Roadmap Printing

"From the World of Print to the Printed World"

September, 2020

1. Societal challenges and economic relevance

Size of the traditional printing industry and its conversion to digital

The global size of the graphical printing industry is 700 Billion € (end user value). Within this industry, the market size for equipment and materials manufacturers is about 350 B€.

The transition from traditional analog printing techniques (such as offset and screen printing) to digital printing offers huge growth opportunities. The digital production printing market grows at a compound annual growth rate (CAGR) of 8% until 2025. In 2020, around 18% of the printing market value was achieved using digital printing, representing a value of 126 B€. Within the digital printing market, inkjet is the fastest growing printing technology. The market value of the inkjet printing industry was 34 B€ in 2019 with a predicted growth to 47 B€ in 2025.

New applications and the use of printing for manufacturing

Next to growth in digital printing for graphical applications, industrial printing has emerged as a new and fast growing industry with a wide range of new applications and markets. Industrial printing leverages on the advances in digital printing technology and targets printing on virtually any substrate. Within industrial printing the application range of printing technologies is extended far beyond graphical applications, by using printing as a game-changing manufacturing technology for functional 2D and 3D structures. Examples of established successful applications in industrial printing can be found in domains such as textiles, packaging, ceramic tiles, 3D printing of metals, polymers and ceramics, food, pharmaceuticals, display graphics, printing of OLED display materials and coatings on displays. Industrial printing is forecasted to grow to a 120 B€ industry by 2025. Although a large part of this industry will still be based on analog printing technology (such as screen printing and flexography), also in industrial printing new digital technologies are growing fast.

3D Printing / Additive Manufacturing

Over the past twenty years, 3D printing technology has been evolving into a true (additive) manufacturing technology for production of 3D products. Products are built up in a layer-like fashion using an expanding range of technologies and materials. The technology has initially been successfully applied in prototyping of all sorts of products. The largest growth and potential is however found in the production of functional parts and products.

The range of applications and markets is very broad including automotive, aerospace, biomedical, healthcare, food, transport, consumer goods, energy and electronics.

3D printing can potentially disrupt the ways industries manufacture and supply products, with a potential significant impact on sustainable manufacturing. It enables local manufacturing which reduces transportation and storage needs. Smaller series of products can be manufactured cost effectively as with this digital manufacturing technology no costs are needed to switch to new designs and products. 3D printing allows for on-demand production of exactly the required amount of products, eliminating over-production and stocks. On top of that, products can be designed using sophisticated software tools to meet requirements at minimum weight and thus saving material and energy.

The global size of the 3D printing industry has reached 11,9 B € in 2019 and has consistently shown an annual growth of 20-25% over the past ten years. It is forecasted to reach 29 B € in 2023.

Economic perspective and position of Dutch ecosystem

All markets for *digital printing* will grow rapidly in the coming decade, as indicated for some segments in the table below. Market size is either indicated in value of equipment (printers) and materials, or end-user value of printed products.
The term commercial print is meant to designate graphical printing, also often called 'graphic arts', with applications such as books, magazines, marketing material, manuals, posters, banners and displays. Industrial print is the use of printing as part of an industrial production process, such as the use in textile printing, printing on ceramic tiles, packaging or decoration.
Given the knowledge and experience available within the Dutch High Tech Systems and Materials industry, and the excellent international position of the Dutch academia in related relevant scientific areas, we have good opportunities to capture a significant part of the forecasted growth.

Industry size (B €)		World 2020	World 2025	NL 2020	NL 2025
Commercial print (digital print, end user value printed products)	graphics	112	153	3	4
Industrial Print (digital print, excl. 3D printing, end user value printed products)	graphics	12	18	0,12	0,2
3D printing / AM (OEM equipment & materials + services value)	functional	13	37	0,2	0,4
Printed Electronics (analog & digital print, end user value)	functional	7,8	17,3	0,07	0,15
Total B €		**144,8**	**225,3**	**3,4**	**4,8**

Total Dutch R&D expenditure (M€)		2020	2025
Dutch R&D expenditure		200	310

The expected growth in the Netherlands originates from our strong position in terms of required knowledge and expertise in fields as fluid dynamics, mechatronics, embedded systems, composites, polymer materials, advanced materials and nanotechnology for jetting and 3D printing of functional materials as well as 3D products. These areas of expertise are strongly developed within the Dutch High Tech Systems industry. For the required technologies and knowledge for future generations of inkjet printheads and 3D printing technology we can build on our strong position in the field of multifunctional micro and nano-systems, micro-fluidics and materials and composites.

Societal challenges addressed in this roadmap

Manufacturing has been highlighted by the European Union as one of the key enablers to tackle major European challenges and their subsequent targets, in particular for growth and creating high quality value-added jobs. The Horizon 2020 Framework Programme and its successor program Horizon Europe support and promote research and innovation in enabling technologies. One of the priority actions covers advanced manufacturing and processes.

The European Technology Platform MANUFUTURE launched the European 'Factories of the Future Research Association' (EFFRA) in 2009 with the objective to encourage (pre-competitive) research on production technologies within the European Research Area. This was to be achieved through engagement with the 'Factories of the Future' (FoF) initiative, which is a Public Private Partnership (PPP) with the European Union (Bessey, 15 May 2012). Vision documents and roadmaps have been established to support the goal of competitive, sustainable and resilient European manufacturing. The role of 3D printing (Additive Manufacturing) is highlighted as a key advanced manufacturing process by which a broad range of benefits can be realised, including its potential for supporting environmental sustainability in the manufacturing industry.

Impact of printing as an enabler for Digital Fabrication

Advanced digital printing technology, as a truly digital manufacturing technology, is one of the key enabling technologies that is about to revolutionize the manufacturing industry. It offers a game changing alternative to the traditional manufacturing paradigm. After the industrial revolution and the digital revolution, now is the time to prepare for a "digital industrial revolution" enabled by a new manufacturing paradigm called "Digital Fabrication". Digital fabrication entails on-demand manufacturing, with zero-waste, no need for stocks, high flexibility, fast-turnaround, small and custom-size series, personalization, mass customization and very short (localized) distribution and supply chains. In this new manufacturing paradigm, *designs* rather than *products* will be distributed around the globe as digital files over the internet. These designs will then be locally manufactured into physical products. The implications of this will be profound, with a clear positive contribution to major societal issues such as scarce resources and minimizing environmental impact (low/zero waste, lower energy and material use, shorter logistic chains). Innovation within the European high tech manufacturing industry has been a huge driving force for economic growth in the past. Within Europe, the Dutch high tech systems industry has a strong proven track record in high-tech manufacturing combined with the Dutch chemical, material and composites industries, which is among the largest and most advanced in Europe. Now is the time to anticipate and team-up for the next wave of innovation that will again fuel future growth and by doing so, support Europe in an effort to reclaim part of its heritage in manufacturing.

Printing technology is a key enabling technology for Digital Fabrication, as described above. The European strategy underlines the role of technology as the ultimate solutions-provider for tackling the challenge of increasing Europe's economic growth and job creation. 3D printing is enabling manufacturing to take place closer to the markets being served, also securing supply chains on a more local level. Key enabling technologies are identified and expected to help turn innovative ideas into new products and services that create growth, high-skilled value-added jobs, and help address European and global societal challenges. Advanced and flexible manufacturing processes, enabled by advanced printing technologies, are a key factor behind many high-value products or services, including (but not limited to) for products that rely on photonics, advanced materials, micro/nano-electronics and biotechnology, all referred to, along with advanced manufacturing systems, as key enabling technologies (KETs).

In addition to the above, digital printing as a truly Digital Fabrication technology also contributes to sustainability by minimization of the use of scarce resources. It enables on-demand, decentralized manufacturing, with no need for stocks and (intercontinental) transport, thereby minimizing its carbon footprint. Furthermore, Digital Fabrication, and in particular 3D printing, contributes to a level playing field in which many SMEs and individuals across Europe can and will contribute in the design and creation of products which are manufactured locally. This offers opportunities for sustainable and inclusive growth in Europe, stimulated by creativity and innovation. This can be complemented and enabled by establishment of local digital manufacturing infrastructures where Europe can increase its global impact through innovative designs and high tech equipment and materials development.

Connection with Key Enabling Technologies
This roadmap demonstrates a clear connection with the following key enabling technologies:

- Engineering and Fabrication Technologies
- Digital Technologies
- Advanced Materials Technologies
- Nanotechnologies (micro- & nanofluidics)
- Life Science Technologies

Societal challenges and KIA's addressed in this roadmap

	Health and healthcare	***Security***	***Agriculture, water and food***	***Energy transition and sustainability***
match	++	+/-	+	++
examples	*Implants (Xilloc), tissue(UM), organs, hearing aids (Embedded Acoustics Elacin), dentures (NextDent), diagnostics, personalized drugs, organ-on-chip, food (TNO), ophthalmic lenses (Luxexcel)*	*Authentication (Joh. Enschedé), anti-theft, track & trace, food-safety via smart packaging w/ sensing, monitoring/logging, IoT (TNO)*	*Personalised healthy food, resource scarcity and alternative proteins (DSM)*	*Digital 'on demand' printing (Canon Production Printing) and production, low/zero waste, no global transport, design global & manufacturing local, local and digital supply chains, lowering carbon footprint, less landfill, light weight 3D printing of advanced designs and minimal material use, use of renewable and circular materials to create local circular solutions*

2. Applications and technologies

For industrial printing, including 3D printing, it is very beneficial to leverage on technology developed for graphical printing, such as inkjet or other material deposition technologies and for software design, control and monitoring solutions. In general, specific characteristics and advantages of printing technology in manufacturing are:

- Highly efficient use of (scarce) material, because printing is an additive process and adapting to market demand preventing overproduction;
- Contactless material deposition on substrates & no masks required in case of digital inkjet technology;
- Very accurate deposition of materials on (sub-)micron scale (in quantity as well as in position);
- Possibility to create complex 2D patterns, 3D structures or objects consisting of a range of (mixed) materials;

- Flexible and high speed production process capability;
- High design freedom in 3D printing which enables unique complex products, embedding of functionalities and less assembly steps;
- Enabling on demand production allowing for local manufacturing motivating new and innovative logistic business models.

With its roots in graphical printing, printing technologies such as inkjet have rapidly progressed over the past decades. However, major further technology and material advancements are required to match the far more stringent requirements for applications in industrial printing.

2.1 Application domains

Graphics industry

The shift from analogue printing (offset, flexo, gravure, screen printing) for graphics applications (advertisements, books, brochures, packaging, labels) towards digital printing (print on demand, just in time) will fuel the transition towards inkjet as the main digital printing technology for these markets. Existing and new Dutch companies will benefit from this transition by tapping into the vast knowledge and experience base present within the Dutch printing ecosystem. For graphical applications, increasing speed and reliability at a cost effective level are main technology challenges, next to adaptation of the technology to meet the high demands in print quality and wide range of paper types in the graphic arts industry where inkjet technology is prone to one day replace offset printing.

Textiles

Digital inkjet printing on textiles replaces part of the analog printing done traditionally with rotary screen printing. Speed and reliability and the range of printable dyes need to be improved for further market penetration. A further step includes adding high tech functionality to textiles. Wearable electronic functions are expected to reach the market in the next decade, such as solar powered personal electronics, wearable displays or lighting for emergency purposes, electronics for safety and integrated health monitoring devices. Applications will also emerge from adding tailored and controlled substances to fabrics for example as insect repellants, anti-bacterial agents or to provide active self-cleaning properties. Broadening the field of use of printheads and advanced materials is a key challenge for this field.

Decoration and printing of security features

Decorative layers or patterns can be applied using inkjet or other printing technologies, not only on 2D but also on 3D surfaces. Inkjet advantages in this field will allow mass customized decoration solutions for various 2D and 3D products and packaging: mobile phones, objects for sports, cars and trucks, home decoration etc. Printing of security features on documents, packaging or other products for anti-counterfeiting is also an emerging and fast growing market opportunity.

Industrial 3D printing and additive manufacturing

Speed to market, customization, responsiveness and new services are four strategic value drivers in product manufacturing in the future. Therefore, additive manufacturing has been identified as key potential technology in markets like automotive, aerospace, biomedical, transport, energy and the process industry. 3D products can be produced using a range of additive manufacturing technologies starting from powders (polymers, metals), liquids (polymers) or pellets and filaments (polymers). This will open up new markets with new products that could not be made before and lead to new supply chains and business models for existing products. Unique products can be made of complex structures which prevent assembly steps, without using production tooling like moulds. 3D printing encompasses the move to using fully functional materials so that 3D printed objects will have a full set of end requirements. For example, 3D printing with discontinuous and continuous fibers enables making composites with shape freedom that was not possible before. Also, additional functionalities like sensors can be included in the manufacturing step.
Additive manufacturing of end-use parts is the fastest growing sector within the total 11,9 billion US $ (Wohlers report 2020) 3D printing sector. Major challenges comprise of extending the range of materials (polymers especially), production speed, quality and reproducibility, precision, certification and qualification, and cost.

Printed electronics

Printed electronics can create huge opportunities for existing and new industries. Examples are printing of etch resist patterns for PCBs (Printed Circuit Boards) or antennas, printing of conductive 'inks' on flexible foils or paper, OLED displays, large area OLED lighting panels and RFID-tags. Printing conductive tracks under atmospheric conditions as well as masks or other functional material on solar cells also offers a huge market potential. A different approach to creating conductive patterns is to print metal tracks or circuits directly from the pure metal vapor or liquid phase. An interesting application for the semiconductor back-end industry is filling of holes in silicon wafers with conductive material to accomplish TSVs (Through Silicon Vias) for interconnections in stacks of chips or for supporting and cooling of high brightness LEDs and chips. Another opportunity is jetting of fine structures of conductive or other functional material on plastic foils that have a patterned wetting/non-wetting surface resulting from a patterned pre-treatment with an atmospheric (micro) plasma. Printing technologies are also used in manufacturing of batteries, and for large area electronics as encountered in organic LED, photovoltaics and new generations of (thin, flexible) displays. The difference between PCB's and large area electronics might be the ultimate drive to high-speed roll-to-roll printing.

Food and nutrition

Consumers are more conscious about their food choices and there is a demand for personalized nutrition. Through smart AI and health sensors it becomes easier to make personalised dietary recommendations, however it is still difficult to produce these products efficiently and cost-effectively. With 3D food printing the combination of 3D printing technology with personalized dietary advice to create healthier food products for individual consumers is possible. 3D food printing has been developing our the last years and very first commercial applications are launched. In order to achieve the nutritious value in combination with texture for the right taste and bite experience developments on equipment process and food formulations are needed. In this application domain connections between HTSM and Agri-food programs have emerged.

Biomedical & healthcare

Implants and complex 3D biomaterial structures, like heart valves, organs or bones for human implants that are printed exactly customized to a patients' need can be envisaged for the future and first applications have been demonstrated. Issues like the influence of shear stress on biological material when it is ejected from an inkjet printhead will become important. 3D printable tissue and scaffold materials are being developed that are resorbable in the body. Dental applications that involve printing layers or components, even inside the mouth, are advancing and first applications are commercialized.

Examples of other application areas are edible or implantable disposable micro drug dosing devices, micro dosing equipment for fast and large scale titrations (advanced drug effectiveness screening) and very thin and localized coatings on bio-implants. Inkjet research is also ongoing for positioning of magnetic or other functional 'marker' particles, cells or drugs for use with MRI imaging techniques or controlled drug deployment.

Printing can also be used to produce sensors for diagnostic purposes (lab-on-chip) or even integrated in 'medical microfactories'. Medical microfactories are generally understood as a standalone, dedicated manufacturing solution for a specific medical problem or condition. For example an in-theatre human skin printing station 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.

Pharma and healthcare

In order to improve the efficiency of healthcare the effectivity of medication is an important topic. With all available technologies as AI and sensor technology the possibility for tailoring the treatment to the need of the individual patient is becoming a possibility. But in order to translate this personalized therapy advice into medication also the need arises for a flexible production technology. With 3D printing it will become possible to create unique medication, personalized on demand. A second opportunity for 3D printing is in the development of medication. The cost of medication is strongly related to the years required for the development and approval of medication. The different development stages include a variety of series sizes required and a flexible production technology can aid in the short lead times for small series production.

2.2 Common scientific & technological challenges

Common scientific and technological challenges have been identified and subsequently categorized in the following three fields.

Printing process fundamentals

Complex interactions between core components of a printing system have to be investigated and thoroughly understood.

Taking inkjet printing as an example, physical studies are needed towards smaller droplets, higher jetting frequency, higher accuracy, tuning of droplet size and shape and drying/fixation/curing on the substrate. In addition, the effects of viscosity, surface tension and many other fluid parameters on the printing process are still poorly understood. All these areas require in depth fundamental and applied research on micro fluidics, ink-chamber and channel acoustics, thin film piezo actuators and sensors, wetting & non-wetting behavior of fluids on surfaces, surface modification and characterization, material and microstructure related topics, drop positioning and drop formation, surfactant chemistry and its impact on liquids during jetting, feedback principles and the like. In general, there are still many aspects of the inkjet printing process of both low as well as highly viscous liquids or complex liquids such as suspensions which are not sufficiently understood. The same holds for inkjet printing processes in which phase transitions and heat transfer play a role. Research should also include the development of a much larger variation in stable surface modifications/coatings of nozzles given the rapidly increasing variation of materials that need to be printed, and the study and reduction of fouling or blocking by such inks of the increasingly smaller nozzles.

3D printing is a relatively new technology to the industry being developed in a consumer environment originally and although its potential is disruptive, it is facing a number of challenges like availability of suitable (polymer and metal) materials, design for 3D printing, speed of production, quality and reproducibility, establishing of standards, qualification and certification processes. Also the handling and protection of confidential digital designs creates hurdles and new opportunities in the market. Technology challenges thus range from material developments, printing process improvements and integrated software solutions to allow for digital design, development and manufacturing.

Core components: printers, printheads and materials

New generations of print technology need to be developed, enabling smaller feature sizes (from 10 micrometer down to 1 micrometer range or even smaller), higher throughput (e.g. jet frequencies from kHz to MHz range), wider range of materials to be processed (ranges of viscosities, polymers, suspensions, metals), higher integration densities (more nozzles per mm^2), added sensors, intelligence and control principles to increase reliability, accuracy and lifetime. For inkjet a transition towards fluidic MEMS technology is expected to open up an increasingly wider range of functionalities and applications combined with lower cost for next generation MEMS based printheads. There is a strong link to the theme nanotechnology.

In cases where the functional properties of the processed materials after deposition and drying/fixation are important, e.g. in printed electronics, their dependence on the chemistry of the materials and the processing conditions are often poorly understood.

Understanding and controlling the behavior of materials on substrates is of great importance. Many of the relevant substrates have a complex microstructure (e.g. a fibrous network) at scales comparable to that of the printed material and therefore cannot be regarded as simple continua. The interaction of the 'ink' with this microstructure is poorly understood. It may however result in significant dimensional changes which compromise the accuracy of the 'print' and the shape of the product. Similarly, fluctuations in ambient conditions (in particular relative humidity) have a significant impact on the substrates' properties.

In 3D printing materials have been used that were available in the market but where not developed for the 3D printing process. Especially in polymeric materials this has had very limited success as polymer grades have been optimized for many decades for incumbent manufacturing technologies like injection molding and blow molding. 3D printing processes, be it extrusion, sintering or UV curing type, work differently requiring materials to behave differently leading ultimately to the required final product properties. Developments are ongoing on an increasing scale both by international material manufacturers and printer manufacturers. However, to enable a large adoption in industry product quality, reproducibility, speed of production need to improve further.

System platforms: advanced mechatronics, embedded control and workflow solutions

New mechatronic machine platforms and modules are needed which are faster, more accurate, more reliable, use less energy to operate, have wireless (remote) control, use less and environmentally friendly material and are easier to configure, install, operate and maintain. System design will need to focus on smart system integration of printheads and scalable printhead arrays, hybrid approaches using additive as well as subtractive material processing, substrate handling and flexible engine architectures. Regarding reduction of energy-use, smart machine platforms should support or enable increasingly more ‘green machines’.

New smart platforms and modules are needed that offer added intelligence, flexibility, real time feedback control loops based on vision and acoustic sensing principles, image or deposition quality optimization, lower energy consumption, automated operation, remote monitoring, smart self-diagnostics, self-learning and use of behavioral modeling to reduce downtime and increase predictability. For instance the currently used batch-wise 3D printers will need to evolve into more advanced manufacturing machines where parallel production of parts in a continuous manner is performed. Hybrid solutions should be considered also, consisting of synergetic and smart combinations of additive as well as subtractive material deposition, including placing of ready components on printed functional devices or structures.

New workflow solutions are required to attract production volume to the print machines or make optimal use of the technological new options. Additionally, costs need to be closely monitored and production needs to be cost-efficient, both in terms of labor and waste, especially for small production runs. Digital print and manufacture can add value to digital information flows (e-publishing, e-marketing, on-demand fulfillment) through advanced workflow solutions. These solutions include processes for post-print finishing.

Digital print and manufacture opens the way to make every product different by adding or making use of custom or personalized data. It is important that the right information is combined to communicate the right message. This requires development of new concepts to handle ‘big data’ and incorporate AI solutions.

In 3D printing similar developments are needed. In addition, there is still a lot to be learned about the fundamentals of the technology in order to allow further innovations, optimizations and perfections. Starting with the print processes itself, a better understanding will help to predict resulting final product properties by simulating materials and processes. These models can then be used to optimize designs to the fullest, leading for example to minimal material use to meet required mechanical performance.

2.3 Key Technology Challenges and barriers: recommendations for research towards 2025

Application and technology questions to be resolved for this roadmap until 2025

In order to further develop printing technologies and contribute to the broader vision and promise of Digital Fabrication, a number of challenges need to be overcome. 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, implying that for each challenge mentioned below, specific recommendations for research have been formulated.
In general, for many of the highlighted challenges, it will become increasingly important to use modeling and simulation-based research, design and engineering methods.

Technology challenge area	Research recommendations to address challenges
Process implementation and economics	• Develop approaches and technology advances to improve the reliability and repeatability of printing processes • Research methodologies to improve 3D printing processes to result in printed product qualities that meet market requirements (e.g. mechanical performance, accuracies)
Core process technology	• Research on materials, process fundamentals, process physics and the interaction between these • Implement programme for the improvement of core components of material extrusion / deposition / sintering / melting / curing techniques and systems
Design systems	• Research to develop predictive software tools to aid design for 3D printing including material, process and printer specific predictions • Research appropriate methodologies for (hybrid) product design data handling, eliminating current limitations holding back the adoption of 3D printing and printed electronics
Supporting processes	• Develop standards and quality control methodologies tailored to the specifics of 3D printing and other functional printing methods, allowing a build-up of confidence in the user base
Supply chain support	• Speeding up 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
Improvement and extension of material portfolio	• Research on polymer, metal and ceramic materials in order to meet the performance requirements of products manufactured by incumbent production processes • Fundamental research into novel materials capable of delivering properties required by novel applications • Research into materials suitable for printing of

	multifunctional components • Research into materials for 3D printing to allow for extending the application portfolio • Research into circular and more sustainable materials for 3D printing, re-use of recycled materials, renewable materials and fibers; develop materials for 3D printing that are easy to recycle • Research into materials for fiber reinforced plastic composites for lightweight and mechanical performance for application in mobility markets like aerospace
Material recyclability	• Establish methodologies for the recycling of end-use products • Develop methods for the recovery of valuable raw materials from the waste streams associated with some 2D and 3D printing technologies
Biomaterials	• Research entirely novel bio-functional materials capable of supporting the use of printing in novel human and diagnostic applications

3. Priorities and implementation

In terms of public private partnerships, inkjet printing, 3D printing and other printing techniques provide a challenging and promising innovation platform where fundamental research and product development really come together on the many challenging topics and promising applications mentioned in this roadmap.

The pursuit of opportunities in industrial printing is a global race and collaboration and focus is of key importance in addressing the major common challenges. At the highest level, these challenges have been grouped into three main domains.

Printing technologies, printheads & materials

For many new applications, and especially for using inkjet or inkjet like systems as a digital manufacturing technology, advancements are needed to enable printing of a wide range of functional materials (functional 'inks'). Current state of the art inkjet technology has limitations in jetting inks (functional fluids) in terms of viscosity range, chemical properties (like acidity) and maximum allowable dispersed solid particle sizes and non-Newtonian behavior. It is clear that the range of processable materials needs to be expanded. A similar challenge is facing 3D printing technologies but the type of materials are different (polymers, metals, ceramics, food, pharmaceutical).

In many new applications and research programs worldwide, attempts have been focused on modifying the inks/materials to match existing printheads. In many cases this means sacrificing optimal functional properties of the deposited materials. Changing this paradigm will mean taking up the challenge to modify or develop new printheads to match the inks/materials. In addition, the interaction between jetted droplets and the substrates on which they are printed can limit the usability of inkjet for a range of materials and this requires deeper understanding and modeling. Printing 'without substrates' can be an interesting alternative in some cases. Here, droplets are jetted 'into air' and the challenge is to subsequently dry the liquid droplets in a controlled way to end up with powders with unique properties for application in for example fields as food & nutrition, biomedical and chemistry.

Printing of biological material (DNA, peptides, lipids, enzymes, etc) can require specific surface modification of nozzles and thorough understanding of the interaction between biological materials and nozzle coatings (how to tune adhesion properties, "bio-compatible" sensing principles, etc).

Scientific and technological challenges associated with printing of new semiconductor functional inks containing soluble or dispersed semiconducting materials (advanced organic or inorganic semiconductors) for high-speed and reliable printed electronic devices, micro and nano-sensing structures, etc. include the understanding of micro-droplet formation with these new materials, their interaction with nozzles, the environment and targeted substrate and new printhead concepts.

In digital printing for graphical applications there is still a great challenge to enable the use of more advanced and eco-friendly inks on a wide range of substrates and across a variety of markets. The major challenge here is to become competitive with offset printing technology, to be able to replace 20th century analog printing with 21st century digital technology.

3D printing is in an earlier development and adoption stage. Developments are still also happening at the fundamentals of the technology. New ideas and developments on printers, processes, materials and business models are necessary to expand the advantages of the technology to the fullest.

All of the above will require design, modeling and validation of new types of materials and inks as well as 3D printers and printheads, both at principle/concept level as well as material and micro/nanofabrication, structure miniaturization and implementation of suitable sensing and feedback principles.

Reliability and advanced sensing & control

For inkjet, 3D printing or other printing technologies to further evolve towards a true on-demand digital manufacturing technology it is paramount that reliability and robustness are significantly increased. For example in large area printed electronics it is paramount to be able to apply defect free layers and patterns. In 3D printing product quality, consistency and reliability need to improve to increase the adoption in industrial manufacturing. This implies stringent demands on all levels: printers, printheads, materials and integrated system level. An integrated approach is foreseen in which four approaches towards ‘zero-defect’ printing should be evaluated: prevention, prediction, detection and correction. Advanced sensing and control mechanisms are key aspects as well as smart print strategies centered around nozzle failure prevention and compensation. For micro-dosing applications (in for example areas as biomedical and food & nutrition) it is also often necessary to control and safeguard the exact and constant dispensing of very small amounts of liquids. For this micro flow sensors or other highly precise measurement methods should be developed as part of a closed loop system. For 3D printing systems control of material viscosities, melting, solidification and/or sintering behavior is key to allow for correct processing.

Print Platform Architectures

Many printing system architectures are possible and during past years especially roll-to-roll (R2R) and flat-bed architectures have gained a lot of attention. However, both R2R and flat-bed systems have their own limitations. For non-flexible rigid substrates such as crystalline solar cells or for 3D printing, a R2R system architecture does not provide a solution. At the same time many flat-bed architectures do not meet requirements in terms of speed and modular integration possibilities into manufacturing lines. Next to further developments of both R2R and flat-bed architectures, we also have to think about new approaches (‘beyond R2R’), that can offer flexibility and modularity by providing ‘building blocks’ for factories of the future where printing will be one of the key enabling technologies for on-demand ‘digital fabrication’.

New envisioned architectures and platforms may first be based on hybrid solutions, where 2D and 3D printing technologies will be complemented with existing traditional production technologies, such as pick and place systems for integration of inserts such as chips or LEDs or the use of lasers. At a later stage, as technology advances, more and more production steps will be replaced by printing technologies. New mechatronic platforms need to be devised and developed that allow for flexibility, modularity and integration to enable the design of flexible on-demand manufacturing platforms for small series (individualized) products made from multi materials. New design tools need to be developed to fully benefit from design flexibility and tackle the complexity of 3D, multi-material, ‘freeform’ design problems with realistic constraints. A better understanding of the substrates’ response to printing, handling and ambient conditions is also required to guarantee dimensional stability and quality of products manufactured with the envisioned new printing production systems.

New industrial applications will require new levels high-level control systems and workflow concepts that support the machine operators and production infrastructure in achieving the highest possible productivity.

3.1 Implementation in public private partnerships

Depending on the nature of the topics and the available competencies of participating partners, public-private partnerships will be executed or embedded in one or more of the following structures or programs:

1. *Fundamental or industrial research between industry and universities (example: open HTSM calls, TKI program)*

2. *Printing related TNO program (co-financing and shared research, B2B), printing related Holst program (program lines) and 3D printing related Brighthlands Materials Center program*
3. *Research chair Fluid dynamics of Inkjet Printing at the Eindhoven University of Technology and FOM/IPP Fluid Dynamic Challenges in Inkjet Printing program*
4. *Initiatives related to printing technology in Smart Industry*

1. Fundamental or industrial research between industry and universities
A successful instrument has so far been the funding of individual projects submitted under open STW/FOM calls, including earmarked HTSM calls. As from 2016, work has been done to start an Inkjet Research Program (IRP) as an initiative and joint research program with involvement of TU/e, UT, NWO and Canon Production Printing. The intent was to start a long term collaboration (10 years) in which at least 12 PhD positions would be created. This culminated in the establishment of the research chair and FOM/IPP program mentioned under point 3 below.

2. TNO, Holst program and Brightlands Materials Center related to printing: continuation and expansion
This encompasses the program of TNO related to printing which is in line with this roadmap and is focused on functional material printing and 3D printing. The Holst printing program in line with this roadmap and is focused on printed electronics, systems-on-foil, OLED lighting & displays and solar cells. A further track under development by TNO and partners is its programme on building advanced 3D printing manufacturing systems for food and pharma. The program at Brightlands Materials Center focuses on development of polymer materials for 3D printing and is in line with this roadmap.

3. Research chair Fluid Dynamics of Inkjet Printing at the Eindhoven University of Technology and FOM/IPP Fluid Dynamic Challenges in Inkjet Printing.
To organize inkjet printing related research at the TU/e and to strengthen further the collaboration between Canon Production Printing and universities, the research chair Fluid Dynamics of Inkjet Printing was established in 2015. The mission of the chair is closely connected to fundamental developments in the inkjet-printing industry. To meet the increasing and diverging requirements for future inkjet technologies, a fundamental understanding of the underlying processes is indispensable. Because of the very small time scales and lateral resolutions involved in inkjet printing, it is in many cases not possible to obtain accurate experimental data. Therefore, modeling and simulation of the relevant physical phenomena and material properties with available commercial codes and the development of dedicated models, techniques and algorithms is an essential part of the research. The aforementioned developments in the inkjet-printing industry are contingent on significant advancement in modeling and simulation capabilities.
The collaborations between Canon Production Printing and academic research groups at the TU/e and UT is further extended with the FOM/IPP program i43 “Fluid Dynamics Challenges in Inkjet Printing” which started in 2016. The 12 year program has a total budget of 6.3 Meuro for the first six years, funded by Canon Production Printing, NWO, TKI and the impuls fundings from TU/e and UT. Two FOM group leaders, 3 Postdocs and 11 PhD’s coordinate their research in two program lines “Printheads and Drop Formation” and “Ink Media Interactions” as basis for the total public private research program of Canon Production Printing, which meanwhile involves more than 30 researchers. In the second phase now of this program also UvA, UU and WUR have also become part of the consortium as academic partners.

4. Smart Industry
Smart Industry is about future-proof industrial & product systems; these are smart and interconnected and make use of Cyber Physical Systems. Digitization, connectivity and new manufacturing & product technology are drivers for this:

1. High-quality, network-centric communication between organizations, humans and systems, in the entire value network, including the products or services used by the end-users.
2. Digitization of information and communication among all value chain partners and at all levels in the production process.
3. Granular, flexible, and intelligent manufacturing technologies, adjustable on the fly to meet highly specific end-user demands.

In the coming decade, a network-centric approach to production will replace linear production processes with intelligent and flexible (regional) ecosystem approaches. These networks will interconnect parts, products and machines across production plants, companies and value chains at a highly granular level. The network-centric approach will radically optimize production in existing value chains and, more importantly, the notion of network-centric production finally spells the end of the ‘value chain’ and the birth of the ‘value network’. Within the Smart Industry domain, ICT, Mechatronics, Robotics and Manufacturing are enabling technologies essential to tackle the big challenges our society is facing. Digital printing and 3D printing in particular fits well within the scope of the above mentioned challenge and transition.

3.2 Collaboration and leverage with European and multi-national policies and program

Printing is embedded and acknowledged as a key technology in a multitude of projects and European programs under the following themes and programs:

- Factories of the Future
- Nanotechnologies, advanced materials, biotechnology and advanced manufacturing and processing
- LEIT
- Photonics21 (enabling technologies: printed electronics, OLAE)

In general, printing is recognized as a key enabling technology for production of advanced and new products and systems for a wide range of applications and sectors. European projects in this scope can be found addressing many of the application and technology challenges mentioned throughout this roadmap document. Dutch organizations participate in a number of projects. TNO is member in EFFRA, the organization behind Factories of the Future (http://www.effra.eu/) as well as Nanofutures (http://www.nanofutures.eu/) and is a leading actor to promote 2D and 3D printing technology for manufacturing and related EU programs. A specific example is the role of TNO in The European Additive Manufacturing platform (http://www.am-platform.com). This European AM sub-platform was initiated by the MANUFUTURE European Technology Platform and has published Strategic Research Agendas over the past years. These highlight priorities for future development in 3D printing and are produced in consultation with a large number of industry and academic experts in the field.

Factories of the Future (FoF) is a PPP targeting sustainable growth of the European Manufacturing industry. The latest FoF PPP roadmap highlights 3D printing as a key advanced manufacturing process by which a broad range of benefits can be realized, including its potential for creating sustainable high value European based employment, addressing societal issues and for supporting environmental sustainability.

4. Partners and process

Participants involved and consulted in this roadmap

NTS, TUD, TU/e, RUG, UT, TNO, Holst Center, Brightlands Materials Center, Sioux, Canon Production Printing, Vision Dynamics, Demcon, Bronkhorst, MI partners, Lionix, Reden, Additive Industries, Chematronics, Joh. Enschede, SPG Prints, Ten Cate, Wageningen University, SurfiX, Aquamarijn, ASML, Philips, NXP, Medspray, BPO, Amitek, Scania, Addit, Beltech, SKF, Thales, Solmates, Wavin, DSM Neoresins, Luxexcel, Bruco, Noviomems, DSM, Solvay, BASF, FESTO, KCPK/Bumaga, Berenschot, Promolding, Vertex Dental, AddFab, Additive Industries, Admatec, KMWE, BOM, Syntens, Brainport Industries, Fontys Hogescholen, HTSC TU/e, LIOF, Nextdent, NLR, Xilloc, Ultimaker, InnoVisser, Blue Engineering, Akarton, Additive Industries, Süss Microtec, network of Dutch MKB printing industry “future of print”

Process followed

Engagement and consultation with networks of TNO, Canon Production Printing and university representatives has been an ongoing activity since the establishment of printing as one of the roadmaps within the framework of Point-One. The printing roadmap has been updated five times since it was transferred from the multi-annual roadmap of Point-One in 2011 and it became a separate roadmap in the HTSM topsector.

5. Investments[1]

Roadmap	**2020**	**2021**	**2022**	**2023**
Industry	2,05	2,1	2,1	2,1
TNO	3,9	4,1	4,1	4,1
NLR				
NWO	1,05	1,05	1,05	1,05
Universities	1,6	1,6	1,6	1,6
Departments and regions (excluding TKI)	0	0	0	0
Grand total	**8,6**	**8,75**	**8,75**	**8,75**

European programs within roadmap	**2020**	**2021**	**2022**	**2023**
Industry	0,025	0,025	0,025	0,025
TNO	1,5	1,8	1,8	1,8
NLR	0	0	0	0
NWO				
Universities	0,025	0,025	0,025	0,025
EZK co-financing of European programs				
European Commission co-financing	1,6	1,9	1,9	2,1
Grand total	**3,15**	**3,75**	**3,75**	**3,95**

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[1] R&D in public-private partnership, including contract research; all figures in million euro cash flow per year (cash plus in-kind contribution)