with heated ovens and therefore not suitable for these engineering plastics.

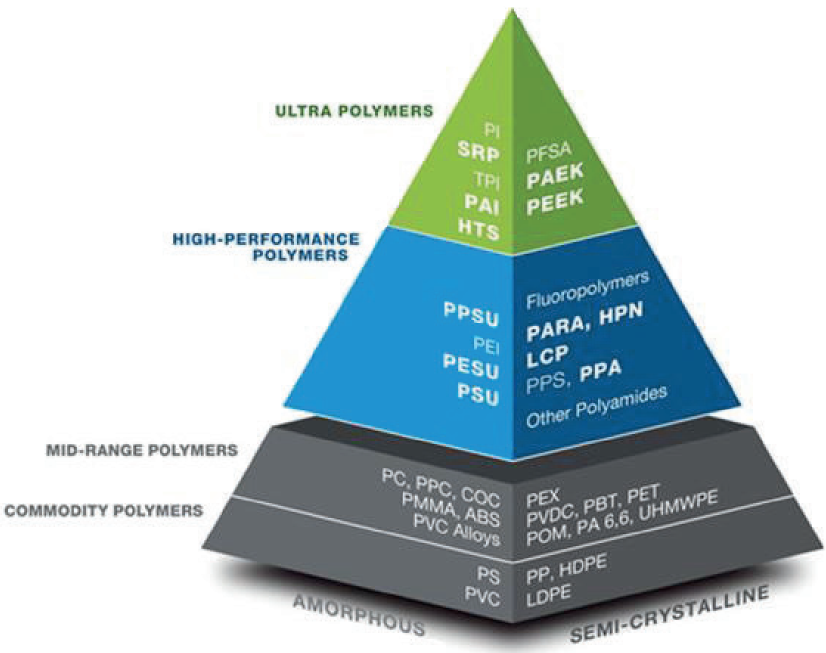


Figure 3.8. *Thermoplastic performance pyramid. (HIS GlobalSpec 2014)*

More than 100 different photocurable resins are commercially available, simulating various thermoplastic polymers. It is difficult to combine material properties in these resins and generally there is a trade-off such as impact strength versus heat deflection temperature. Stability over time and moisture absorption is also an issue. Using fillers such as ceramic nanoparticles, some limitations can be partly overcome.

Metals form the second important group of materials for use in additive manufacturing processes. Unlike the polymers employed in other additive processes, the metals employed by digital fabrication approaches are very similar to metal materials used in conventional manufacturing processes, such as laser cladding or welding filler material.

Powder bed fusion of metals is comparable with the polymer based variant. The main difference is the necessity of support structures. These structures are required for most metals. The high residual stresses experienced when processing metals means that support structures are used to keep the part from deforming. Post processing steps such as stress relief heat treatment and support removal can therefore be time consuming.

Various metals are available for additive processes, including stainless steel, tool steel, CoCr alloys, titanium, magnesium, aluminium and precious metals such as gold, platinum and silver are available. Research activity is ongoing to process copper and magnesium. Process parameters such as applied energy power, scan strategy, process control and powder dispensing have to match the material used.

The particle size will influence accuracy and surface finish in powder based processes. Finer particles will result in smoother surfaces but are difficult to handle. Materials with low thermal conductivity result in better accuracy as the melt pool and solidification area can be better controlled. The materials used display shrinkage of 3-4% when processed. This may lead to part distortion. Elevated powder bed temperatures can be used to reduce this distortion.

In difference to polymers and metallic materials, ceramic materials are considerably more challenging to process. Ceramic materials typically combine a high heat resistance and abrasion resistance, by comparison to metals and polymers, with very limited flexibility and toughness. This limits their processability in a direct AM process to rely on having a very high powder packing density or long process times at high temperatures in order to produce a solid ceramic part. Higher powder packing can be achieved by either depositing the powder layers in the form of a slurry which, after drying, leaves a high density ceramic powder compact that can be sintered by a laser, or simply to apply a slight compression to each layer of deposited powder prior to sintering. The last method typically produces a more porous product, and may require further processing in a furnace to reach the desirable density in the material. Composite materials are macro-physical combinations of different phases with the aim of combining beneficial properties of the basic materials. This makes composite materials a very large diverse group, which strictly speaking includes both polymers with metal, glass, ceramic, carbon or nano particles as filler materials, and also CerMets where a ceramic material is embedded in a metallic material matrix.

Processes

Challenges standing in the way of wide-spread adoption of additive manufacturing in the production of functional end-use products range from process fundamentals, process economics, industrial implementation, consistent quality and control as well as product data handling and specialised training. These aspects are especially relevant as the technology will need to outperform established conventional manufacturing processes in many cases.

The digital nature of additive manufacturing requires a digital workflow for pre- and post-manufacturing. High productivity future additive systems will require specialised datapaths and control systems. Moreover, the development of specialised design software for multi-material and integrated 3D products is currently lagging behind the advances in capability of the processing hardware.

A further persistent challenge to address for the application of additive manufacturing in the production of end-use products is the development and integration of complementary technologies and peripherals like electronics, motion control and software.

A fundamental limitation of current technology is the size restriction to additively manufactured products imposed by the internal build volumes of available machines. The effect of this limitation is that additive processes are currently able to produce small parts, consumer products and medical components, but not large products.

When attempting to enter new markets, new design rules may need to be established before industry consensus can be achieved. Design rules for additive manufacturing are being developed. The design of integrated and multi-material parts is still very premature. In established industries where technical change is slow and investments are long-lasting, customers prefer to work with technology and suppliers with whom they have existing relationships. Also the lack of customer belief in new emerging markets is a barrier.

The disruptive nature of additive manufacturing technology poses a barrier in itself. To take on a disruptive technology the customer needs to see that it functions and that the technology is robust and reliable.

The structure of the value chain also presents a barrier to customers since they do not always experience direct financial benefits. For example, the savings that are made from a reduced inventory arising from flexible short runs could be made elsewhere in the value chain.

3.4 Additively manufactured objects with embedded printed intelligence

Innovative future products will integrate 'ready-assembled' multifunctional devices and structures. The key stepping stone to such products is the inclusion of printed intelligence, such as electronic or electric functionality into everyday consumer products and components for specialist industrial applications.

Integration of such functional structures will allow the incorporation of, for example, sensors, control logic, in-part health monitoring, electronic interfaces, and internal energy distribution or communication devices. Combined with the relatively unconstrained creation of (potentially optimised) structural part geometry, such integration directly within components will allow some aspects of functionality to be tailored specifically for particular uses and user requirements.

This will result in a new generation of extremely capable and high value products for many different applications. Further, it will contribute to the current trend of adding smart functionality to the tangible products that surround consumers today. Figure 3.9 shows a digitally fabricated demonstration component incorporating integrated strain gauges for in-part health monitoring.

Integrated functionality will lead to products and systems that operate more efficiently, are more responsive, easier to interact with and safer to be around for humans. Moreover, it is anticipated that devices that are able to predict their own failure will lead to an entirely new approach to quality management. Environmental benefits also seem possible as systems could be designed to minimise the environmental footprint, for example by switching off when idle.

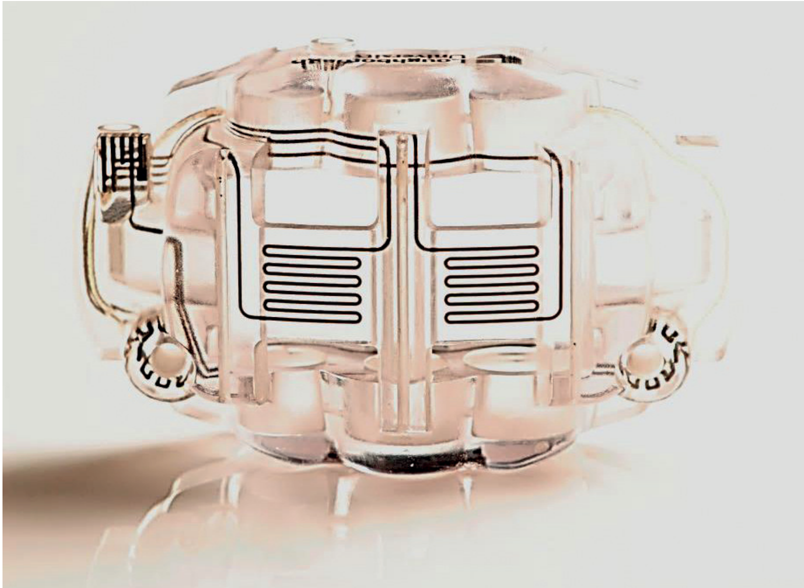


Figure 3.9. *Demonstration part for integrated sensing. (Source: University of Nottingham 2013)*

Fit with Digital Fabrication

Embedded functional structures, such as electronic pathways, are likely to be intricate, complex and to exhibit a three dimensional design. The freedom of geometry inherent to Digital Fabrication processes enables the cost efficient manufacture of such structures. This will lead to highly innovative products delivering completely new functions, user experiences and value propositions.

Within a single manufacturing process, the structural body or chassis of the product and its embedded functionality can be built up concurrently. No existing conventional manufacturing approaches, for example moulding or machining, are capable of efficiently depositing such structures of functional material within parts. Moreover, Digital Fabrication methods can be used to create planar functional structures on top of substrates (for example on part surfaces) but also embed them within components.

One central problem with all portable consumers of energy, such as sensing and computation devices, is that the power driving these systems must be stored within or near the device. Digital Fabrication is expected to have an impact on how energy can be stored within products incorporating embedded functionality.

The technology is used to print batteries on or within products, providing a power source that is as portable as the functionality of the product. The ability to embed electronic functionality within parts and components also opens up the possibility of energy harvesting via routes such as RFID and near Field Communication. As Digital Fabrication is toolless, the shape of the batteries and their specification can be tailored to match the exact requirements of the application.

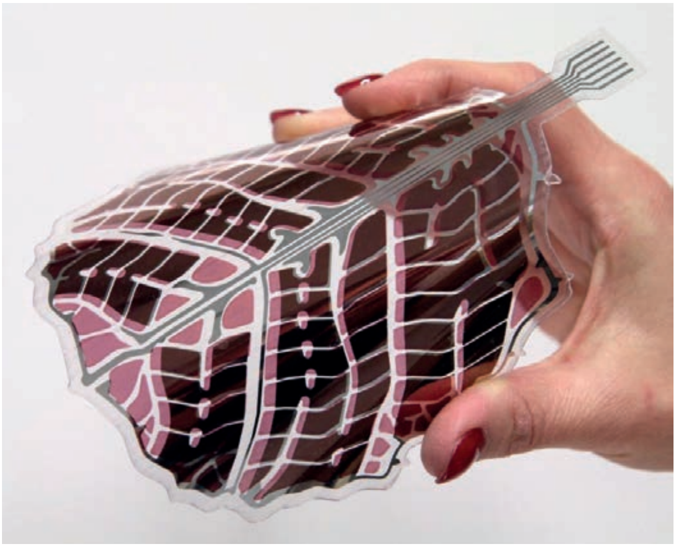


Figure 3.10. *Decorative solar cell resembling a leaf. The cell can be used to power batteryless sensors for lighting control. (Source: VTT)*

Potential

For battery applications alone, a global promising trend is identifiable. The global market size for batteries is forecast to grow to around $74 billion (€54 billion) in 2015 (Battery University 2013). The reason for this growth is the increasing demand for portable electronics. Therefore, it is evident that Digital Fabrication of batteries is an opportunity to enter a large and growing market. Furthermore, the fundamental trend toward distributed computing suggests that the demand for flexible mobile power sources will exist for many years. Combining this with embedding of sensing capabilities paves the way towards intelligent and connected parts and products that will fit with the promise and opportunities associated with the 'internet of things' and big-data. Parts with embedded intelligence will clearly have a long lasting future potential.

Lifespan

The trend towards distributed sensing, computing, and the 'internet of things' is still in an early phase. It is likely that the diffusion of this technology into everyday life lies decades in the future.

The increased capability and availability of data processing and its rapidly decreasing cost (Schaller 1997) makes distributed sensing a more and more attractive proposition. Hence, speculation on the life span of products with embedded intelligence such as integrated logic and sensing or energy sources may be premature.

Technology challenges

Materials

On the materials side, major technology challenges will involve combining several materials successfully for the purpose of printing an integrated product. This implies that the materials used must be compatible on multiple levels. Moreover, the materials and the deposition technology need to be matched for each particular application and substrate.

To achieve the requested physical and mechanical material properties, such as conductivity, strength and stiffness, the inorganic portion of the printed material may be composed of a precise distribution of functional fillers like fine ceramics, metals and/or modifiers.

The development of materials suitable for the Digital Fabrication of printed functional structures has attracted a considerable amount of research in the last two decades. However, this application domain is a very competitive space, which is why progress must be achieved in applications like printed electronic displays within the next 5-10 years if commercialisation of digitally fabricated displays is to be realised. From a business standpoint, it must also be noted that emerging applications require materials in low volumes. Therefore material suppliers may see only a limited incentive to develop specific materials and prefer to sell into markets that are already established, which may obstruct the innovation process in this application.

Particularly for the fabrication of printed electronics the development of suitable materials forms a considerable challenge. The material spectrum required includes dielectrics, conductors, optical carriers, and structural materials with tuned mechanical, thermal and physical properties. The key aspect in these considerations is the interaction of the materials within the

Digital Fabrication process. Parameters such as temperature resistance, viscosity, curing/solidification methods and deposition accuracy are expected to play a significant role.

In sensing applications, both the design and build material of the sensor will be determined by the specific sensing purpose, therefore the required materials need to have the appropriate properties for applications. For successful deposition of materials in Digital Fabrication processes, aspects such as viscosity, adhesion characteristics, and wettability are of importance.

Regarding printed power storage devices, much of the developmental effort towards digitally fabricated components has been expended on small batteries. This has resulted in the manufacture of alkaline, lithium ion and other types of micro batteries. Printed zinc-air batteries have been integrated into electromechanical devices. Further, it is expected that the material requirements will depend on progress in Micro-Electro-Mechanical Systems (MEMS) and nano-scale applications for which power sources of a matching scale are needed.

Processes

Operating existing materials jetting platforms in a reliable round-the-clock configuration poses a challenge at the current state of technology, not only because of the clogging issue of the inkjet nozzles, which causes line defects, but also the heat generation of material curing that may affect reliable operation of inkjet printheads. Also, industrial printing requires a high throughput; however, there is a trade-off between printing speed and accuracy.

A further process-related challenge faced in the multi-layer, multi-material deposition for creating functionally integrated devices is the linkage with other manufacturing technologies with different process parameters, such as speed and process environment requirements. This is due to the fact that digitally fabricated embedded functional structures are mostly manufactured in hybrid manner, combining various additive and conventional technologies. Modular production configurations featuring elements of Digital Fabrication and conventional processes have been introduced to meet this challenge.

Another area that requires significant attention in the Digital Fabrication of complex embedded multifunctional structures is related to the avoidance of process and deposition errors. To realize a viable production setup based on Digital Fabrication, aspects such as error prevention, prediction, detection and correction form a top priority. For the commercial implementation of

Digital Fabrication techniques in the production of embedded structures, reliability of printhead architectures and operation systems are critical.

Figure 3.11 provides an overview of important process and materials-related technology challenges faced in the deposition of intelligent embedded structures, as identified in the Diginova project.

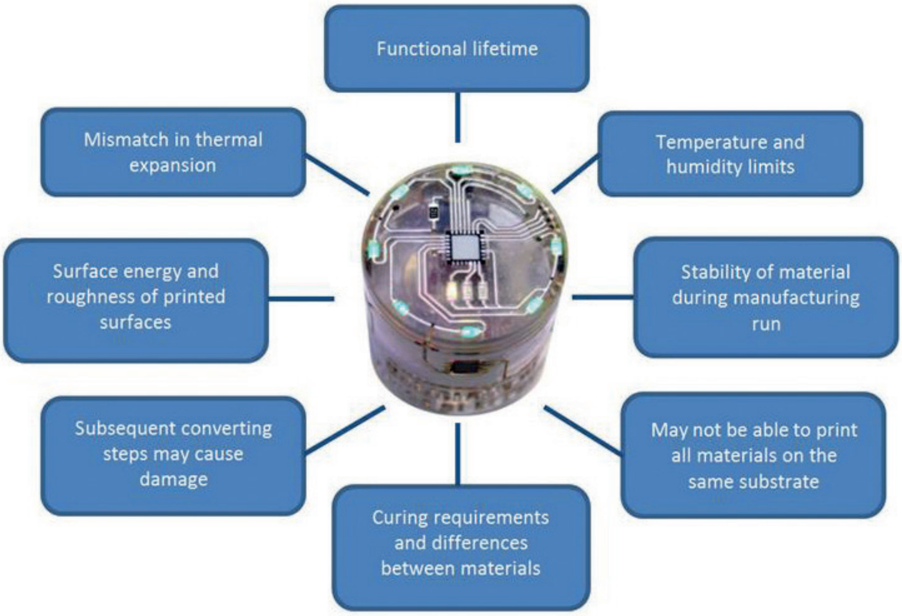


Figure 3.11. *Major technology challenges for embedding functional structures.*

3.5 OLED lighting and displays

OLED (Organic light-emitting diode) technology holds the promise to be one of the most disruptive lighting technologies for the next decades. Unlike traditional lighting technologies that are point sources, with OLEDs an entire surface can be a light source without requiring backlight and filters. When OLEDs are used as small light emitting pixels, the technology also enables the production of displays with unique and advanced properties. Several advantages arise over current traditional technologies such as LED (Light-emitting diode) or LCD (Light-crystal display):

- **Lightweight** and possibility to make layers or displays on **flexible** plastic substrates
- **Wider viewing angles** and improved **brightness**

- Better **power efficiency**
- **Faster** response time
- **Lower cost** potential.

OLEDs seem to be the perfect technology for all types of light emission, but there are also certain disadvantages that need to be technologically overcome:

- **Lifetime.** While red and green OLED materials have longer lifetimes (46,000 to 230,000 hours), blue organic light emitting materials currently have much shorter lifetimes (up to around 14,000 hours (OLED-Info 2013).
- **Manufacturing processes** are currently expensive.
- **Water** can easily damage OLEDs if the active polymers are not properly encapsulated.

It is expected that in the future flexible and transparent OLED panels will be available (for lighting as well as display purposes). This requires flexibility for the entire device, including the encapsulating layer. This technology is now being developed both by research groups and major companies. At the same time, also transparency is difficult to achieve. However, first devices have been in production since May 2011 when TDK introduced a range of mobile phone and other media and communication products.

Figure 3.12. *Flexible display. (Source: Shutterstock)*

Summarising, OLED technology is a hot topic both in academic and industrial research. Although some devices and materials are currently mass produced (in particular for small displays), many technological challenges are still open and provide a huge potential to revolutionise the field of lighting and displays.

Fit with Digital Fabrication

The combination of OLEDs and Digital Fabrication is a combination of two growing technologies, which gives OLED development considerable freedom of design, having the perspective of making devices or objects that could benefit from both customisable shapes (through Digital Fabrication) as well as bright and multi coloured emissive surfaces (OLED technology). However, digitally fabricated products must also compete in terms of durability and sustainability. In other words, the product quality must meet or exceed that of traditional construction, lighting, and display materials for Digital Fabrication products to gain traction, develop growth, and hold sufficient market share to remain competitive for the next 10 or 20 years.

OLED lighting applications offer architects freedom of design and flexibility to find new and creative designs for their individual construction projects, avoiding the limitations linked with ordering mass-produced components. This could be a particularly interesting area. Vacuum thermal evaporation (VTE) which is currently used to produce OLEDs cannot be used for Digital Fabrication in order to respond to these demands.

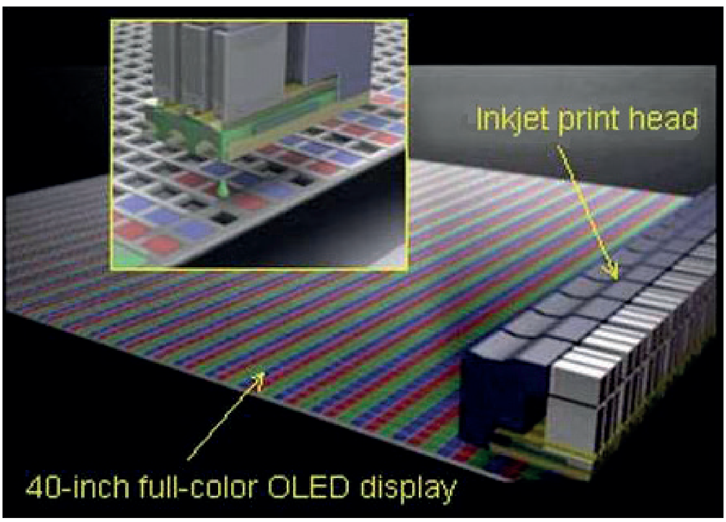


Figure 3.13. *Schematic representation of inkjet printing for manufacturing of OLED displays. (Digital imageMaker international 2014)*

There are now several alternatives for next-generation deposition techniques, including inkjet printing. In small scale, these new deposition techniques have already been used to produce OLED products at very high throughput, process quality and flexibility – advantages that could in the future ease current, critical manufacturing bottlenecks hindering the production of flexible and large-sized OLED products.

Potential

The flexible OLED display market is predicted to quadruple next year. Research firm HIS finds that flexible displays are about to become much more common. In their report they forecast that the global market revenue for flexible OLEDs will increase from $21.9 million (€16 million) in 2013 to $94.8 million (€69 million) in 2014 and will rise to nearly $12 billion (€8.7 billion) by 2020.

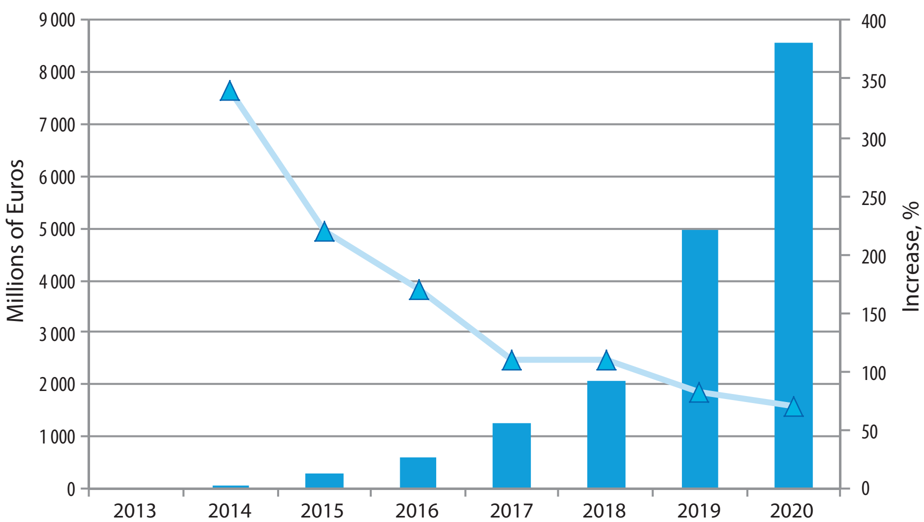


Figure 3.14. *Forecast revenue for flexible OLED displays. (Brewster 2013)*

Recently Transparency Market Research published that the current market was $4.9 billion (€3.6 billion) in 2012 for the major OLED applications:

“The research report on the OLED displays market is analysed based on major applications such as mobile phones, TV, notebooks, tablets, digital cameras, and automotives. The global OLED displays market is expected to reach $25.9 billion (€18.9 billion) by 2018 from $4.9 billion (€3.6 billion) in 2012 growing at a CAGR of 31.7% from 2012 to 2018. Mobile phones are the largest end-user application and accounted for 71% of the total OLED displays market in 2012, but the share of OLED TV displays are expected to surpass the shares of mobile phone displays by 2015." (OLED-Info 2013)

According to Display Search (Hsieh), the OLED lighting market will reach \$6.3 billion (€4.6 billion) by 2018 (see figure 3.15).

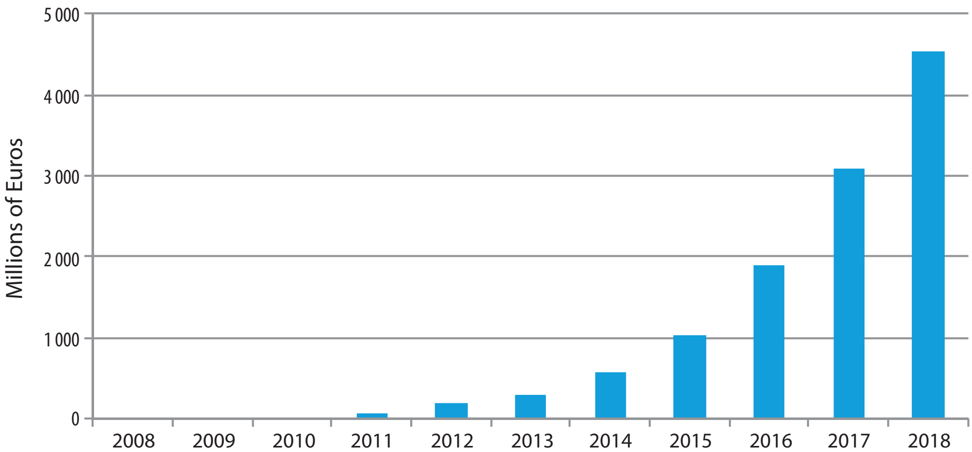


Figure 3.15. *OLED lightning revenue forecast by Display Search. (Hsieh)*

Lifespan

OLEDs are the first light source that can emit light as a 'surface light source', making it a disruptive technology that can transform the way we see our surroundings. In addition, OLEDs are expected to deliver the next generation of displays with huge advantages over current display technologies. Up to now, there is no other technology under development that in the next few years could replace OLEDs. The major display and lighting enterprises like Samsung, LG, Philips and OSRAM are all investing considerable resources in OLED research and development. Also the number of joint-venture OLED related projects is huge, meaning that OLEDs are expected to be a significant market opportunity for the next decades.

OLED lighting is a growing factor in building construction and as OLEDs progressively increase in their overall dimensions this will become even more mainstream. In 5 or 10 years or so, it could be envisioned that one could paint a wall with a colour with OLEDs mixed into it, and when an electrical current would be applied, the whole wall would light up (Wollerton 2012).

Table 3.4. *Development of OLED lighting technology. (DOE 2013)*

Metric	2013	2015	2018	Goal
LER (lm/W)	320	330	350	360
Internal Quantum Efficiency	85 %	90 %	90 %	90 %
Electrical Efficiency	75 %	80 %	85 %	85 %
Extraction Efficiency	40 %	50 %	60 %	70 %
Panel Efficacy (lm/W)	80	100	120	190
L_{70} Lumen Maintance (1,000 hours)	15	20	25	30

Note: Projections assume CRI > 85, 2580-3710 K; 10,000 lm/m^2 emittance.

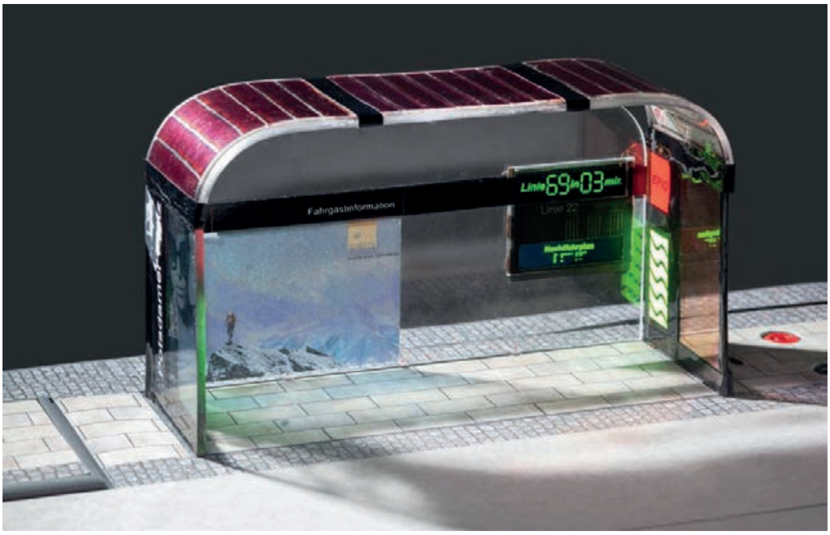


Figure 3.16. *Organic light-emitting diodes (OLEDs) – here at the bus stop of the future – will soon come out of printing machines. (Source: Fraunhofer IAP / Till Budde)*

Technology challenges

Materials

The biggest material challenges for OLED devices are related to the organic conductive layers. The durability of these materials is currently limited: the materials deteriorate under ambient conditions (oxygen, water vapour) dramatically decreasing the lifetime of the products. The solution is to apply an encapsulation (barrier) layer that shields the materials from the environment.

There is a big technology challenge for OLED technology in the field of flexible electronics, with respect to organic device encapsulation. The use of glass as barrier material is the best option for non-flexible and rigid organic electronic devices. There are already OLED products in the market with glass encapsulation such as smart-phone devices, AMOLED TVs and products from the lighting industry. However, for flexible displays different encapsulation materials will need to be used.

Processes

In the process area the biggest challenge is in scaling up to large scale production. Nowadays, OLED devices are mainly produced using thermal evaporation of small molecules. This technology has several disadvantages:

- The use of a vacuum system, making it an **expensive** production method
- **Slow processing** speed, due to the evaporation process
- **Low scalability**, since large systems are needed to deposit on relatively small areas.

In order for OLED technology to become a mainstream technology, it is commonly accepted that the vacuum evaporation process should be abandoned. The idea is to produce OLED devices in a fast and continuous process. However, the feasibility and manipulation of organic light emitting materials remains a big challenge. Some of the technologies that might be used as an alternative for vacuum evaporation include rotary screen-printing, slot-die coating and inkjet printing.

In order to use Digital Fabrication techniques, the most promising process is inkjet printing. For the transparent conductive layer, Digital Fabrication through inkjet printing seems feasible. However, the entire OLED device also requires ceramic and metallic materials to shield the organic material from the environment and to interconnect all the parts of the device. Although it is possible to produce the organic materials by an inkjet printing process, challenges still remain in the field of barrier and electrode fabrication, thereby disabling entirely digitally fabricated OLED devices for the moment.

Future developments must be focused on production of new formulations/ inks to print both organic and encapsulation layers with low production costs and commercial viability. Concurrent with these developments, TCOs must also be produced using new technologies that enable reduction of processing costs and allow for higher market implementation, thus forwarding digital fabrication of OLED devices.

Faster market expansion will take place when a number of challenges are overcome:

- Decreasing power consumption by material integration
- Increasing lifetime of organic materials and encapsulation materials
- Reducing production costs
- Enabling flexibility in form/shape.

Besides these technical challenges, OLED panel costs (materials, production process costs) need to come down in order to be commercially viable.

3.6 Smart windows

'Smart windows' can also be called 'switchable windows' or, in some applications, denoted as 'smart glass'. They can change the light transmittance by applying an electrical current, automatically or on demand, in response to an environmental signal such as sunlight or temperature sensed by a light/ temperature sensor. When activated, the glass changes from transparent to translucent or tinted, blocking some or all wavelengths of light.

The application of such windows can help to save energy in highly glazed buildings by reducing cooling and heating loads and the demand for electric lighting; focusing their use on the control of glare and solar heat. On the other hand, there are aspects that could be critical e.g. material costs, installation costs and durability, as well as functional features such as the speed of control, possibilities for dimming, and the degree of transparency.

The present marketplace for smart windows can be based on a number of different technologies, such as Thermochromic, Electrochromic, Photochromic, Suspended Particles (SPD's) and Polymer Dispersed Liquid Crystal (PDLC's) devices. Under development are other technologies such as Micro-blind and Nanocrystal devices.

The tint possibilities for electrochromic windows provide higher value in comparison to thermochromic windows, giving them diversity for interior and exterior architectural, automotive and other applications.

Figure 3.17. *Electrochromic Printed Electronics prototypes: free design for customised applications. (Source: CeNTI and Ynvisible)*

Fit with Digital Fabrication

Digital Fabrication could be very beneficial for Smart Windows technologies. Manufacturers have underlined the requests from architects to have fine-tuned and optimised window panes in order to control parameters such as temperature, light, feel and ambience of the room or to control the electronic functionalities incorporated. The objective will be to adopt Digital Fabrication technologies that enable the on-site fabrication of very specific fine-tuned windows that fit individual requirements given by the particular concept of a building division or room.

Potential

With the ability to mould different designs, smart windows can occupy a prominent place in the advertising, marketing and interior design industries. According to the market research report 'Global Smart Glass market 2012-2017, by technology (Thermochromic, Liquid Crystal, Suspended Particle Display, Electrochromic, Photochromic), Applications (Architectural, Transportation) and Geography' published by Markets and Markets, the global Smart Glass and Smart Windows market is expected to reach $3.8 billion (€2.8 billion) by 2017 at a CAGR of 20.3% from 2012 to 2017.

Some technical opportunities include developing electrochromic coatings that are less costly and more adaptable to the smart windows needs, which would drive faster adoption and consequently increase sales of the materials.

The market is highly dependent on the development of new forms, materials and processes that will address the current issues of shelf-life, cost, and others.

Lifespan

Smart windows can help to save energy and because windows are architectural elements, smart window customisation is likely to be a good commercial opportunity.

The demand for smart windows, or windows with functional capabilities such as variable tinting in response to electrical or thermal changes, will be driven by the green building movement, attractiveness of the convenience they provide and the potential for cost savings. The research firm NanoMarkets believed already in 2011 that the market for smart windows will grow substantially over the next six years, becoming a billion-dollar market by 2015 and then more than doubling by 2018. They also foresee even greater growth for the electrochromic segment of the dynamic glass market. Electrochromic windows could become the first smart window type that will find significant markets in each of the application areas.

Technology challenges

The impact of Digital Fabrication on the set of materials used for smart windows will initially be low, as Digital Fabrication is particularly useful in patterning materials that are continuously being developed for products produced with analogue technology. The main impact is expected to arise when demand for customised patterned windows or mirror elements arises. It is expected that the main driver for these innovations may initially come from the automotive industry and from the aerospace industry.

2D Digital Fabrication technology covering all types of inkjet methods and laser ablation are high resolution techniques that would be useful in the processing of smart windows. Employing high throughput technologies may not prove to the most commercially viable option regarding the level of customisation that may be required for smart windows, and also the wide range of different applications/functionalities needed for different smart windows installed in the same structure (aircraft, vehicle, floor/division of a building). Therefore, the opportunity is about developing 2D Digital Fabrication technologies that will allow for the development of specific designs and specific functionalities integrated into an individual window panel.

Currently, the types of Smart Windows under discussion are either colourless when transparent or dark blue when opaque. There are new opportunities for research into material that could switch between transparent and a range of opaque colours.

3.7 Printed sensors

Printed sensors have been around for many years, specifically sensors where the deposition of electrode materials is done by using screen printing, but we are seeing more and more sensors demonstrators for which functional printing is used to create the entire sensor. Processing by printing methods enables cost effective fabrication of large area sensor arrays on flexible substrates for various applications. This is well suited for multiple sensing layers for sensor fabrication which is one of the main trends in the sensor industry at the moment. Although printing has been used to fabricate some elements of sensors like electrodes, fully printed sensors are not yet on the market.

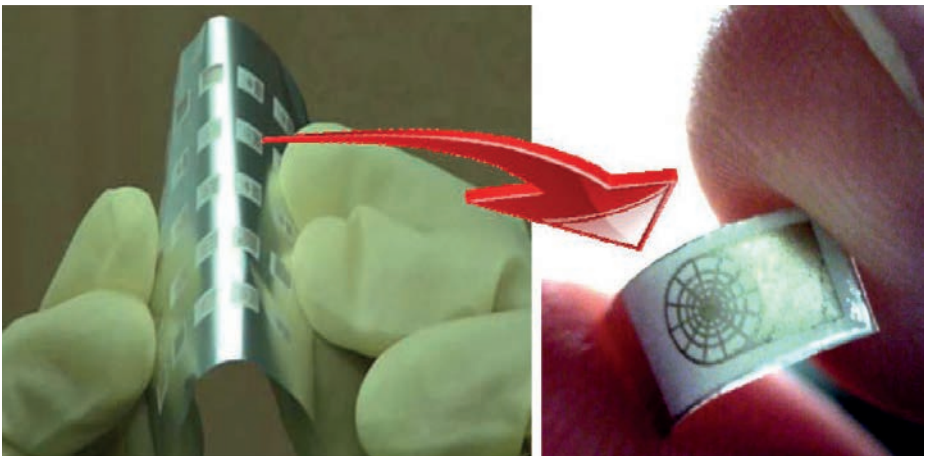


Figure 3.18. *Thermocouple sensor. (Source: Wang 2010)*

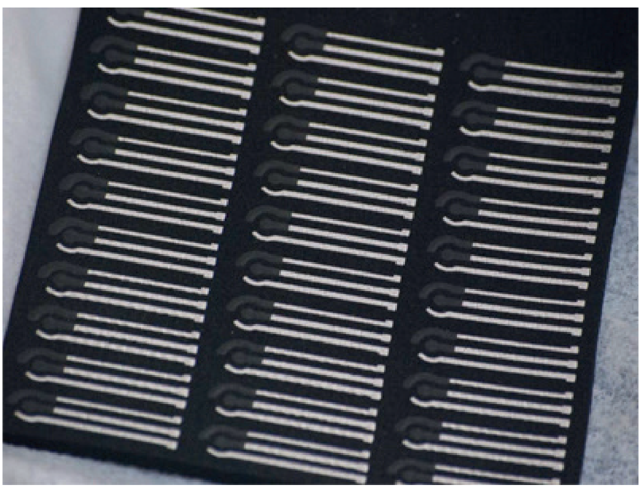


Figure 3.19. *Printed electrochemical sensors to detect any contaminants present in seawater, for example: phenols, TNT (trinitrotoluene) and copper. (Developed by the team of Prof. Joseph Wang of UCSD, University of California, San Diego)*

Fit with Digital Fabrication

Printed and flexible sensors are an important part of printed electronics. The typical idea associated with printable electronics is to use a low cost manufacturing process, usually a roll to roll process, to increase the manufacturing speed and reduce the waste of unused, or removed, material and therefore a roll to roll process reduces the cost of the electronic devices. However, as the need for customised products in low series increases, production methods for printed sensors might change from centralised mass manufacturing to locally produce integrated printed sensors with specific requirements.

Digital Fabrication is able to provide capabilities to produce printed sensors tailored to a specific application for a final consumer. In certain fields, for example medical care, this is going to be extremely important and useful, as the sensor capabilities increase, the solutions need to be more and more customised and their method of production becomes more flexible, simpler and faster.

Potential

Printed and flexible sensors are an important area in printed electronics. The biggest market is for biosensors and a good example is the glucose sensor currently used by diabetics. Printed and flexible sensors already represent a $6.3 billion (€4.6 billion) market in 2013 according to IdTechEx. The figures also suggest that the total market for printed, flexible and organic electronics will grow from $16 billion (€12 billion) in 2013 to $77 billion (€56 billion) in 2023.

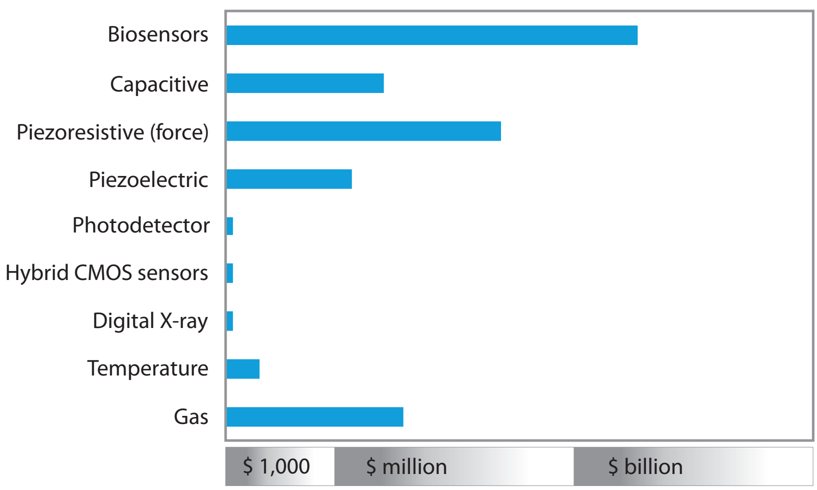


Figure 3.20. *Market of printed sensors in 2013. (Igbenehi 2012)*

According to IDTechEX's latest report, projections for the next 10 years indicate that biosensors will still have the biggest market share, while Hybrid CMOS (Complementary metal-oxide-semiconductor) sensors will be the second most significant sector in 2024 in terms of revenues, driven by the replacement of silicon by organic or quantum dot semiconductors as photosensitive material in a number of applications.

Lifespan

Printed sensors are already present in the market for some applications, primarily those that require short lifetimes and that focus on cost reduction and/or weight reduction with full integration.

The IDTechEx market study mentioned previously, predicts a rapid growth over the next 10 years.

> *"The compound annual growth rate (CAGR) of printed and flexible sensors will be 22.1% over the next ten years. In the main, printed and flexible sensors are creating new markets using their unique advantages of flexibility, area and functionality."* (Igbenehi 2012)

Recent studies (Igbenehi 2013) in 2013 point out that biosensors have the biggest market share within the printed and flexible sensors segment.

> *"Printed and flexible sensors already represent a value of $6.3 billion in 2013. The biggest market is currently biosensors, where disposable glucose test strips are used to improve the lives of diabetics. However, other types of printed sensors are emerging, taking advantage of the latest materials. By 2024, these emerging applications will take a significant share of the total printed sensor market."*

We expect that printed and embedded sensors will have a long-lasting impact on society, for the next 20 years and beyond, especially in the field of biomedical applications.

Technology challenges

Future development is related to integration of sensors with other functionalities into an integrated smart system. The key challenges to be faced are related to integration of different components and especially interfacing to printed electronics circuitry.

Currently the market is accepting new products with integrated sensors and improved hardware and software. There is a need for the continuous development of new functional inks, to increase the range of applications for printed sensors, and also the optimisation of existing digital printing systems to maximize output and lower cost.

Printed sensor manufacturing needs a number of different materials with completely different properties, but still compatible with each other: see the table 3.5 below for an overview of required materials.

Table 3.5. *Features of inks for the manufacture of sensors.*

Property materials	Specification materials
Conductive materials	metal particles and conductive polymers
Semiconductor materials	semiconductor polymers and ceramic materials
Dielectric materials	polymers and ceramic materials
Functional materials	materials that have properties that can be easily controlled by external parameters

In order to enable Digital Fabrication of printed sensors, the value chain has to be closely connected so that materials can be adapted to process technologies and vice-versa. New materials, manufactured by new kinds of processing methods, should at least have similar properties as the materials they are replacing.

The printing methods that are so far most commonly used for printed sensors are screen printing, gravure printing and inkjet printing. Figure 3.21 shows some characteristics of these techniques.

Functional inkjet has received a lot of attention because of its ability to create very small features in a very flexible way. This could make inkjet highly suitable for digitally fabricating sensors. Other techniques, like flexo- and rotogravure are very high throughput processes and are therefore highly suited for roll-to-roll products.

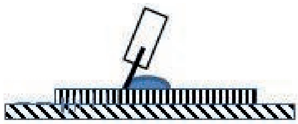
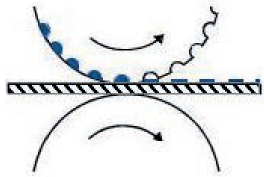
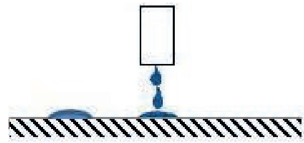
Screen printing	Gravure printing	Inkjet printing
		
(+) Most mature (+) Rather inexpensive (+) Roll-to-roll compatible	(+) Allows thick and thin films (+) Good scalability (+) High layer quality (+) High resolution (+) Roll-to-roll compatible	(+) High resolution (+) Flexibility (digital method) (+) Substrate independent (+) High resolution (+) Roll-to-roll compatible
(-) Requires masks (-) Waste of ink (-) Limited resolution	(-) High cost of cylinders (-) Highly demanding	(-) Nozzle clogging

Figure 3.21. *Most common techniques for Printed sensors.*

3.8 Personalised diagnostics & drug delivery

Personalised Medicine is the tailoring of medical treatment and delivery of health care to the individual characteristics of each patient—including their genetic, molecular imaging and other personal determinants (Tufts 2010). In particular, personalised pharmaceuticals and diagnostics hold significant potential for the application of printing technology.

Personalised Pharmaceuticals and Pharmacogenetics

There is wide individual variation in the pharmacodynamics of administered drugs, effectiveness, and the appearance rates of adverse effects. Despite these variables interacting to produce large physiological variance, clinicians mostly prescribe stochastically based on patient anamnesis and anthropometrics, with respect to drug data and patient populations. The benefits of pharmacogenetics are not reserved only to increase patient safety but also offer benefits in therapeutic response (drug efficiency), a higher standard of care, and a cost effective treatment.

The release of drugs from an appropriate dosage form at prefixed time intervals and at a predetermined rate represents a significant challenge for scientists involved in pharmaceutical studies (Matricardi 2013). One well known example which requires strict control is the hormone insulin, a peptide that regulates the metabolism of carbohydrates in the body and is used as a drug to treat diabetes (Duke University 2013).

Personalised Diagnostics

Many people who routinely manage illnesses, such as diabetes, will regularly use personal diagnostics for measuring their biological state such as the hydroxybutyrate monitor seen in Figure 3.22. Point-of-care diagnostic machines will use printed diagnostic tools to assess blood, urine, or saliva samples in the home or pharmacy, and will print personalised pharmaceuticals on the basis of the diagnostic information. This type of diagnostic device will open up personalised medicine to a greater number of people, will increase drug efficiency and ultimately lead to increased patient safety in the delivery of pharmaceutical products.

Figure 3.22. *A carbon nanotube based biosensor, used in the personal management of diabetes, for the detection of 3-hydroxybutyrate (HB) in blood serum. (Fars 2013)*

Biosensors, defined as a specific type of chemical sensor comprising of a biological recognition element and a physico-chemical transducer, are set to take a leading role in personal diagnostics.

Fit with Digital Fabrication

Printing technologies will allow the automation of pharmacokinetic analysis and identification of a suitably safe and efficient drug. In addition, printing technology could be used to generate a tailored prescription. The printed drug would contain a patient specific dose and release rate matching a defined metabolic profile.

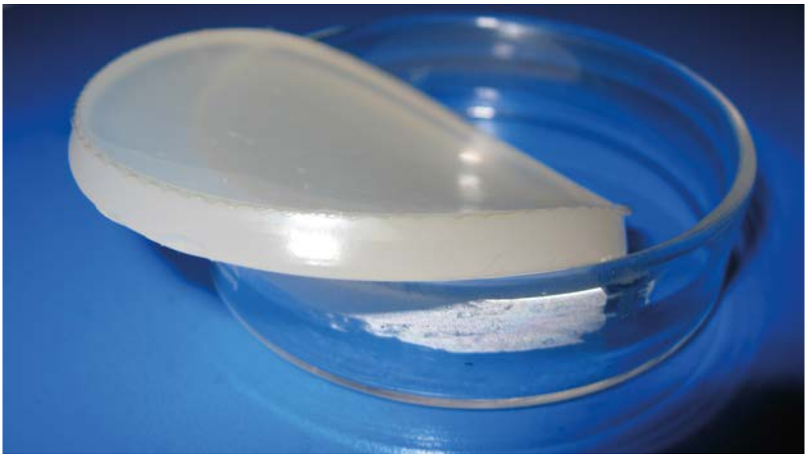


Figure 3.23. *Xylan-based hydrogel contains 90 per cent water, but remains mechanically quite durable. (Source: VTT)*

One possible application of personalised pharmaceuticals is controlling the means of drug release, so that it can be tailored to specific routes of administration. This can be achieved by using printed smart materials including hydrogels which react to changes in the physical, chemical or biological environment.

Potential

The European pharmaceutical market represents one of Europe's highest performing high-technology sectors, which is estimated to be worth over €500 billion (EFPIA 2013). Machinery able to customise dose and release time of drugs through inkjet printing could offer huge cost savings and aftercare benefit. For example, a report by the UK NHS entitled '*Prescribing for Diabetes in England*' reported that over 5 years, the cost of drugs and treatments alone in order to treat people with diabetes had risen by 40% from over €530 million in 2004/5 to €770 million in 2009/10 (HSCIC 2010). In total, an estimated €16 billion is spent a year on treating diabetes and its complications, with the cost of treating complications due to poor disease management a significant element.

Personal diagnostics are in their infancy but market reports suggest the US market alone is set to exceed $3 billion (€2.2 billion) by 2018 (McKinsey 2013).

The automated tracking and management of conditions which require long term pharmacy have significant benefits to health service providers. As an example, the NHS in Britain spends over €10 billion per year on non-drug related complications of type 1 and type 2 diabetes, a cost which could be significantly reduced with better monitoring systems in place.

Genome-based diagnostics are evolving rapidly as many pharmaceutical companies focus on the development of targeted therapies and consider the benefits for a diagnostic test to pair with a specific treatment. Such tests are showing potential in reducing tremendously the costs of clinical trials (close to 2/3rds of the clinical trial costs in some cases). A recent report estimates over $130 million (€95 million) in savings for pharma companies per approved compound (Martinez de Lecea 2012).

Lifespan

Personal diagnostics is a need which is set to increase. For example, type-2 diabetes, a disease with an enormous and unmet clinical need, is forecast to reach 300 million patients globally by 2025 (Amiram 2013).

Personalised medicine is a rapidly developing field, and we estimate that the lifespan for new technology for personalised diagnostics and drug delivery, underpinned by bioprinting and digital manufacturing, exceeds 20 years.

Technology challenges

Personalised Diagnostics & Drug Delivery systems are at the forefront of modern medicine. The use of advanced printing techniques such as ink jetting will allow the creation of systems to diagnose, monitor and prescribe at point of care and, as such, will have a significant positive effect on patient safety, drug efficiency and overall quality of care. The market for personal diagnostics is currently small in relation to the overall pharmaceutical market, and the lack of technological infrastructure is a significant barrier to growth.

Specific research challenges are:

- In materials processing, very short lead time, automated processing of proteins and resorbable polymers, with controlled doses of specific pharmaceutical products.
- In machine development, diagnostic printer platforms, able to produce diagnostic devices for a range of conditions from the same basic unit.
- In the clinical sciences, identification and development of biomarkers for drug compatibility and disease identification, greater understanding of the relationship between drug dosage and personal genetic predisposition, and the development of biosensor bioreceptors.

Close collaboration between the clinical sciences, biomaterial scientists and machine developers is key to bringing the promise of printable personalised medicine to the clinic and market.

3.9 Medical microfactories

Medical microfactories are generally understood as a standalone, dedicated manufacturing solution for a specific medical problem or condition (Figure 3.24). For example an in-theatre human skin printing station will be a dedicated microfactory intended to solving the problem of supplying on-demand biocompatible skin sections that match the patient's specific requirements. In the same way an in-vivo musculoskeletal tissue 'printer' will be a microfactory which provides on-demand 3D printing of cancellous and cortical bone, and cartilage, to a localised part of the musculoskeletal system with a suitable mix of medical grade materials that promote high quality tissue regeneration.

Medical microfactories can also be desktop size fabrication points for a number of custom made medical devices such as dental aligners, prosthetic sockets, lower and upper limb orthotics or surgical instruments. Although currently a number of general purpose additive manufacturing and 3D printing technologies are being used for such purpose there is a clear trend towards the specialisation of specific equipment for in-clinic/in-theatre operation.

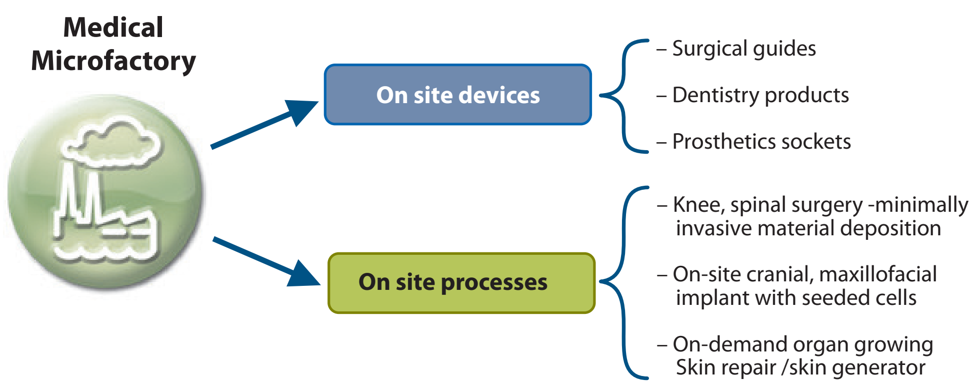


Figure 3.24. *The medical microfactory concept.*

When brought into a medical framework the characteristics of a microfactory should include:

- Portability. A medical microfactory is portable and can be transferred easily to the point of need.
- Connectivity. Able to access distributed data, for example a cloud-based server with multiple sub-manufacturing branches.
- Completeness. Integrating all required elements.
- Customisation. Able to provide a patient specific outcome according to pre-defined conditions and medical treatment.

Fit with Digital Fabrication

The key reason for the adoption of additive manufacture within medical microfactories is the ability to make personalised geometry from a variety of digital scanning methods (considering both external shape and internal structures, depending on the application). In addition, for a range of applications it is attractive to make highly porous structures with a range of micro and macro porosities, and additive manufacture techniques also provide this functionality. Finally, the medical microfactories approach is about embedding that functionality within a very short lead time system, in order to provide a rapid one stop service to the patient.

Two specific potential future applications are medical devices and cellular therapies.

Medical Device Example: Orthotics

Defined as medical devices used externally to the body, orthotics are normally prescribed to alleviate a number of conditions for different parts of the body. One example is the provision of foot and ankle-foot outhouses using digital manufacturing (Figure 3.25). By integrating a patient information system, 3D scanning, a CAD modelling engine, pressure sensing and an inverse dynamics simulation system, the resulting orthotics are custom made and optimised to a specific patient, and can be manufactured by two different approaches: a centralised manufacturing unit, or distributed 3D printers.

Other orthotic application areas, following the same digital supply chain have been shown in Figure 3.26.

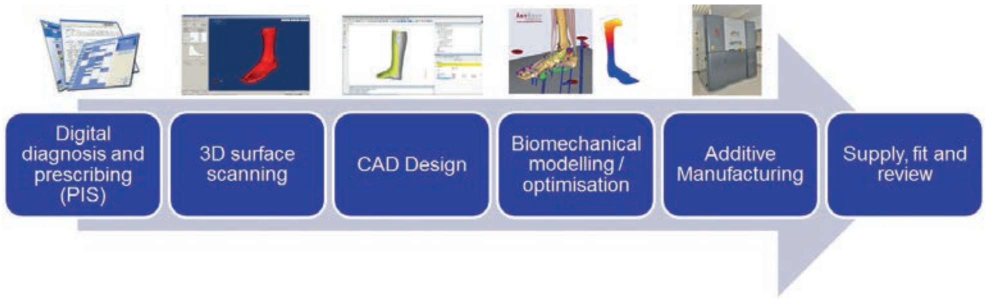


Figure 3.25. *Disrupted foot/ ankle-foot orthotics supply chain by additive manufacturing. (European Commission Framework Seven Program 2009)*

Figure 3.26. *A group of foot, ankle-foot orthotics and wrist splints designed at Newcastle University for the 3D: Printing the future exhibition at the Science Museum, London.*

Tissue Engineering Scaffolds

The basic tissue engineering premise is outlined in Figure 3.27. In its most basic form, tissue engineering is about assisting the natural repair mechanisms in the body to repair defects which would not normally heal by themselves, by providing structural support and biological stimulus to the defect site.

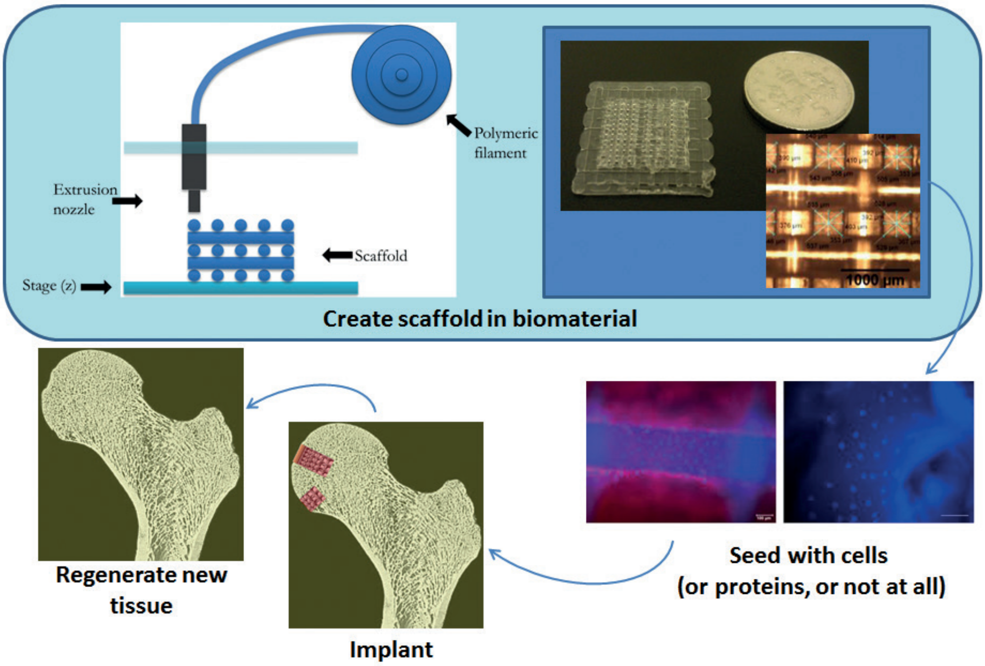


Figure 3.27. *A simple View of tissue engineering. (Source: University of Newcastle)*

Scaffolds, made of a variety of materials (natural, synthetic, biodegradable), provide the structural support for cell attachment and subsequent tissue development.

Several groups (Benning 2013, Calvert 1998, Calvert 1997, Xiong 2001) and companies (e.g. Envisiontec, Sciperio, MicroFab Technologies) have developed AM-based technologies that can co-process cells and biomaterials. These systems are built to make use of a wide variety of polymers as well as bone-cement-like pastes or slurries, solutions, dispersions of polymers, reactive oligomers, gels and currently living cells.

Potential

The worldwide medical device, technology and equipment market is forecast to be worth over €300 billion by 2018 (Espicom 2013), with the ageing population driving growth long term.

The medical market will increase as 3D scanning technologies, printers, and materials fall in price and experience widespread adoption. The market – still in its infancy and worth a mere €8 million in 2012 – is estimated to grow to €1.4 billion in 2025 (Dickens 2013). A significant portion of that market is expected to be related to new niche medical device applications, many of which have potential to be delivered through dedicated medical microfactories.

The market penetration of AM can be measure in the adoption of commercial technologies currently applied in the medical domain. Manufacturers of medical equipment, like surgical instruments and biomaterials, had €250 million worth of 3D printers in their inventory in 2012, and that number is expected to reach €700 million by 2019 (Lux Research 2013).

Figure 3.28. *Blood haematology analyser. (Source: Shutterstock)*

Lifespan

The emergence of fully functioning, custom built, specific purpose medical microfactories is at least a decade away from widespread adoption across different medical sectors. The concept of a medical microfactory requires a paradigm shift as systems will tend to migrate from full size manufacturing facilities for mass made artefacts with small/non variations, into modular small-scaled systems (desktop type) with capabilities to produce products typically featured by: short lifecycles, small batch sizes, high levels of variability and miniaturisation. Studies for potential Bio-Additive Manufacturing (BAM) applications forecast its main capabilities to be developed in the next 15 years (Bourell 2009), however due to the mass media exposure of additive technologies it is expected that more medical equipment manufacturers that previously did not consider using additive manufacturing will start doing so in the coming years.

Technology challenges

- For medical device microfactories very low lead time, automated processing of biocompatible polymers and composites, going beyond what is currently possible, is required, with 3D printing at the centre of a single stage additive manufacture or hybrid manufacturing process.
- For tissue engineering microfactories clean co-processing of resorbable biomaterials with cells and proteins, to create complex 3D structures is required. Materials with a combination of excellent mechanical properties and excellent biological properties are a key need.
- Integration: the development of medical microfactories for specific healthcare applications (for example for arthritis, diabetes, cancer, assistive devices for the ageing population, or for orthotics and prosthetics) with the active involvement of healthcare professionals provides the best environment for integrating the technologies into a healthcare setting.

3.10 Potential for Digital Fabrication evolving to mega- and nano-scale

One potential future development could be the extension of Digital Fabrication technologies to both very large as well as very small size length scales. This applies particularly to the field of Additive Manufacturing/3D printing. Additive manufacturing is clearly leaving the ‘nursery room’ and is becoming a mature production technology for a wide range of industries as well as an enabler for design and fabrication by individual consumers. It can also be envisioned that similar base principles of Digital Fabrication could be applied to build very large or very small objects. We would like to introduce the terms ‘Mega-scale Digital Fabrication’ (MDF) and ‘Nano-scale Digital Fabrication’ (NDF) for large and small scale Digital Fabrication, respectively.

Following the above assumption it can be envisioned that in the future we might not only make things in a different way by using Digital Fabrication technologies, but we could also make completely different things and materials. Looking 10 to 20 years into the future, Digital Fabrication could revolutionise the way we see and construct the world around us.

Mega-scale Digital Fabrication

In the 1990anineties digital laser printers and desk-top publishing revolutionised graphic design. Currently digital 3D printers are revolutionising industrial design. One can imagine that in the future we will be printing buildings and revolutionising architecture and construction. The technological perspective of '3D printing' large structures on-demand and on-location could help meet the growing demand of housing and also provide this in remote locations or under high time pressure.

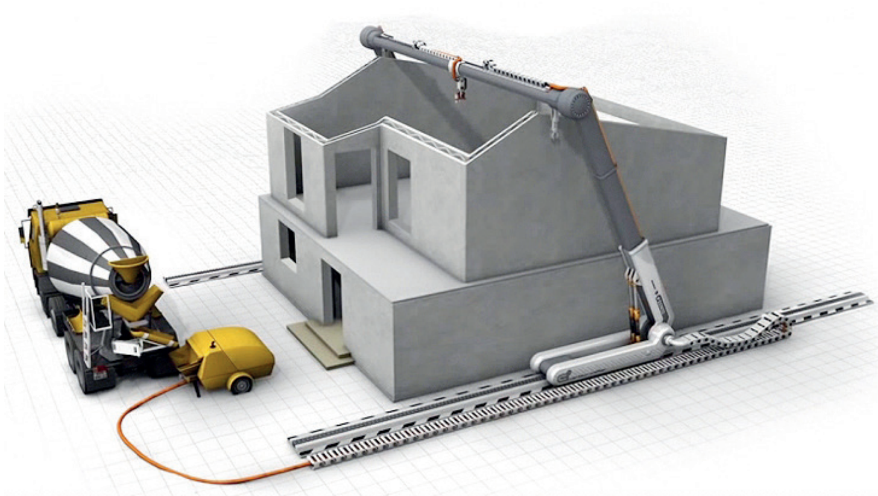


Figure 3.29. *Artist impression of the so called 'Contour Crafting' technology that enables Digital Fabrication of buildings. (Grozdanic 2014)*

One of the envisioned and currently investigated possible MDF technologies is called Contour Crafting. It was proposed by an American professor, Behrokh Khoshnevis, of the University of Southern California (USC) and his initial ideas were published in 2006. Currently, there is considerable, worldwide interest in this field. The working principle has similarities to Fused Deposition Modelling, a technique that is well known and used in many 3D printers where objects are created by deposition of molten polymers. The system consists of two crane-like arms and a crossbeam that carry a 'printhead'. The entire machine runs along a set of tracks and can work on all parts of the house simultaneously. Building material is 'jetted', or 'poured', from a 'printhead' to construct a building layer-by-layer. The inventors of this device estimate it can build an entire two-story house in just under a day. Additional work is required when it comes to window head jambs and metal ceilings, which can be done either by hand or by cranes. With the current status of Contour Crafting technology it is not yet possible to build structures with multiple/mixed materials in one process. The rest of the process is almost completely automated. If current barriers are overcome, it can be envisioned that building and construction of virtually any design could be carried out using MDF in the next 10 to 20 years.

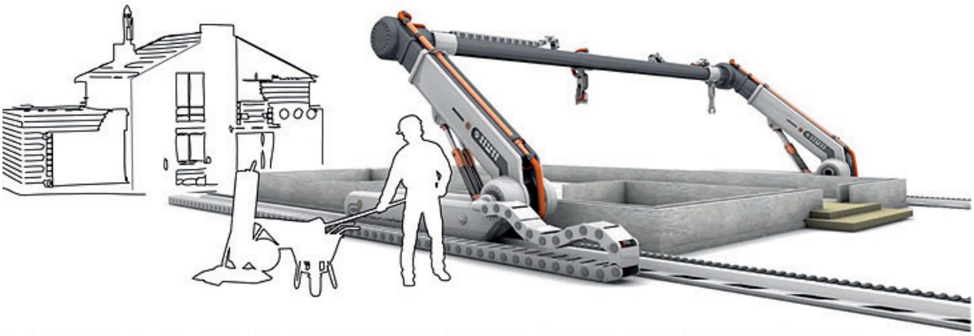


Figure 3.30. *Mega-scale Digital Fabrication decreases the demand for labour compared to the traditional building and construction methods. (Grozdanic 2014)*

This technology could prove to be very beneficial for the building and construction industry. Using this technique the labour costs, building waste and production times can be greatly reduced. Furthermore, freedom of design enables architects to depart from the traditional architectural choices and limitations. This has implications for the aesthetics of the building, as well as material use. Additive construction allows for building and façade shapes that minimise material use, while preserving structural strength by optimisation of form and function.

Even further in the future, MDF could be one of the key factors in enabling extraterrestrial habitation. NASA has acknowledged this, and is funding experiments aimed at building lunar structures and buildings that could potentially be erected outside of earth.

Nano-scale Digital Fabrication

Compared to MDF, at the other far end of the length scale is atomic precision manufacturing. Already in 1989, IBM had manipulated single atoms to deposit them in predetermined positions. IBM used a scanning tunnelling microscope (STM) to manipulate single Xenon atoms on a nickel crystal and this can in fact be considered as a Digital Fabrication method on the atomic scale. (Eigler 1990)

It is envisioned that someday we will be able to use an atom-by-atom manufacturing process to produce materials with improved performance. In an even further step, these materials would be made and directly embedded in a product, and there would be no more need for expensive or scarce intermediate material stocks. Only the simplest materials carrying the required fabrication elements would be required.

For example, one could build mechanical parts atom-by-atom taking carbon as raw material. The resulting material could be a diamond-like material: stronger than any metal, and very lightweight. In the biomedical domain, molecular sensors and targeted medicine could revolutionise the medical world. The range of possible applications would be almost endless and could include:

- Efficient solar photovoltaic cells
- Efficient, high-power-density fuel cells
- Single molecule and single electron sensors
- High-density computer memory
- Molecular-scale computer circuits
- Display and lighting systems
- Responsive (or smart) materials
- Ultra-high-performance materials
- Highly selective catalysts
- Precisely targeted agents for cancer therapy
- Biomedical sensors (in vitro and in vivo)
- Selectively permeable membranes.

Another interesting concept is that of claytronics. The idea is that self-assembling, small particles, sometimes called nano-robots with internal computing power and communication means to the outside world, or so-called catoms, are able to interact with each other to form and to transform into any type of physical 3D object that users can interact with. The idea is that catoms can be re-used indefinitely so that material scarcity would no longer be an issue.

It is difficult to predict what the future will hold in the field of nanotechnology combined with Digital Fabrication, but one thing is certain: as the semiconductor industry continues to obey Moore's law, the atomic limit of electronics structures and transistors will be reached within 15 years. This certainly would boost applications for advanced nano-materials and devices such as claytronics.

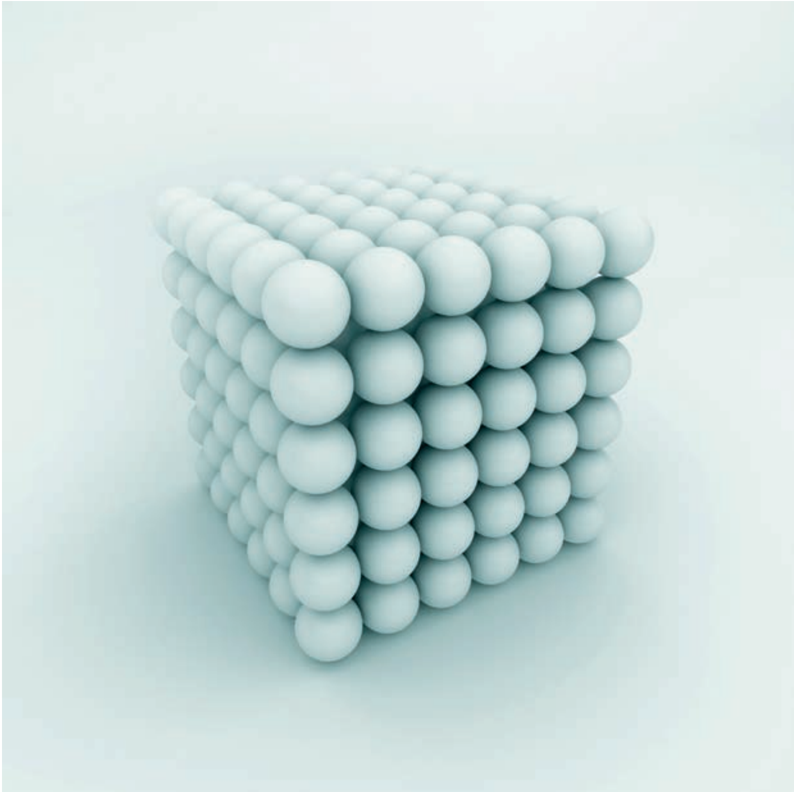


Figure 3.31. *Artist impression of catoms, the building blocks of the Claytronics concept. Catoms can be programmed individually and interact with each other to form physical 3D objects. (Source: Shutterstock)*

4 The bright future of Digital Fabrication

4.1 Introduction

As presented in this roadmap, Digital Fabrication technology promises to enable a number of exciting new products and applications. However, it may be the case that the promising applications outlined in the previous chapter will only be the start. There is reason to believe that Digital Fabrication will lead to radical innovation in many areas. One characteristic of such radical innovation is that its effects are often unforeseeable. This suggests that Digital Fabrication may change the world we live in more than we anticipate. Analysing the drivers behind this technology and the challenges associated with it is nevertheless an informative task. After all, in the words of Neil Gershenfeld, “the world of tomorrow can be glimpsed in tools available today”.

This chapter will demonstrate that Digital Fabrication processes in their current state of technology readiness still face a number of challenges which limit their viability to specialist and niche applications. Despite these limitations, some industries have been shown to be particularly efficient in adopting the currently available technology. This has already resulted in ground breaking products, such as body conforming in-ear hearing aids or digital ceramic tile printing.

A recurring theme in the implementation of Digital Fabrication is the transition from niche applications to wide spread acceptance as a routine manufacturing method. For this to become reality in the general manufacturing sector, many different kinds of technical and non-technical barriers must be overcome. The Diginova project correspondingly places a great emphasis on identifying business drivers and related barriers, and pairing them with possible approaches. This methodology results in the identification of key technology challenges.

For applications based on the additive deposition of flat structures on top of substrate materials, referred to in the context of this roadmap as ´digital printing´, ink jetting technology has emerged as a technology of exceptional importance. Domain experts agree that the process of ink jetting is still in an early phase of its technology life cycle and that significant research activities and new product development are still ongoing. It is believed that ink jetting techniques will be central to many future manufacturing scenarios and that the technology will proliferate across many sectors.

Table 4.1. *Technology variants of five highly relevant Digital Fabrication processes.*

Name	Summary of operating principle	Available build materials
Powder bed fusion	Using a thermal energy source, such as a laser, to selectively fuse regions of a powder layer. Processes belonging to this category include Laser sintering, Selective Laser Melting, Direct Metal Laser Sintering and Electron Beam Melting.	Nylon 12, Nylon 6, PP, PS, TPU, PEEK, PEKK, stainless steels, tool steels, titanium, aluminium, cobalt-chrome, nickel-based alloys, ceramics (alumina, zirconia, mullite)
Material extrusion	Processes based on the extrusion of material through a heated nozzle. Processes include Fused Deposition Modelling and various low cost systems aimed directly at the consumer.	ABS, PC, PPSU, Ultem (PEI), PLA
Vat photopoly-merisation	Employing a laser system to scan the surface of a vat of liquid photopolymer resin that hardens when irradiated. The main process of this type is stereolithography.	Photopolymer resins based on acrylate, epoxy and vinylether chemistry
Material jetting	Based upon the deposition of acrylate photopolymer and other materials via ink jetting heads. In photopolymer processes, droplets of liquid monomer are formed and then exposed to ultraviolet light to initiate polymerisation. Commercial material jetting platforms include ProJet from 3D Systems, Eden/Connex from Startasys/Objet and VoxelJet (binder jetting).	Acrylic-based photopolymer materials or binder materials
Directed energy deposition	Heating and melting build materials while depositing raw materials, displaying similarities with traditional welding and laser cladding. Commercial manufacturers include Trumpf and Optomec.	Various weldable metals and engineering ceramics

For the Digital Fabrication of discrete 3D structures a number of technology variants known under the collective term ´Additive Manufacturing´ are available, all of which are based on the principle of building up component geometry in a layer-by-layer fashion. Many of the operating principles underpinning Additive Manufacturing have their origin in rapid prototyping technology originating from the 1980s. In 2012, the ASTM has published a list of such processes with an eye on their use as genuine manufacturing processes, resulting in a comprehensive list of technology classes and definitions. Table 4.1 summarises five technology variants which carry high relevance to Digital Fabrication and also provides a brief overview of the materials deposited by these processes.

Acknowledging that the decision to adopt this technology will be made by the community of commercial users, the following section discusses the general business drivers of Digital Fabrication technology as identified over the course of the Diginova project. The subsequent section reports on a set of collective technology challenges associated with all variants of Digital Fabrication, including ink jetting processes and the various Additive Manufacturing technologies. The following section proceeds with the analysis of key technology challenges faced in the most promising applications of Digital Fabrication as identified in the previous chapter. Accepting that an additional range of non-technical barriers are bound to have an effect on the speed and extent of technology adoption, the next section analyses a variety of such issues. The closing section summarises the recommendations for further research activity made throughout this chapter and highlights the requirement for a formulation of a strategic research agenda at the European level.

4.2 The business drivers behind Digital Fabrication

The specification of an effective technology research agenda requires a thorough understanding of the motivators for the use of such technologies. In the Diginova project such aspects have been analysed in the form of ‘business drivers’. A business driver can be understood as a descriptive rationale supporting the vision of a manufacturing future based on Digital Fabrication. Ideally, the identification of business drivers is backed up by empirical observations and expert accounts.

The Diginova project provided a unique opportunity to engage with a large group of over 120 technology users and domain experts to survey their views on the driving forces behind the spread of Digital Fabrication technology. Table 4.2 presents the main drivers seen to motivate the adoption of Digital Fabrication technology in a generalised way.

Table 4.2. *Main business drivers.*

<table>
<tr><th colspan="2">Business drivers for all Digital Fabrication technologies</th></tr>
<tr><td colspan="2">• Increasing design freedom, including feature size
• Independence of economies of scale
• Product customisation/ customer input/ personalisation
• Reduction in lead times
• Supply chain consolidation and decentralisation
• Reduced raw material waste
• Reduction of hazardous waste</td></tr>
<tr><th>Drivers for digital printing technologies</th><th>Drivers for Additive Manufacturing technologies</th></tr>
<tr><td>• Improved deposition accuracy
• Greater material range
• Ink/ toner substitutability
• Substrate substitutability</td><td>• Part light weighting
• Geometry/ topography/ thermal optimisation
• Build material substitutability
• Reduction in unit costs
• Reduction of process energy consumption
• Additional functionality/ multifunctionality/ material gradients</td></tr>
</table>

The information collected by the Diginova project suggests that some business drivers act as common motivators for the adoption of all technology variants of Digital Fabrication. Other business drivers have been identified to promote the diffusion of more distinct variants of the technology, such as ink jetting or Additive Manufacturing.

The data collected throughout the Diginova project suggest that there are three highly prominent motivators for the adoption of Digital Fabrication: the design freedom inherent to the approach, the capability of creating customised products and an independence of economies of scale. All three aspects stem from the toolless nature of Digital Fabrication, meaning that tooling is not employed and tooling expenses are not incurred. These drivers are widely believed to lead to innovative products which can be customised or differentiated and which can be manufactured efficiently in small production runs.

Reduction of lead times forms a further highly relevant business driver. The collected data suggest that it is a relevant factor in practically all applications based on Additive Manufacturing. In contrast, in applications based on ink jetting technology, the reduction of lead times appears to be a pronounced driver in graphical printing and industrial printing applications. It has been suggested that this is due to the fact that the implementation of Additive Manufacturing in industry is still in an early phase of technology diffusion and is facing incumbent conventional manufacturing technologies exhibiting longer lead times.

Beyond the technical aspects of the core processes, several aspects relating to supply chain innovation have been identified as driving forces behind Digital Fabrication. Particularly in the area of printed products with paper and paper-like substrates as well as in the area of 3D fabricated consumer, defence and electronics applications, supply chain consolidation and decentralisation are identified as highly relevant business drivers. Implementing Digital Fabrication in industries driven by these factors will open up new supply chain possibilities and distribution models for a variety of products.

Such changes in supply chains are also seen as opportunities to reduce the environmental impact of manufacturing. Effectively, the creation of a distributed manufacturing structure based on Digital Fabrication may limit the need to transport intermediate and finished products over large distances. Further environmental benefits may be realised through the characteristics of the processes themselves. As Digital Fabrication technologies are capable of building up components by incrementally adding material, significant waste streams associated with some subtractive conventional manufacturing processes, such as machining, can be avoided. Especially where energy intensive raw materials are used, such as titanium, the elimination of raw material waste has been shown to lead to substantial energy savings.

A further environmental aspect to consider in the performance of digitally fabricated products is the impact of such products during their useful life. As such products are likely to be differentiated for particular applications and exhibit high degrees of fitness for purpose, they are also likely to have a smaller environmental footprint during their use-phase. These benefits can be achieved by harnessing Digital Fabrication's ability to create highly complex products for the manufacture of extremely efficient products, for example by light weighting methods in the aerospace industry.

4.3 General technology challenges

Establishing Digital Fabrication as an accepted manufacturing route demands the collaboration of a number of scientific disciplines and industrial sectors. In particular, these efforts will draw on inputs from two groups of supporting industries: the industries producing the process equipment itself and the sectors providing the complementary innovation in raw materials. Thus, it is assumed that further evolution of Digital Fabrication technology will be the result of collaboration by organisations in the printing, electronics and industrial equipment industries combined with raw materials provided by the polymer, speciality metals and engineering ceramics industries.

Corresponding to this, fundamental technology challenges lie in the combined creation and further development of suitable core deposition processes and materials. On the basis of these system and material combinations, novel products and components will be created by the technology adopters. These products will feed into existing or novel supply chains. At the end of these supply chains it will be necessary to identify and develop markets for novel products enabled by Digital Fabrication.

The collaborative efforts in the Diginova project have identified two focus areas associated with significant technology challenges. These relate firstly to the core deposition processes themselves and secondly to the provision of matching and viable build materials. The following sections summarise the findings in these two areas over the course of the Diginova project.

Deposition processes

A number of Digital Fabrication processes and technology variants have been developed and commercialised from the mid-1980s onwards. These developments took place in the fields of digital printing and Additive Manufacturing, which came into existence as technically distinct fields. As more recent technological approaches such as the material jetting variants of Additive Manufacturing technology demonstrate, there is growing common ground between both technologies. By choosing Digital Fabrication as its subject, Diginova combines both approaches in a single analysis, effectively exploring this technological convergence.

The various inputs by domain experts and technology specialists over the course of the Diginova project have revealed that a number of technology challenges exist in this common ground. As broad areas of key technology challenges, the following six categories have emerged:

- Process implementation and economics
- Core process technology
- Design systems
- Supporting processes
- Supply chain development
- Education, legal and political agenda.

Falling into these broad areas, the Diginova partners have produced a catalogue of key technology challenges, each based on a pairing of a technology barrier with a specific resolution approach. It was also possible to make a judgement in terms of the urgency of resolving the technology challenges with respect to the most promising applications identified for Digital Fabrication. The general technology challenges identified and their associated levels of comparative urgency are presented in Figure 4.1, with the least urgent challenges being located in the centre and the most urgent challenges on the margin of the circle.

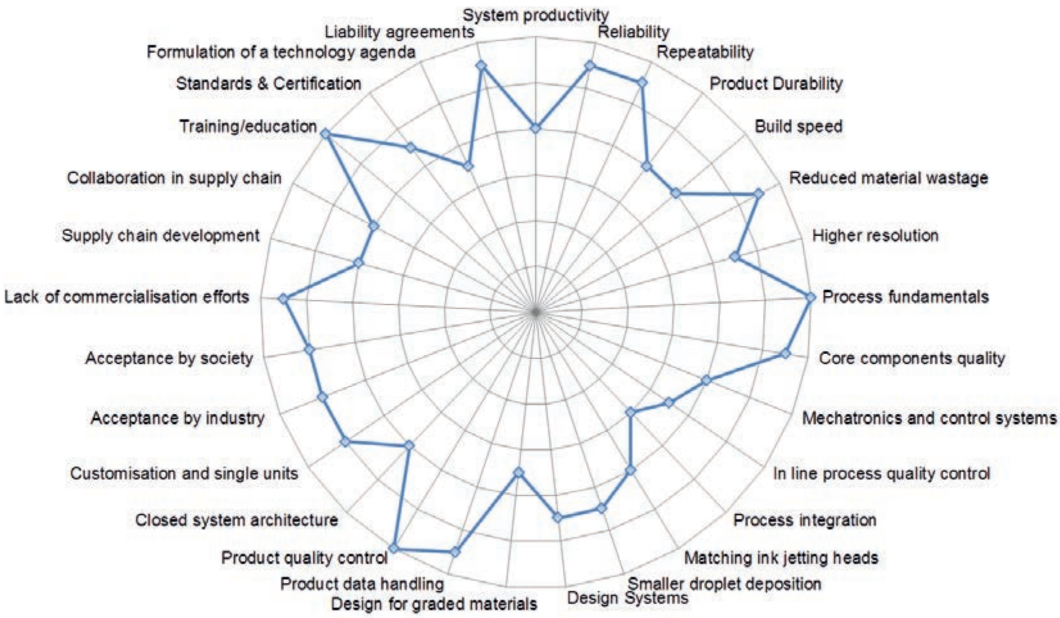


Figure 4.1. *Key technology challenges and urgency. The most urgent challenges are situated on the outer margin of the circle and less urgent are closer to the centre point.*

This roadmap document takes the position that all technology challenges will need to be addressed to release the full benefits inherent to Digital Fabrication technology. The data presented suggest, however, that to address some areas urgent research recommendations should be made. In terms of the broad categories presented above, the following areas are identified as particularly pressing:

Table 4.3. *Process related technology challenges and research recommendations.*

Technology challenge area	Research recommendations to address challenges
Process implementation and economics	• Develop approaches to improve the reliability and repeatability of the Digital Fabrication processes • Research methodologies to reduce the amount of wasted raw materials on some Digital Fabrication processes
Core process technology	• Understand and develop process fundamentals, process physics and chemistry • Implement programme for the improvement of core components of material deposition engines
Design systems	• Research appropriate methodologies for product design data handling, eliminating current limitations holding back the adoption of Digital Fabrication
Supporting processes	• Develop quality control methodologies tailored to the specifics of Digital Fabrication, allowing a build-up of confidence in the user base
Supply chain support	• Address the lack of commercialisation efforts by supporting near to market technology development
Education, legal and political agenda	• Develop a strategy to establish the required training for Digital Fabrication on multiple levels, including engagement in schools, professional training, and tailored courses in higher education • Research requirements for a legal framework improving user confidence in the commercial implementation of the technology.

Raw materials

The various techniques employed in the field of Digital Fabrication are able to process a large variety of materials. The domain experts providing input to Diginova have repeatedly expressed that the evolution of deposition processes and build materials must go hand-in-hand. Another phenomenon observed is that the vast majority of materials used by Digital Fabrication were developed with the objective of being similar to conventional manufacturing materials.

Despite this, polymers processed by Digital Fabrication differ significantly from those used in conventional processes such as injection moulding. Even where the materials are chemically identical, their resulting physical and mechanical properties differ significantly.

Similar to polymers, the additive deposition of ceramics via Digital Fabrication is hampered by limitations with respect to the application of pressure during processing. This means that it is very difficult to achieve pore elimination in the material during single step processing and in most cases it is necessary to apply a secondary process step to reach the desired material properties in the product.

For metals the situation is quite different: in full melting processes only very small amounts of material are melted and solidified at a time, making the solidification process rapid and the crystals formed comparably small. In metallurgy, small crystals are generally associated with high strength and toughness both of which are highly desirable properties. On the other hand, this apparent improvement in material properties may be misleading, since it could tempt the user to accept a material with points where the fusion has failed in the material. These products may exhibit the strength required for an application but have insufficient fatigue resistance.

Moreover, the move to novel product designs and applications created via Digital Fabrication will require going beyond attempts to match the properties of conventional materials. It is believed that the implementation of Digital Fabrication will require entirely novel material properties and processing environments. While this aspect poses a considerable challenge, the Diginova partners stress that this is not a “necessary evil”. Rather, this provides a unique opportunity to make a leap ahead in terms of the functionality of deposited materials. This is due to many traditional (analogue) fabrication technologies demanding that the materials be tuned to the fabrication process, thereby encroaching on functionality.

In the systematic analysis of technology challenges relating to materials, a group of general challenges relating to raw materials were identified. As suggested above, it will be necessary to develop and supply materials with improved properties alongside the introduction of new deposition processes. These must be suitable for the process environments employed by the various Digital Fabrication technologies and at the same time be capable of delivering the functional performance required by the product applications. To reach broad acceptance of Digital Fabrication technology within the user community, it will be necessary to at least match the performance of conventionally processed materials, particularly in single material applications such as the manufacture of functional end-use components.

A further materials-related challenge identified by the Diginova project is the lack of recyclability of the materials used in currently available Digital

Fabrication technologies. There is a requirement to establish recycling processes for the recovery of the potentially valuable raw materials processed during the Digital Fabrication processes after the product's useful life. However, it is also necessary to obtain reusable raw materials from the process-borne waste streams occurring in some Digital Fabrication technology variants such as polymeric laser sintering. Such recycling methodology would further reduce the environmental footprint of some Digital Fabrication processes.

These aspects will be particularly critical for the development of novel types of biomaterials. Such materials are central for Digital Fabrication driven innovation in human and medical applications. These materials, possibly containing living cells, will have extremely stringent process requirements and will lose their functional performance through slight deviations from optimal process parameters. The information gathered over the course of the Diginova project suggests that such applications are currently still in their early stages.

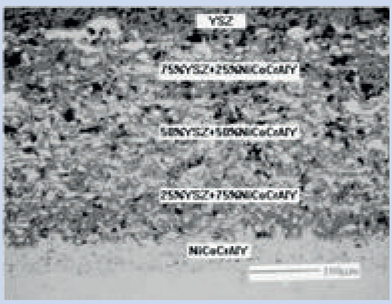
Table 4.4. *Material related technology challenges and research recommendations.*

Technology challenge area	Research recommendations to address challenges
Improvement of material properties	• Research materials matching the performance of conventionally processed polymers, metals and ceramics • Fundamental research into novel materials capable of delivering properties required by novel applications enabled by Digital Fabrication • Research into materials suitable for the Digital Fabrication of multifunctional components • Research methodologies to reduce the amount of wasted raw materials on some Digital Fabrication processes
Material recyclability	• Establish methodologies for the recycling of end-use products manufactured via Digital Fabrication • Develop methods for the recovery of valuable raw materials from the waste streams associated with some Digital Fabrication technologies
Biomaterials	• Research entirely novel bio-functional materials capable of enabling and supporting the use of Digital Fabrication in novel human and diagnostic applications

Further material innovation challenges

CerMets / Graded materials

CerMets are material composites of Ceramics and Metals. Well known for cutting tools the material is ideally designed to have the combined properties of both a ceramic and a metal. High abrasion resistance and hardness of ceramics is combined with toughness derived from the metal matrix. A well known example is the combination of the ceramic Tungsten Carbide (WC) and cobalt as the matrix material. By successive addition of material it could also be possible to create functional graded materials, from a tougher core to a harder and abrasion restistant surface. Research in this field has been ongoing since the mid-1990s. Functional graded Cermet materials have been made by Direct Energy Deposition technology involving a widely used and mature technology also known as laser cladding. However despite significant progress, one of the primary challenges is still to achieve a sufficiently high density of ceramic material in the metal matrix.



Functional graded ZrO_2/NiCoCrAiY thermal barrier coating.

Carbon nanotubes

Single-walled and multiwall carbon nanotubes (CNT) have also demonstrated promise as key components of a biosensor device. Cygnus Inc. has developed a wearable glucose monitor, based on the coupling of reverse iontophoretic collection of glucose and biosensor functions. The Glucowatch biographer is a wearable device which provides up to three glucose readings per hour for up to 12 hours (Tierney 2000).

4.4 A survey of key technology challenges for major opportunities

After looking at the general technology challenges associated with the materials and processes fundamental to Digital Fabrication, it is necessary to gain an understanding of the impact of these technology barriers on individual applications. It is thereby possible to obtain a more detailed picture of the avenues towards the desired economic and social benefits resulting from the diffusion of Digital Fabrication.

By analysing the most promising applications together with their key technology challenges identified in Chapter 3, it is possible to pinpoint individual concrete recommendations. Such application focussed recommendations should be very helpful in the formulation of a future Digital Fabrication research agenda.

Digital graphical printing

The use of Digital Fabrication in graphical print applications places a great emphasis on throughput, product quality, ink compatibility, and deposition accuracy. The following list contains the key technology challenges pertaining to this major opportunity, both in terms of materials as well as processes. In the view of Diginova, it is critical that these challenges are addressed in future research.

Materials

- Development of low cost materials and inks to become more competitive with traditional printing techniques.
- Development of colour pigments or dyes for use in inks that exhibit excellent light fastness.
- Reducing the size of colour pigment particles. Development of colour pigment particles in inks with a size in the range of 10 to 50 nm holds significant promise.
- Development of new inks with excellent performance in eco-aspects.
- Finding alternatives for solvent based inks and UV curable inks (to improve the sustainability and safety of inks). Promising inroads could be made with water based latex inks or water based UV curable inks.

Processes

- Cost: Formation of ultra-thin layers, matching the layer thickness of ink in offset printing (<1 micrometre).

- Speed: Development of inkjet printheads that enable higher speed through higher jetting frequencies and/or by using printhead arrays comprising of a higher number of nozzles. MEMS is a key enabling technology for new generations of printheads.
- Print quality: High speed in-line image quality inspection systems for closed-loop measurement & control.
- Compatibility of inks with very wide range of substrates.
- Stable jetting of ultra-small droplets (1 pl) at very high frequencies.
- Methods for high speed fixation and drying of inks.

Digital textiles

Technology challenges for digital textiles are to an extent similar to the ones that were identified for digital graphical printing, including lowering of ink costs, improvement of colour properties, matching of inks to a wide range of 'receiving media' (in this case textiles), eco-aspects and achievement of highly reliable printing processes combining high speed, quality and reliability. For the realisation of digital textiles with added smart functionally the following challenges should be addressed by a programme of research:

- Viability of embedding suitable electronic components. Collaborative efforts need to be set up with the electronics industry. Develop embedded functional but at the same time flexible and inconspicuous electronic components.
- Continuous development and improvement of functional inks.

For functional textiles in clothing the following challenges have been identified as pertinent:

- As clothing is worn by humans all materials must be completely safe.
- Achieve haptic and visual properties comparable to traditional garments or at least acceptable.
- Garments must be sufficiently UV insensitive and wear resistant.
- An essential criterion for the materials is that they must be cheap enough to enable an attractive value proposition.

For fully 3D printed textiles/garments, the following challenge is seen as critical:

- Processes to completely (3D) print textile garments and the associated required materials need further research and development to ensure that fully printed garments are robust, flexible and capable of producing properties that are comparable to traditional garments.

Functional end-use parts and products

The truly routine application of Digital Fabrication in manufacturing applications is facing major challenges at the current state of technology. These range from process fundamentals, process economics, industrial implementation, consistent quality and control as well as product data handling and specialised training. These aspects are especially relevant as the technology will need to outperform established conventional manufacturing processes in many cases.

The following specific challenges towards the mainstream implementation of Digital Fabrication for the manufacture of functional end-use products should be addressed by a programme of research:

- Increased deposition speed and system productivity.
- Improved core components of Digital Fabrication system, including new approaches to scanning or sources of energy and the transition from point processing to line-processing to plane-processing to volume-processing.
- Reductions in manufacturing cost.
- Improvements in productivity, repeatability and reliability.
- Reduction of process-borne waste streams on some platforms.
- Lacking suitability of existing design tools and product data handling.
- Establishment of a framework of standards and regulation, including product liability.
- Lacking education and training opportunities.
- Development of novel materials, matching or exceeding the properties of materials used in conventional processes.

AM objects with embedded printed intelligence

The multi-layer, multi-material deposition of functionally integrated devices is a challenging opportunity for Digital Fabrication. This is due to the fact that digitally fabricated embedded functional structures are mostly manufactured in hybrid manner, combining various additive and conventional technologies. Modular production configurations featuring elements of Digital Fabrication and conventional processes have been introduced to meet this challenge.

The Diginova project has identified the following list of main challenges towards the realisation of novel products with embedded printed intelligence:

- Combination of multiple materials into a single integrated product.
- Improvement in the reliability of printhead architectures and operation systems.

Figure 4.2. *Monitoring of sports performance. (Source: Shutterstock)*

- Systems for the control and avoidance of deposition errors, including error prevention prediction, detection and correction.
- Requirement for specialised design software for multi-material and integrated 3D products.
- The currently available palette of build materials for functionalised embedded structures is severely lacking. Required material types include: dielectrics, conductors, optical carriers, and structural materials with tuned mechanical, thermal and physical properties.
- Ensuring materials compatibility and matching process and materials requirements, including parameters such as temperature resistance, viscosity, curing/solidification methods and deposition accuracy.

OLED lighting and displays

In order to allow Digital Fabrication of OLED lighting and displays, the most promising process is inkjet printing. For the transparent conductive layer, Digital Fabrication through inkjet printing seems feasible. However, the entire OLED device also requires ceramic and metallic materials to shield the organic material from the environment and to interconnect all the parts of the device. Although it is possible to produce the organic materials by an inkjet printing process, challenges still remain in the field of barrier and electrode fabrication, thereby disabling entirely digitally fabricated OLED devices for the moment.

To realise the Digital Fabrication of OLED lighting and display products, the following technology challenges should be addressed with a programme of research:

- Development of viable solutions for encapsulation of the active organic materials to ensure a long lifetime. This is of particular importance for OLEDs on flexible substrates since for rigid substrates glass encapsulation can be used.
- Reduced production costs.
- Enable flexibility in form/shape.
- OLED devices should be produced in a fast and continuous (in-line) process. Some of the technologies that might be used as an alternative for current vacuum evaporation technology include rotary screen-printing, slot-die coating and inkjet printing.
- Future developments must be focused on production of new formulations/inks to print both organic and encapsulation layers with low production costs and commercial viability. Transparent conductive oxides must also be applied using new deposition technologies to enable reduction of processing costs.

Smart windows

The impact of Digital Fabrication on the set of materials used for smart windows will initially be low, as Digital Fabrication is particularly useful in patterning materials that are continuously being developed for products produced with analogue technology. The main impact is expected to arise when demand for customised patterned windows or mirror elements arises. It is expected that the main driver for these innovations may initially come from the automotive and aerospace industries. Currently, these types of smart windows are either colourless when transparent or dark blue when opaque. This opens new opportunities for research into material that could switch between colourless transparency and a range of opaque colours.

The following key technologies must be resolved to realise the Digital Fabrication of smart window products. These challenges should be addressed in a programme of research

- Develop hybrid manufacturing solutions where Digital Fabrication technologies are used for patterning of materials that are applied with analogue technologies.

- Developing 2D Digital Fabrication systems that will allow for the development of specific designs and specific functionalities integrated into an individual window panel in short production runs.
- Develop cost-effective digital material deposition technologies that can process the required range of materials for smart windows in small production runs.
- Currently, the known types of smart windows are colourless when transparent and switch to dark blue when opaque. Develop materials and solutions to enable switching between transparent and a range of opaque colours.

Printed sensors

The printing methods that are so far most commonly used for printed sensors are screen printing, gravure printing and inkjet printing. Inkjet has received a lot of attention because of its ability to create very small features and deposit multiple materials in a contactless and very flexible way. This makes inkjet the prime technology candidate for Digital Fabrication of sensors.

Technology challenges that need to be addressed by research in this field are:

- Integration of different components and materials with completely different properties in one sensor system, ensuring compatibility.
- Establishing suitable and reliable interfaces to printed electronics circuitry.
- Continuous development and improvement of new functional inks.
- Optimisation of existing digital printing technology towards maximization of output and lowering of costs.
- Value chains for printed sensors need to be established and developed such that materials can be adapted to process technologies and vice-versa. New materials, manufactured by new kinds of processing methods, should at least have similar properties as the materials they are replacing.

Personalised diagnostic and drug delivery

Personalised diagnostics and drug delivery systems are at the forefront of modern medicine. The use of fundamental printing techniques such as ink jetting will allow the creation of systems to diagnose, monitor and prescribe at point of care and, as such, will have a significant positive effect on patient safety, drug efficiency and overall quality of care. The market for personal diagnostics is currently small in relation to the overall pharmaceutical market, and the lack of technological infrastructure is a significant barrier to growth.

Figure 4.3. *Loading amplified DNA samples to agarose gel with multichannel pipette. (Source: Shutterstock)*

Specific challenges that must be addressed by future research include the following:

- In materials processing: very short lead times, automated processing of proteins and resorbable polymers, with controlled doses of specific pharmaceutical products.
- In machine development: diagnostic printer platforms, able to produce diagnostic devices for a range of conditions from the same basic unit.
- In the clinical sciences: identification and development of biomarkers for drug compatibility and disease identification, greater understanding of the relationship between drug dosage and personal genetic predisposition, and the development of biosensor bioreceptors.
- Close collaboration between the clinical sciences, biomaterial scientists and machine developers should be established because this is key to bringing the promise of printable personalised medicine to the clinic and market.

Medical microfactories

The key reason for the adoption of Digital Fabrication within medical microfactories is the ability to make personalised geometries based on digital scanning. In addition, for a range of applications it is attractive to make highly porous structures with a range of micro and macro porosities. The emergence of fully functioning medical microfactories is at least a decade away from widespread adoption, but offers a big opportunity in future.

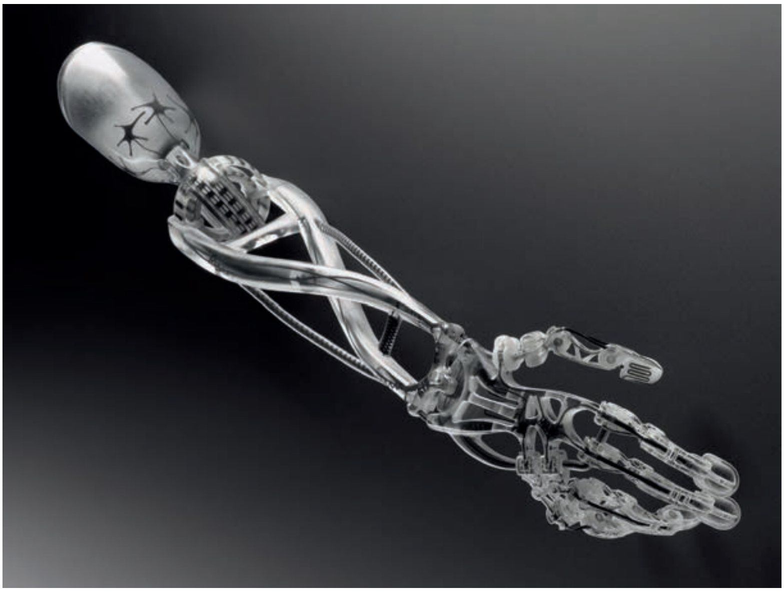


Figure 4.4. *Demonstratio piece for digitally fabricated body parts. (Source: Image courtesy of Jennie Hills/UK Science Museum , arm design by Mary Amos, Matthew Cardell-Williams and Scott Wimhurst at the University of Nottingham)*

Specific technology challenges pertaining to this application are:

- For medical device microfactories very short lead time automated processing of biocompatible polymers and composites, going beyond what is currently possible, is required, with 3D printing at the centre of a single stage additive manufacture or hybrid manufacturing process.
- For tissue engineering microfactories clean co-processing of resorbable biomaterials with cells and proteins, to create complex 3D structures is required. Materials with a combination of excellent mechanical properties and excellent biological properties are a key need.
- Integration: the development of medical microfactories for specific healthcare applications (for example for arthritis, diabetes, cancer, assistive devices for the ageing population, or for orthotics and prosthetics) with the active involvement of healthcare professionals provides the best environment for integrating the technologies into a healthcare setting.

4.5 Complementary challenges

A firm grasp of technological challenges relating to processes and materials is vital for the formulation of a research agenda towards Digital Fabrication. Often, though, significant challenges exist outside of the technical domain. These obstacles may slow or even halt the diffusion of Digital Fabrication technology if left unchecked. This section considers non-application-specific barriers which are not directly related to materials or processes and makes recommendations for research to tackle these.

Artistic and engineering design

Digital Fabrication enables new, unique capabilities that the present conventional manufacturing processes cannot offer. These will enable manufacturing business models focussing on customisation, functional integration and embedding, and make possible dramatic improvements in product performance, manufacturing cost and process energy consumption.

The promising applications discussed in this roadmap demonstrate that the innovative products enabled by Digital Fabrication will be unlike existing products. Besides the manufacturing systems themselves, an evolution of complementary design tools must take place to release the benefits residing within Digital Fabrication. Engineering design and analysis capabilities are central to product development, and with Digital Fabrication's great versatility in respect to product variation, complexity, and decentralised production, product development may in many cases become a widely distributed process involving many different special competences. This requires the development of specialised design software and modelling tools for multi-material and integrated products not only for the purpose of specialists but also for non-experts.

Case Study: Innovation of design methodology in early applications of mass customisation by means of additive manufacturing technology: in-ear hearing aids and clear dental aligners - new CAD systems and models had to be developed to enable efficient shape modelling and part design.

Contemporary design methods and designers have a working method that is based on the traditional paradigm of design for manufacturing (DfM), which amounts to a set of normative rules describing how conventional assembly, machining, injection moulding, etc. should be carried out. As Digital Fabrication technologies are much less restrictive than such conventional techniques, design systems explicitly or implicitly based on these rules are no longer useful. Further layers of complexity are added by process capabilities that are completely novel to manufacturing practice, such as the simultaneous deposition of multiple materials, possibly incorporating graded functionality.

To ensure that the design systems do not impinge on value creation through manufacturing systems, novel design frameworks are essential. Taking a user-centric and perhaps optimistic position, the Diginova consortium suggests using performance and functionality over the entire product life cycle as a guiding principle. Thus, this roadmap is able to state a revised design paradigm of Design for Digital Fabrication (DfDF), which may serve as a starting point for research into novel design systems. The design philosophy complementary to Digital Fabrication can be defined as "the synthesis of shape, size, geometric mesostructure, material composition and microstructure to best utilise manufacturing process capabilities to achieve the desired performance and other lifecycle objectives in a product."

The following concrete challenges have been identified over the course of the Diginova project:

- Implementation design tools suitable for the generation and handling of complex geometries such as latticework and honeycombs, and computational optimisation of topology and geometry.
- Provision of design systems capable of representing multiple-materials for embedded functional structures, moving away from a shape-focused approach to an approach with an emphasis on local properties.
- Linkage between design systems and process constraints of the various Digital Fabrication technology variants, but also with conventional manufacturing technologies for combined digital fabrication/ conventional manufacturing.
- Development of design tools that are sophisticated enough to allow participation of non-specialist users in the design process. This will allow the end-users of the products to join in on the design process and enable business models focused on customisation or co-creation.

Intellectual property issues and legislation

Currently available technology makes it difficult to control and limit the sharing of intellectual property. As is evident in the battles to control the sharing of literature, music and other media, even if the legislation on ownership of intellectual property is unambiguous, it is possible for individuals and organisations to access and share information, making the efficient enforcement of such laws difficult. Therefore, to alleviate the risk faced by profit seeking manufacturers and designers of losing control over their proprietary designs, these concerns must be addressed. An opportune way to do so would be to integrate the management of intellectual property within the design systems. This could be accomplished, for example, by developing a file format that limits the number of times the file could be copied, saved, or executed for fabrication without the loss of critical information, similar to how evaluation copies for some types of software are distributed today.

Balancing the benefits of access through the open-source model with other benefits available through the protection of certain intellectual property should demand the attention of policy makers and legislators, albeit in a manner which does not hinder the emergence or development of Digital Fabrication markets. Taking the business model underpinning the popular iTunes service as an example, it is reasonable to assume that it is possible for products or designs to migrate to an electronic format and to be reproduced as a copy of the original.

A further source of political concern is that Digital Fabrication technology may be used by consumers who may not automatically be held accountable for their products. A particular issue is that illegal or restricted items such as firearms could be manufactured. As stressed by the Diginova partners, however, at the current state of the technology it may be equally easy (if not easier) to manufacture such hazardous items using conventional methods. Therefore, the Diginova partners would argue that the lesson from history is that innovative distributed manufacturing activity does not automatically prompt significant regulatory concern.

In the long term, advanced Digital Fabrication will allow the consumer or non-expert user to produce complex products. It is the consensus among the Diginova partners that policymakers and regulators should maintain a watch on such developments and be ready to act where necessary. Defining who has legal responsibility for the quality and safety of digitally fabricated products will be a key step in developing a mass-market for Digital

Fabrication. If a consumer were to procure a digitally fabricated product and it was later found to be faulty, who would be legally responsible? Such product failure may be due both to the original design and potential an errors made by the operator of Digital Fabrication technology. The problem could also be the result of an issue with raw materials, process parameters or the Digital Fabrication system itself, further complicating matters.

Such uncertainty may deter risk averse end-users from accepting and purchasing products which are digitally fabricated as they will be unsure of what legal recourse they have in the event that a product is faulty. It is difficult to gauge what the appropriate legislative response should be at this stage. Moreover, it is perhaps also too early to define whether the designer, the equipment supplier or the digital fabricator should carry the ultimate responsibility. In Digital Fabrication, many business models and supply chain configurations are still embryonic, so it may be possible to assign responsibility to identified points in the supply chain. In consequence, the businesses upstream and downstream can adjust their activities accordingly. Most importantly, the policymaker should ensure that the safety of products is high enough to inspire consumer confidence.

The following recommendations for research are made by the Diginova consortium:

- Specify research requirements for a legal framework improving user confidence in the commercial implementation of the technology.
- Produce case studies related to current developments on an ongoing basis to monitor and develop suitable ways to control activities proactively, avoiding issues of future legal responsibility.

Sustainability

To evaluate the environmental performance, it will be necessary to take into account the entire life cycle of a product created with the process. There are several aspects throughout the life cycle of digitally fabricated products that will potentially lead to improvements in sustainability.

Due to the additive nature of the technology as well as the reduced waste streams, the adoption of Digital Fabrication technologies may lead to significantly decreased raw material requirements during the process stage. Also, the adoption of Digital Fabrication, which may be independent of established supply chains, may enable manufacturing operations located near the end-users of products. Therefore, it is expected that Digital Fabrication technologies will be able to reduce the environmental impact resulting from logistics and product distribution. The next, and perhaps most important, aspect to consider is the impact occurring during the product's useful life. Generally the case can be made that a component's fitness for purpose is a main determinant of its environmental efficiency. As discussed in the context of novel design systems, Digital Fabrication promises the realisation of new generations of products which are highly fit for purpose, in consequence this should lead to a reduction in the environmental footprint of such products. Whether or not the adoption of Digital Fabrication will have an effect during the disposal stage of the product life cycle is unclear.

In summary, the adoption of Digital Fabrication is believed to motivate manufacturers to create a new generation of environmentally more benign products. To achieve this, the following recommendations for research can be made:

- Explore the various environmental effects of the adoption of Digital Fabrication, benchmarking conventional manufacturing processes against Digital Fabrication technology variants used in similar applications.
- Increase the awareness of Digital Fabrication sustainability by researching and publishing results of comprehensive life-cycle analyses.
- Develop and offer innovative design tools providing the possibility to utilise sustainability as one criterion and guide in product development and design.

Training and Education

It is necessary to develop both basic and comprehensive training and education in the area of Digital Fabrication, to respond to the challenges brought by the new technologies, new material properties and the design of the totally new types of products. These processes are relatively new and consequentially there are a limited number of experts in this area. Without a broader understanding of the processes and facilities that Digital Fabrication offers, the development and uptake of the techniques will be limited and slow.

The recruitment of staff with sufficient technical expertise and knowledge is often a barrier to the growth of businesses as well as research institutions. There is, and will always be, a competition between companies to acquire skilled personnel whose expertise is scarce. Specific training modules need to be developed encompassing design/modelling, processes, materials and applications.

To address this requirement, it is recommended that a strategy on multiple levels should be developed to improve the complementary skills base required. This will further promote the diffusion of Digital Fabrication. Such a strategy should include engagement in schools, professional training and tailored courses in higher education.

4.6 Summary of recommendations for research

This chapter has outlined the journey of the Diginova project, from surveying domain experts on technology challenges and reasons for the adoption of the technology, to assembling recommendations for research aimed as inputs for the formulation of a European agenda towards Digital Fabrication.

By formulating a value chain for a typical commercial user of Digital Fabrication technology, it is possible to observe a pattern of technological convergence. While the current fundamental research activity takes place in relatively distinct fields, movement downstream in the value chain suggests that technological convergence is taking place.

It is the belief of the Diginova partners that this observation requires the formulation of a joined-up research agenda towards Digital Fabrication at the European level.

One cluster of recommendations that has recurred throughout the Diginova project is circled around the joined-up development of materials and process capability. This will be especially relevant where heterogeneous materials are combined into functional structures. Emphasising such an approach in the formulation of a research agenda will have a significant positive effect on the prospects of technology diffusion of innovative Digital Fabrication processes. In Figure 4.5, such materials development activity is shown on the margin of the generic operations chain of the users of Digital Fabrication, indicating that the challenges in this field must be overcome in collaboration with the supporting industries producing the required materials.

A further ‘upstream’ insight resulting from Diginova is that there is currently a significant lack in design systems which are capable of delivering the designs needed for successful implementation. It is important to note that the value proposition of digitally fabricated products is without exception based on advanced product design. This suggests that without complementary innovation in the area of design systems it will be difficult to gain traction for the technology as a whole.

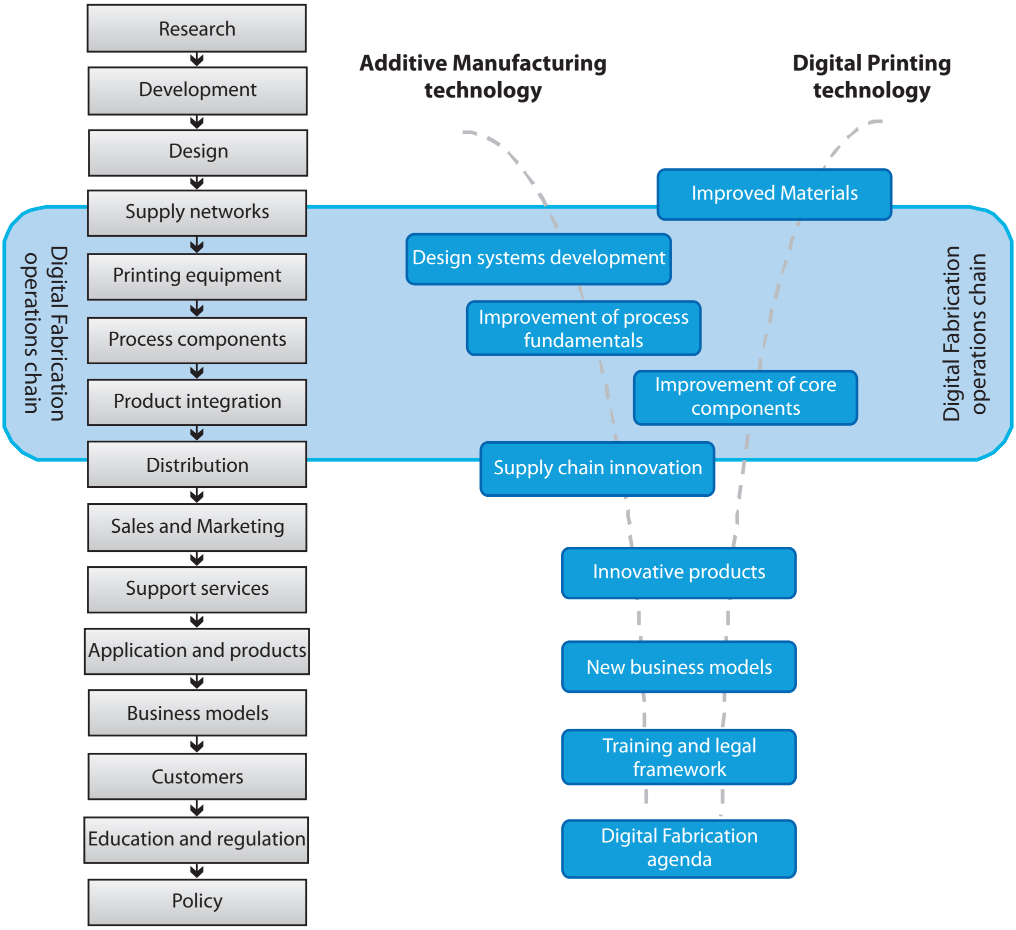


Figure 4.5. *Technological convergence downstream.*

The majority of technology challenges and recommendations for further research identified by Diginova concentrate on the process fundamentals and core components of the Digital Fabrication and additive manufacturing platforms surveyed. It appears that the main generic drawbacks of currently available systems are associated with a lack of process reliability and productivity. It is paramount that these central issues are confronted with an aggressive research agenda if the European economy is to maintain the technological lead it is currently enjoying in these areas.

The overall economic impact of the technology will to a large extent depend on the supply chain configurations and innovative products that will result from future diffusion of Digital Fabrication technology. As a group of technology experts that are not convinced by claims of an impending radical reordering of the current status quo in the manufacturing industry, the Diginova partners agree that it is very likely that a professional manufacturing industry will be responsible for the widespread implementation of Digital Fabrication. It is expected that the economic benefits will be enjoyed by high-value manufacturing businesses within this industry and feed through to consumers in the form of highly innovative, attractive, functional and sustainable products.

These aspects will of course require that the basis for new product development, business models and also consumer confidence is created in the form of a coordinated programme of research towards establishing a supporting legal and educational agenda.

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Appendix 1. Diginova project

Diginova was a 2 year coordination and support action project under FP7, call identifier FP7-NMP-2011-CSA-5, with the following main objectives:

Determine current status, assess and promote the potential of Digital Fabrication. Particular attention was given to the impact of Digital Fabrication on the manudacturing and materials industries. All Diginova findings would serve as input for making a roadmap for Digital Fabrication and this should clarify the potential for growth in a sustainable European manufacturing industry.

The 20 European project partners in the Diginova project consisted of large enterprises, small and medium sized companies, universities and knowledge institutes. The parties that were active in Diginova are listed below.

Participant no.	Participant legal name	Country	Organization type
1 (Coordinator)	Océ Technologies	NL	Multi-national industry
2	3D-Micromac AG	D	SME
3	University of Cambridge	UK	University
4	Coatema Coating Machinery GmbH	D	SME
5	OLED Technologies BV	NL	Industry
6	Key Management Consult BV	NL	Industry
7	Centre for Nanotechnology and Smart Materials	P	SME
8	University of Nottingham	UK	University
9	University of Manchester	UK	University
10	Newcastle University	UK	University
11	Sintef	NO	Research centre
12	Teesside University	UK	University
13	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO	NL	Research centre
14	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.	D	Research centre
15	Centre for Process Innovation Limited	UK	SME
16	VTT Technical Research Centre of Finland	FI	Research centre
17	XaarJet Limited	UK	Multi-national industry
18	Xennia Technology Limited	UK	Multi-national industry
19	Nanogap Sub-nm- SA Powder	ES	SME
20	InnovationLab GmbH	D	SME

Third Party under Special Clause 10

N/A	Xaar Technology Limited *Linked to partner 17: XaarJet Limited*	*UK*	*Multi-national industry*

Appendix 2. Roadmap creation process

From the point of view of drafting the Diginova roadmap, the most important deliverables of the Diginova project are illustrated in Figure A1 below. In the final roadmap, all deliverables and findings of the Diginova project have been used. During the work on the roadmap, we had several video conference meetings of the project group as well as one meeting in Amsterdam, and all WP5 participants took a part in the writing process. The most promising opportunities came from a workshop organised by the representatives of WP2 and WP4. After this work, a draft version of the roadmap was sent to stakeholders for comments.

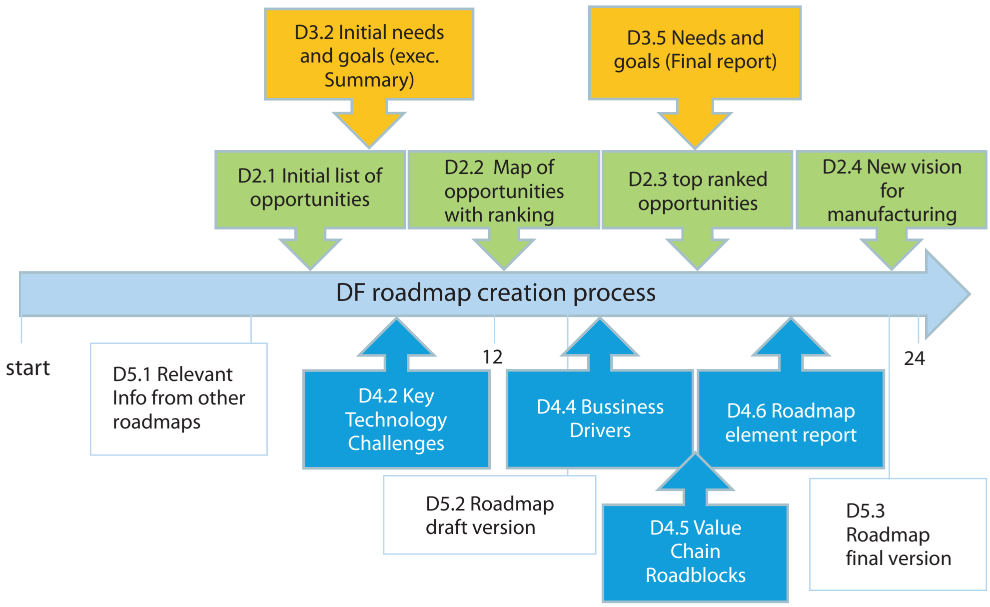

Figure A1. *The timing of the deliverables of the Diginova project and their relation to the Diginova roadmapping activity.*

Figure A2 shows how the lists of opportunities for Digital Fabrication were developed. At the first stage, a 'long list' with 78 opportunities was defined and this was narrowed down to a short list of 20 most promising opportunities. Each of the 20 identified opportunities was further ranked against the following set of criteria:

Criteria for ranking:

1. New materials: how significant is the potential for development or use of new materials?
2. Fit with Digital Fabrication paradigm: to what extent will an opportunity benefit from advantages resulting from digital fabrication?
3. Sustainability: what is the economic life expectancy of a specific opportunity?
4. Market potential: What is the estimated size of future revenues resulting from the pursuit of a specific opportunity? Contribution to material well being in Europe?
5. Developmental compatibility: to what extent is an opportunity in line with the 6 key assumptions for development of EU manufacturing economy (see Deliverable 2.1 for a description of these 6 assumptions)?
6. Feasibility?
7. Viability?
8. Contribution to human betterment?

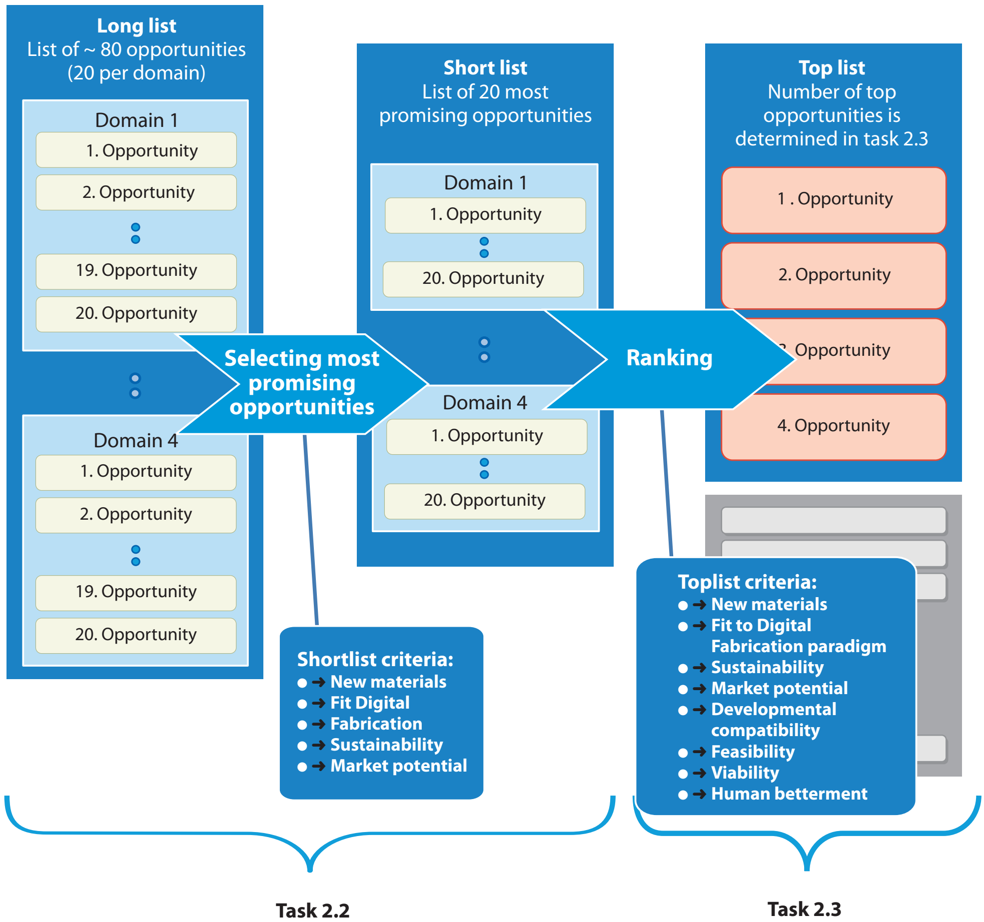

Figure A2. *Graphical representation of the process that has been followed in the Diginova project for identification of most promising opportunities for Digital Fabrication.*

Stakeholder Engagement Activities

Figure A3 positions the stakeholder engagement activities as part of a broader approach that has been followed within the Diginova project to identify the most promising (market) opportunities where a shift to Digital Fabrication will add great value. In the middle, the process and outcome of facilitated workshops (at conferences and seminars) and round table discussions with experts of the project consortium are illustrated. On the top and bottom, two stakeholder engagement steps where the outcome of the expert workshops are presented to relevant stakeholders of Digital Fabrication to check the plausibility of the outcomes.

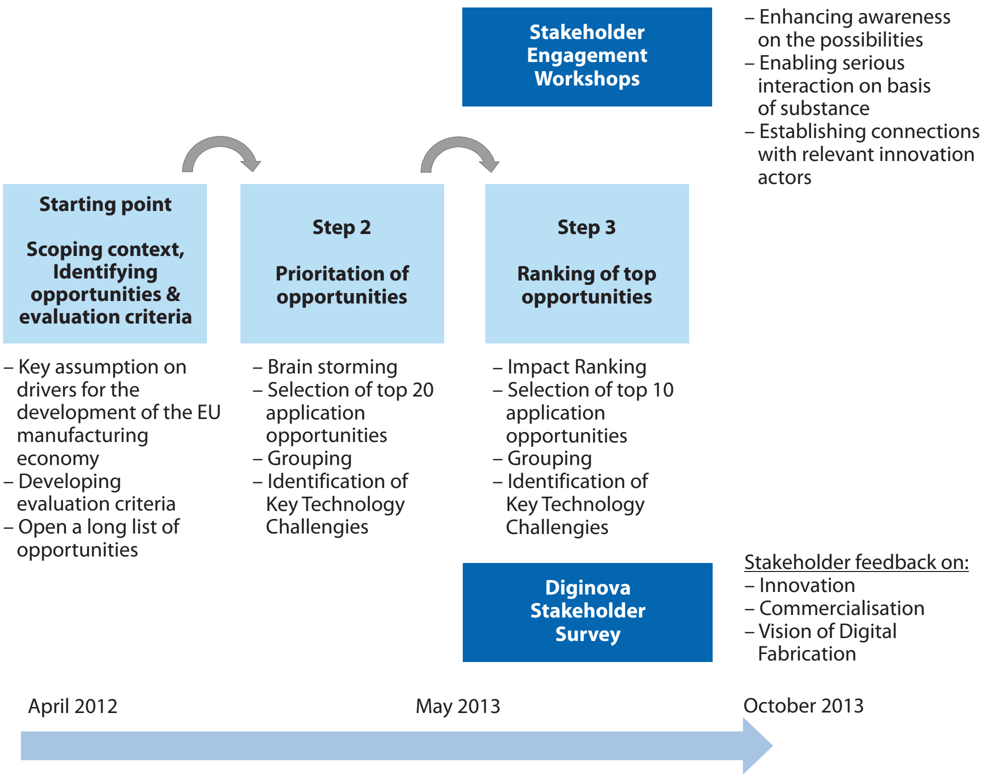

Figure A3. *Positioning stakeholder engagement activities in relation to other Diginova actions.*

Appendix 3. Summary of Key technology challenges (KTC) of Digital Fabrication

Application Domain	Digital Printing	Additive Manufacturing	Printed Electronics	Human Applications
Key Technology Challenges	Digitisation of Traditional Printing Industry Decoration of Products & Surfaces Packaging Textile Printing Display Graphics	Durable goods Integrated Electronics Sensing Power Generation & Transmission Energy Storage	OLED Lighting & Displays Smart Windows Printed Sensors Thin Heating Elements Smart Textiles	Medical Micro factories Personalized Diagnostics & Drug Delivery Tissue Engineering Scaffolds Treatment Planning Tools (Organ-on-a-Chip) Digitally fabricated garments
Cost: Productivity	2	1	2	3
Cost: Reliability	1	1	1	2
Cost: Repeatability	1	1	1	2
Cost: Durability	2	2	2	2
Cost: Speed	1	2	2	3
Cost: Reduced scrap	1	1	1	2
High resolution	2	1	1	3
Better materials / chemistry	2	2	1	1
Biomaterials	3	3	3	1
Process fundamentals	1	1	1	1
Core components (laser, printhead)	1	1	1	2
Matching printheads	1	2	2	3
Smaller droplets	2	2	1	2
Design Systems	1	2	1	3
Design for FGM graded structures	3	1	3	2
System platforms (mechatronics& control)	1	2	2	3
In line process quality control	1	3	2	3
Process integration	2	3	2	3
Product quality control	1	1	1	1
Product data handling	1	1	2	1
Closed Systems /lock in	2	2	2	2
Flexibility (batch of 1)	2	1	2	1
Acceptance by industry	2	1	1	2
Acceptance by society	3	2	1	2
Effort for Industrial implementation	1	1	1	2
Supply chain development	2	2	2	2
Collaboration in supply chain	2	2	2	2
Training/education	1	1	1	1
Standards & Certification	2	1	1	3
Environment: recycling	2	2	1	2
Liability agreements	1	2	1	1
Digital Agenda Development	2	3	2	2

Legenda:

TRUE with the following priority:
1: Time priority 2015 – 2020 (short-term)
2: Time priority 2020 – 2025 (mid-term)
3: Time priority >2025 (long-term)

As the world is becoming ever more digital, decentralized and connected, the transition from analogue to digital technologies has a profound impact on many industries, markets, consumers and value chains. Well known and clear examples of this transition can be found in the music industry, in photography, printing and communication.

Similar to many other industries, also the manufacturing industry will make the transition to the digital realm, and when it does, manufacturing also will change beyond recognition. Established (analog) fabrication methods and technologies will be replaced by Digital Fabrication technologies and solutions. This is expected to lead to a revolution in the manufacturing industry that needs to be anticipated, understood and supported.

'We've had an industrial revolution. We've had a digital revolution. Now is the time for a digital industrial revolution.'

SEVENTH FRAMEWORK PROGRAMME

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