European Construction Sector Observatory

Integrating digital innovations in the construction sector

The case of 3D Printing and Drones in construction

Trend Paper Series

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1. Integrating digital innovation in the European construction sector

While most industries have been through fundamental changes over the past few decades, the construction industry has been hesitant to embrace digital innovation. In fact, IT spending does not exceed 1% and only agriculture and hunting seem to spend less. As a result, its labour productivity has only slightly grown, at a quarter of the rate in manufacturing[1] over the past two decades and it may fall behind in the race for innovation.

This does not mean that there is no innovation helpful for the sector. Building Information Modelling (BIM), the Internet of Things, 3D laser scanning and component printing, big data analytics, augmented reality, drones etc. are some examples of innovations, which could have a major impact on the construction sector. These are mostly innovation from other branches of industry, but could help the construction sector build faster, better and cheaper, while maximising resources use and increasing construction companies' profitability.

The issue is rather for construction companies to adopt and integrate new technologies in their processes and their daily operations – and hence transforming their business model. In other words, integrating digital innovation is not only about adopting a new technical tool itself (a drone or a 3D printer), but changing the business routine and helping human resource to adapt and build new capacities. One of the objectives should also be about maximising the use of digital innovations, and especially the data that they generate – and this is where part of the struggle is for construction companies.

Aware of this gap, policy-makers have developed policies and supported initiatives aiming to facilitate the integration of such digital innovation in the construction sector. The European Commission has developed the Construction 2020 Strategy, followed by an action plan, with a pillar specifically dedicated to financing and digitalisation. Other crosscutting policies and (financial) instruments such as the Cohesion Policy or the Horizon 2020 and Competitiveness of enterprises and SMEs (COSME) 2014-2020 support the research, technological development, uptake of technical innovations along the construction value chains.

However, progress in the sector has been limited and innovations are often adopted at a slow rate, and in a fragmented manner (i.e. not throughout the whole construction value chain, or by a specific set of actors only such as large construction companies vs. small and medium-sized enterprises - SMEs). For example, a digital innovation such as BIM is often used by architects, engineers and sometimes by contractors, but the operation and maintenance actors have so far shown limited interest and/or faced difficulties, in integrating such a digital technology in their process, impeding the full realisation of BIM potential benefits.

This paper will hence look at the policies and initiatives from both policy-makers and public sector to foster the implementation of two of the most promising digital innovations in the construction sector: 3D printing and drones. The study will then dwell into the drivers, opportunities, and challenges around their adoption. It will then draw recommendations for EU policy makers and other relevant actors on how to support and foster the adoption of drones and 3D printing by construction companies.

The following section will introduce 3D printing and drones, i.e. what they are, and how construction companies apply them in practice. It will also present their respective market, and the drivers and obstacles that explain their relative progress in terms of their adoption by construction companies. Section 2 incorporates a series of case studies, demonstrating how these digital technologies are applied, and what the construction sector actors does to foster their implementation and development. We will draw some key lessons learnt, highlighting some of the key success factors and blockers explaining their success and/or

[1] See more information at https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/improving-construction-productivity

failures. Section 3 will then conclude by providing insights and recommendations to construction sector actors on how they can best support the integration of 3D printing and drones in the sector.

2. Background of 3D printing and drones, and their market development

This section presents what 3D printing and drones are, and how and when (at which stage of the value chains) construction companies are using them in practice. It will also present their respective market, and the drivers and obstacles that explain their relative progress in terms of their adoption by construction companies.

2.1. 3D printing: from concept development to niche market

"Eventually, 3D printing will become a common or even standard feature in the fabrication process"[2].

3D printing refers to the production of physical objects layer-by-layer by an automated and usually computer-controlled machine, often based on digital 3D models. The machine either melts metal or powdered solids or ejects liquid or semiliquid materials, which overall include polymers, metals, ceramics, and mortar or concrete[3].

While digital innovations so far have occurred mainly in the design, engineering, and operations and maintenance phases of construction, 3D printing regards mainly the actual construction phase. In fact, 3D printing has been applied to build (mostly smaller-scale) buildings, bridges, printed moulds, building components, architectural models and interior design.

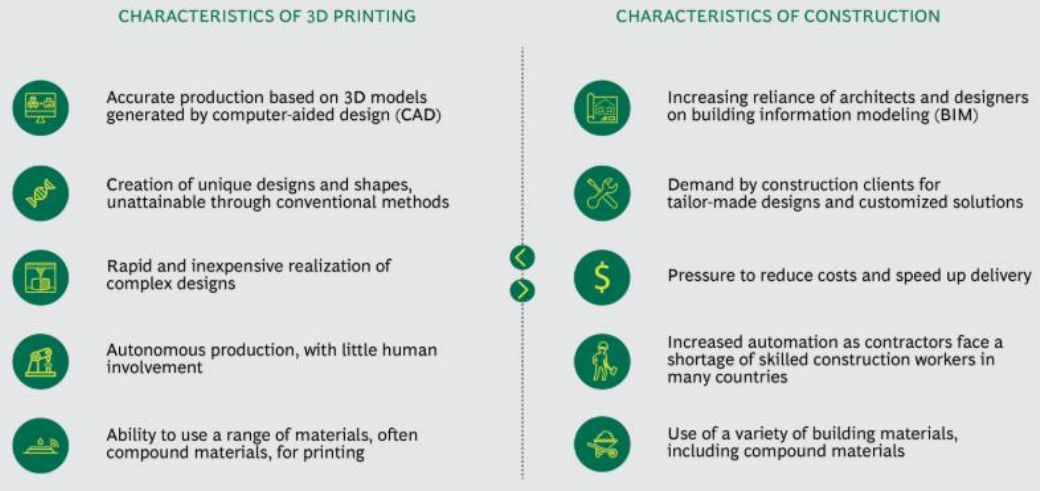
Table 1: Examples of application of 3D printed solution in the construction sector

Area of application	Typology	Examples
Buildings	Compact single houses; social housing, office building	• Yhnova project in Nantes, France to build social housing • Five 3D printed house in Eindhoven, the Netherlands • 3D printed building in Copenhagen, Denmark • Dubai Future Foundation office building
Bridges	Pedestrian bridges, cyclist bridges	• 3D printed footbridge in Madrid, Spain • 3D printed footbridge in Amsterdam, the Netherlands • 3D printed cyclist bridge in Amsterdam, the Netherlands
Printed moulds	Unique design, shape and form (i.e. non-standard objects)	• Double-curved wall panel for the London Crossrail Project • Hilo Project in Dübendorf, Switzerland
Building components	Facades, joints, partition walls, power sockets	• A roof canopy's network of steel for the office building 6 Bevis Marks in the City of London (complex nylon sleeves 3D printed
Architectural models	Small-scale models	• Used for the work related to Sagrada Familia, Barcelona, Spain
Interior design	Interior and furniture design	• IKEA's first 3D printed wall decoration Omedelbar Hand or knitted armchair • Steelcase's 3D printed wall decoration • Ventury's Eiffel chairs

2 See more information at https://www.bcg.com/publications/2018/will-3d-printing-remodel-construction-industry.aspx
3 Ibidem.

The adoption of 3D printing in the construction industry generates increasing attention from policy-makers and the industry. With rapid urbanisation, climate change and resource scarcity, 3D printing represents a way to make the construction process cheaper, faster and better. In other words, the inherent characteristics of 3D printing make it a "natural fit with construction", as shown in the box below[4].

Figure 1: Linkages between 3D printing and Construction



Source: BCG, 2018.

Several specialist companies have emerged, and several large established companies—not just construction firms but also manufacturers of building materials (e.g. Lafarge for concrete) —have started investing in 3D printing. In fact, the number of companies active in 3D printing in construction has grown from 20 start-ups in 2013 to 65 offering services such as prototyping solutions for architects and engineers, software and design tools, and large structural components or even entire buildings[5].

While start-ups and SMEs are playing a key part in developing 3D printing processes, major construction players such as Aecom, Vinci and Bouygues have started acquiring stakes in, and/or collaborating with, specialist 3D printing technology. The academia (MIT, ETH Zurich, TU Delft, or Loughborough University, Nantes University) also plays a key role, providing and supporting the knowledge development process, by participating in numerous 3D printing pilot projects (such the social housing in France – see Section Case Studies - or the footbridge in Spain).

At the same time, the use of 3D printing in the industry remains limited with a total value of all outputs worldwide estimated at less than USD100 million (in an industry with annual revenue of USD10 trillion globally). In terms of projects, less than 40 large-scale demonstrations were realised globally as of the start of 2018. This is partly explained by:

1. **The new and disruptive nature of the 3D printing** as a technology. 3D printing in construction is an innovation, and as most innovations, it follows the traditional development cycle, illustrated in the below figure. As of today, 3D printing is at a stage between the demonstration and the early stage of niche market. This means that the market is not fully ready yet and still needs to be educated about the potential of 3D printing (some have security concerns about 3D printing, some are trying to refine their own 3D printing process, including software or robotic systems). The education around 3D printing concerns the clients but also the users of the technology – who need to adapt their behaviour and processes in order to achieve the full potential of this technology[6]. Finally, as 3D printers demand

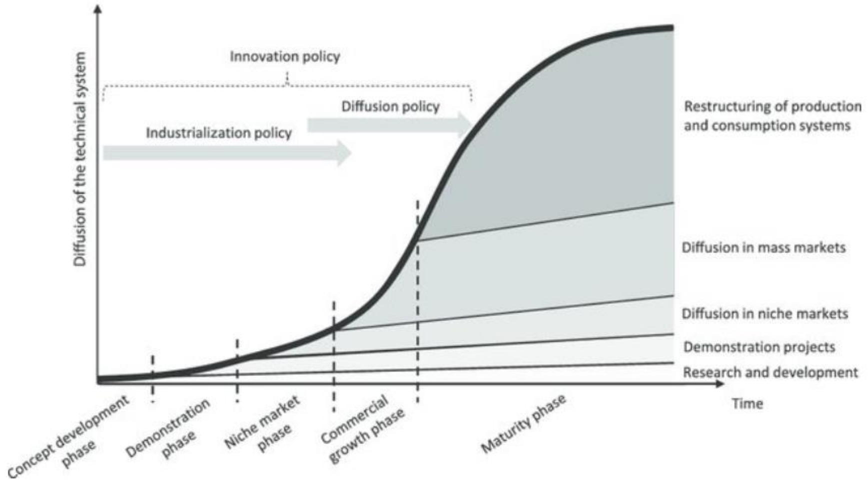
4 See more information at https://www.bcg.com/publications/2018/will-3d-printing-remodel-construction-industry.aspx

5 Ibidem.

6 For example, architects and designers will have less constrains with 3D Printing, and will be able to design complex shapes. That said, the construction industry tends to be traditional, and it is not certain that architects and designers will be interested in exploiting new design opportunities.

important R&D and marketing efforts, their price is still high (the price of a mainstream onsite concrete printer is about USD500,000 to USD2,000,000).

Figure 2: The five stages of diffusion of innovations

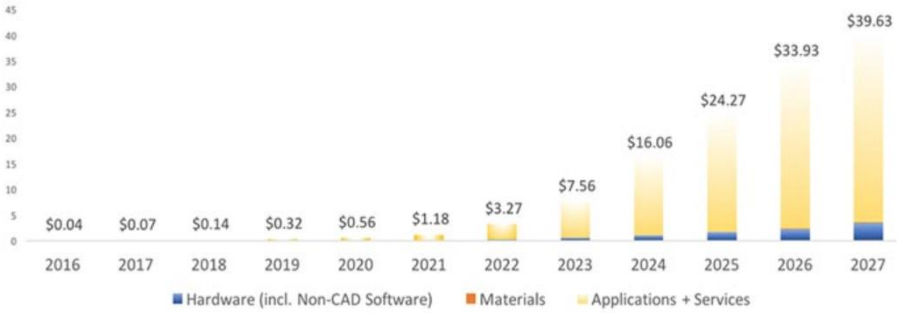


Source: Swedish Energy Agency (2014)

2. **The limited scope of application in the broad construction sector:** 3D printing is so far limited to residential and commercial small-scale vertical construction and the nonstandard shapes and components. Its penetration in standardised components requiring structural reinforcement (present in industrial and infrastructure construction) has been so far limited.
3. **The lack of specific regulations and standards around 3D printing** in the construction sector.

However, the 3D printing market is expected to grow significantly in the next years to come, from USD 0.04 billion in 2016 to almost USD 40 billion in 2027 (see the graph below).

Figure 3: 3D printing Construction market revenues between 2016 and 2027, divided in hardware, materials, and applications and services (USD, billion)



Source: 3D Natives, 2018

This growth is expected to be driven by applications and services linked to 3D printing (USD 36 bn in 2027), followed by USD 3.5 bn in machinery and USD150 ml in material. In terms of products used in 3D printing, concrete seems to be the most advanced one, in comparison to metal and other liquid or semi-liquid products.

Several factors explain the actual and predicted growth of the 3D printing in the construction sector. These can be related to:

1. **Political factors**: Policies and in some cases regulations and instruments foster the implementation of 3D printing in the construction sector. Often these public sector initiatives tackle horizontal issues such as resource and energy efficiency or circular economy (including waste recycling), and may generate opportunities for technologies maximising resource use such as 3D printing. In other cases, policies may directly support 3D printing. This is the case of the UK and its National Strategy for Additive Manufacturing, which estimates that used in the construction sector, 3D printing could generate more than USD1 billion to annual GDP and create 15,000 jobs by 2025. Outside Europe,

public institutions in China, United Arab Emirates and Saudi Arabia already intend to use 3D printing for houses construction (e.g. the UAE is aiming for 25% of new buildings to be 3D printed by 2030). This may generate important market opportunities for EU construction companies.

2. **Economic factors:** As the 3D printing technologies, materials and equipment develop, their costs will decrease and their efficiency will improve. At the same time, 3D printing may benefit from increased awareness, and wider adoption in the construction industry. Overall, this may lead to economies of scale, and increased R&D investment in 3D printing.
3. **Market demand factors:** As mentioned earlier, 3D printing provides architects with more options when it comes to the design of buildings and their components. Indeed, 3D printing allows fabricating complex shapes onsite or offsite, flexibly and cheaper than traditional methods. In addition, 3D printing helps addressing the issue of construction labour shortage observed in numerous European countries; shortening construction time and making it more predictable with 3D printing process able to work 24/7; maximise resources use, while offering the capacity to use recycled materials; reducing costs which is increasingly important for project owners (including government and industry clients).

Therefore, 3D printing will most likely bring drastic changes to the construction sector. As presented in this section, such a technology responds to several key concerns of both the industry and policy-makers, whether directly related to the construction sector (low productivity, labour shortage or building materials prices), or crosscutting issues (environmental impacts, such as recycling of construction waste and resource efficiency). While prospects seem rather positive, the 3D printing for construction market remains slow to take off and faces important challenges. The next section will delve into some concrete examples, showing the opportunities and challenges that construction actors face when adopting 3D printing, and will draw some key lessons learnt for policy-makers and the construction industry.

2.2. Drones: picturing the future of construction

"While dozens of industries use drones, the fastest growing commercial adopter is the construction industry"[7].

In the context of construction, drones represent unmanned aerial vehicles (UAVs) or unmanned aircraft systems (UASs), organized in two entities – an operator from the ground and the drone itself with a communication system connecting the two. Drones vary in their level of autonomy, from remote-controlled to automatically navigated, using on-board flight software, planning trajectory with the help of GPS and sensors, incl. camera and video equipment, infrared and heat sensors[8]. The benefit of drone use is in the data acquired by the drone sensors, which once gathered, can be processed and analysed to deliver important insights for businesses or the public.

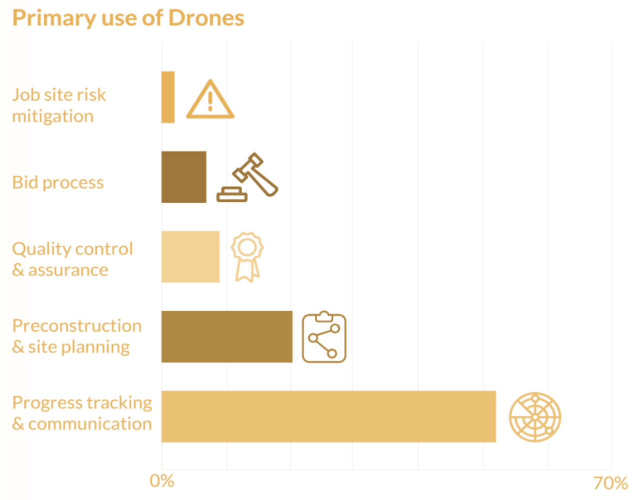
In theory, drone services can be plugged into all stages of the construction value chains, from the pre-construction through the entire construction phase by providing field information for planners and real estate developers, to the final stages of a construction project, providing assessment and impact reports. Drones increase efficiency and productivity in all these stages by surveying the site for progress; verifying contractor's reports; identifying discrepancies; and assisting in confirming compliance with regulations - e.g. storage of materials or waste.

In practice, drones are already in use in the construction industry, as shown in the figure below.

7 See more information at https://blog.dronedeploy.com/the-rise-of-drones-in-construction-5357b69942fa

8 PwC report 2018, Skies without limits, https://www.pwc.co.uk//intelligent-digital/drones/Drones-impact-on-the-UK-economy-FINAL.pdf

Figure 4: Primary use of drones by construction companies



Source: DroneDeploy 2018[9].

They are particularly valued for their capacity to provide cheap and efficient ways for the:

- ✓ **Mapping of construction sites**

  Drones offer the possibility for accurate mapping of surface areas with exact coordinates and measurements, creating cartographical representations of land and construction sites in real time[10]. Drones equipped with heat sensors can deliver thermal imaging, volumetric measurements, e.g. assessing the volume of a stockpile and materials quantities**.**

- ✓ **Communication and management activities**

  Improved communication and collaboration in terms of real time accurate data exchange between different construction value chain actors can potentially reduce the time needed for the design stage or for implementing changes during construction[11]. Drones allow for tracking of the construction process progress against the schedule, providing a real-time view of the site, which helps better manage resources.

- ✓ **Collecting three-dimensional information**

  3D information collected by drones can be integrated within existing BIM systems. Existing drone software platforms provide 3D "as built" representations of the construction site, which can easily be compared to original designs to ensure that the architectural plans are being followed. This allows for tracking of volumes change over time, revealing of features of the field that are not visible from the ground, such as archaeological wall remains, and depressions etc.[12].

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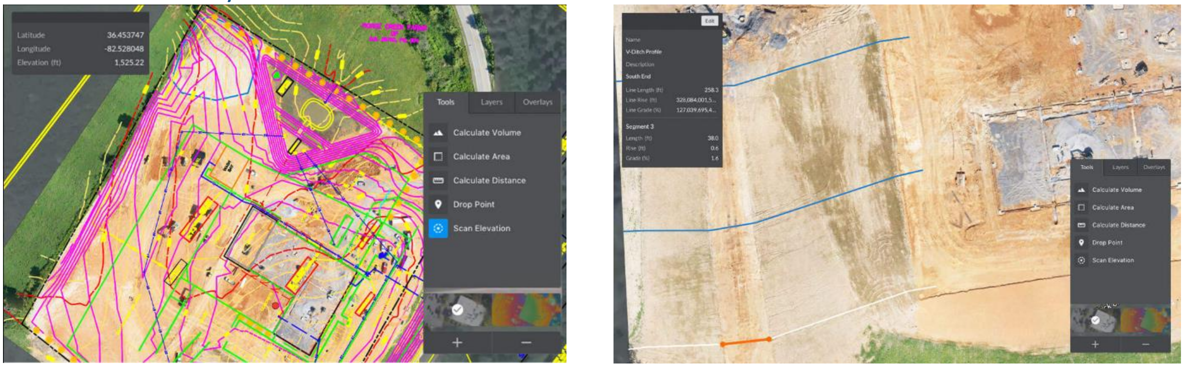
9 Drone Deploy, Trends report 2018, https://blog.dronedeploy.com/the-rise-of-drones-in-construction-5357b69942fa

10 http://versadrones.com/solutions/site-land-mapping/

11 Construction Global 2018, How will drones revolutionise the construction industry, https://www.constructionglobal.com/equipment-and-it/how-drones-will-revolutionise-construction-industry

12 http://versadrones.com/solutions/3d-surveying-reporting/

Figure 5: Scan and analysis of a construction site



Source: Kespry, In: Engineering.com[13],

✓ **Building surveys**

In the case of large or difficult construction sites, drones can provide a solution through easy air access, e.g. to structures otherwise needing additional equipment to reach, structures that are built over water bodies etc.[14]. A building survey of a roof for example using traditional methods would require the erection of a scaffold, use of cherry picker and ladders, which is both time consuming and costly[15]. Construction sites need to undergo inspections and surveys to stay on track with the progress of the building process and the safety standards. Drones use is associated with gains in productivity, up to 400 times increased efficiency in site surveying, 40% lower costs, improved data quality and survey accuracy[16]. Compared, traditional surveying methods are labour intensive and with lower accuracy.

✓ **Site inspections**

Drones enable site inspections to be done more regularly and cover larger areas more efficiently, as no disruption of working schedule is involved and health and safety risks can be reduced. Field personnel is exposed to less risk on the site, when performing tasks such as measuring stockpiles.

✓ **Visualisation**

Drones provide visualisations of construction progress or of ready buildings, useful for real estate agents and developers for marketing purposes.

Figure 6 illustrates some of the benefits of drones used in construction, including the aspect of security surveillance as one of the advantages. Outsourcing such tasks to technological solutions is advantageous in increasing security, e.g. protecting effectively from vandalism or theft, while minimising risks for the security staff. A survey among drone manufacturing company DroneDeploy's customers shows savings achieved of up to 20 times, significant time gains, safety and communication improvements and higher accuracy in measurements. It also shows that most commonly, drones in construction are used for progress tracking and communication in around 50% of cases.

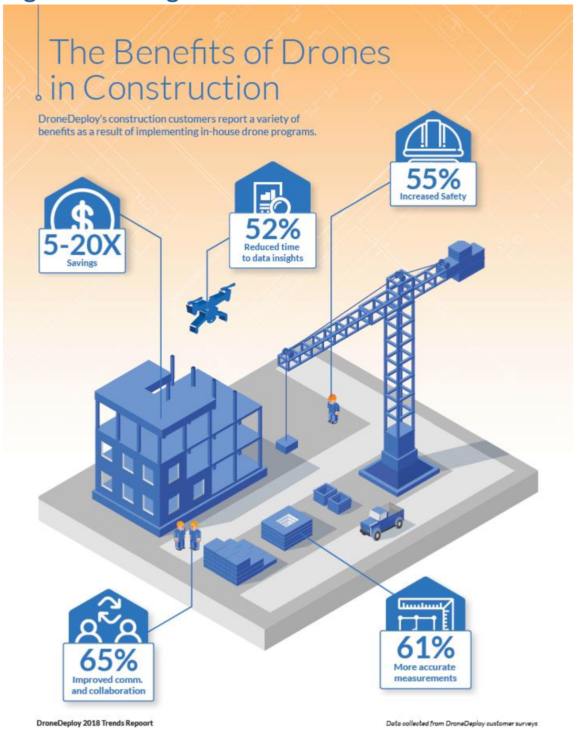
[13] Engineering Magazine, Are drones becoming essential to construction, https://www.engineering.com/BIM/ArticleID/16686/Are-Drones-Becoming-Essential-to-Construction.aspx

[14] The Balance Small Business 2018, How UAVs are being used in construction projects, https://www.thebalancesmb.com/how-drones-could-change-the-construction-industry-845041

[15] Construction Review Online 2018, Utilizing drone technology in construction, https://constructionreviewonline.com/2018/03/drones-in-construction/

[16] PwC report, see above

Figure 6: Using drones in construction



Source: DroneDeploy 2018[17].

As a result, the drone market in Europe is steadily growing. A 2018 PwC study on the impact of drones on the UK economy by 2030, estimates that drones could potentially add up to EUR 47.3 billion to the country's gross domestic product (GDP) and up to EUR 18.0 billion in net savings. A European Commission estimate also projects growth in the drone economy, with a market reaching over EUR 10 billion per year in the next 20 years and creating more than 100,000 direct jobs.

Segmented according to final use, military, leisure or commercial, globally, the defence industry remains the largest market for drones, estimated to be worth EUR 61.3 billion for the 2016-2020 period[18]. However**, the fastest growth is projected to come from businesses and civil governments, globally expected to equal a spending of EUR 11.3 billion for the same period, with the largest share, EUR 9.7 billion, accounted for by the construction industry.** With the US drone market dominated by the defence sector's needs and the Asian focused on recreational use, Europe could seize the opportunity to lead in the commercial drones market. Worth EUR 85 million in 2016, it is projected to grow by more than 200% to EUR 2.6 billion by 2025[19].

The main contributors to the industry's growth are the increased demand for high quality data and for enhanced data processing and accessibility. The development of drone software also drives the market growth. The lower cost of gathering high quality data, previously collected with manned aviation or satellites, makes drones a primary tool for companies interested in geospatial analyses and photogrammetry (making measurements from photographs). The height-projected growth in the commercial drone economy for construction is also connected to businesses' requirement for data to be meaningfully processed to deliver value. Customers expect data to be accessible and available anywhere and on any device and drones' automated capabilities in data processing and delivery derive a solution for companies to stay up to date. The development of new power sources for drones will affect their popularity as well, as battery life currently represent one of the main technological obstacles for the safe use of drones.

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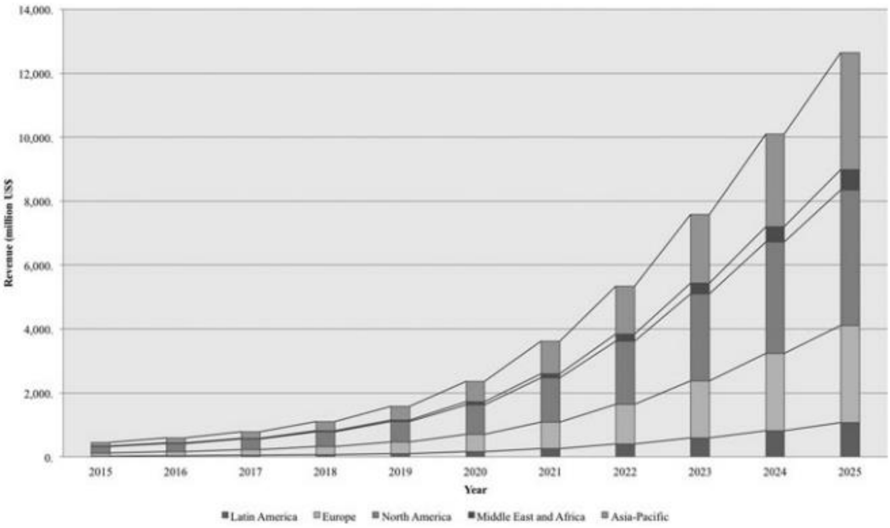
17 Drone Deploy, Trends Report 2018, see above

18 Goldman Sachs Research 2016, Technology driving innovation: Drones, https://www.goldmansachs.com/insights/technology-driving-innovation/drones/

19 Technologist, Europe's drone opportunity, https://technologist.eu/europes-drone-opportunity/

Additionally, public sector demand for more efficient maintenance solutions represents a potential growth driver. As public sector construction or reparation works projects often face budget limitations, the need to maximise resource use and reduce uncertainties in terms of project delivery timing arises. In the case of road reparations for instance, work delays can be avoided by using 3D printing drones (see Case studies).

Figure 7: Projected commercial drone revenue from 2015 to 2025



Source: de Miguel Molina et al., 2018[20].

In terms of providers, the drone market involves big companies as well as SMEs. Drones use varies largely in the size of investment that companies need to make, depending on their final purpose and technical sophistication. Thus, generally, costs are not necessarily a barrier for the use of drones for big and small construction companies.

As indicated by the positive market outlook for drones in construction, construction firms are in the process of adopting drones in construction. In fact, a Gartner survey (2018) covering construction companies reveals that 72% of construction firms will either begin using drones or are considering using them within the next two years[21]. More specifically, 27% of companies already use drones, 31% expect to use them in the next two years, while 14% think about using drones in the future. As using drones may require additional skills and capacities, large construction companies may be leading in terms of drones adoption rate, in comparison to SMEs. That being said, several construction companies prefer to outsource the use of drones to drones suppliers, rather than internalizing the costs (i.e. buying the drones, and the necessary software).

In terms of segmentation, drones are used in all types of projects and by construction companies along the value chains. That said, the real estate sub-sector is among the most important markets: the demand for drone services continues to rise, and uses have expanded beyond producing photos for marketing materials. There architects are one of the key drones users, as they can use them to get both interior and exterior pictures[22].

The main market players in the global drone market are the Chinese company DJI, who occupies 72% of the drones manufacturing market (producing both commercial and hobby drones)[23], followed by the French company Parrot. Geographically, in the EU, the UK hosts the largest number of drone manufacturers, 34 companies, followed by Italy, Germany and France (Table 1).

[20] Ethics and Civil Drones. European policies and proposals for the industry 2018; The Drone Sector in Europe, de Miguel Molina, M.; Santamarina-Campos,V. (Eds.).

[21] See more information at https://blog.capterra.com/drones-in-construction/

[22] http://www.cpbj.com/article/20171114/CPBJ01/171119945/going-up-drones-play-a-bigger-role-in-residential-commercial-real-estate

[23] TIME magazine, Genius companies 2018, http://time.com/collection/genius-companies-2018/5412498/dji/

Table 2: Drone manufacturers by European country

Country	Number of manufacturers
UK	34
Italy	31
Germany	30
France	28
Spain	16
Austria, Netherlands, Sweden	8
Portugal, Romania, Slovenia	4
Belgium, Bulgaria, Czech Republic, Finland	3
Estonia, Hungary, Latvia	2
Denmark, Greece, Ireland, Luxembourg	1

Source: de Miguel Molina, M. et al. 2018

In terms of manufacturers, who specialise to cater specific industries, the focus lies not only on the drone hardware, but also increasingly on the software and applications offered. Drone manufacturers partner up with software firms, hardware firms and camera makers in the product development process. Consequently, drones for commercial purposes are more expensive than the ones for leisure purposes, with some drones offered by European manufacturers costing over EUR100 000, representing a sizeable investment for smaller construction companies. Additionally, following the logic of the software industry, the licence for relevant software applications is subject to a yearly fee. However, the large costs do not necessarily represent a barrier for drones' use for smaller companies.

These high costs associated with commercial drones have paved the way for more affordable market options, with companies offering drone services, instead of selling the actual drones. This results in a market segmentation of companies offering the product only (drone and software), companies that offer the product and services, and companies, specializing only in drone services[24]. In terms of market segment, big companies operate in more than one segment, with companies producing for the military industry or for leisure also catering for commercial drone use.

Software companies are strategic partners to drone hardware manufacturers. The market for drone software is characterised by high specialization, with the European companies developing specifically for commercial drones, including integration with BIM. The companies dominating this market are Airware (USA), Dedrone (Germany), DroneDeploy (USA), MapBox (USA), PIX4D (Switzerland), Redbird (France), SkyWards (USA), and Skyworks Aerial System (USA). Their specialized services range from industry adapted drone data processing and analysis, through developers of drone detection systems, flying simulators and drone data sharing platforms.

Airware acquired the French Redbird in 2016, illustrating how **the drone market is also driven by strategic partnerships and globalisation.** Such partnerships also signify a general direction of the market in the long term, toward an integration of services and competences in a cluster or umbrella of companies or possibly within one company in the future.

Strategic partnerships and globalisation in the commercial drones market

The use of drones in construction is often outsourced with construction companies purchasing the services of drone companies. However, strategic partnerships have emerged between drone technology companies and construction big players. In 2016 the US drone analytics enterprise Airware acquired the French start-up Redbird, established in 2013, which had been specializing in drone data analytics for construction and mining companies. Airware, founded in 2011, originally specialized in drone operating

[24] Ethics and Civil Drones. European policies and proposals for the industry 2018; The Drone Sector in Europe, de Miguel Molina, M.; Santamarina-Campos,V. (Eds.).

systems, later expanding its services to data collection flights, providing cloud management and analytics services to industrial clients and in 2016 starting the production of drone hardware, thus covering end-to-end drone services. Redbird on the other hand, is not a drone hardware producer; it provides drone services through a cloud platform, which requires the end user, the construction company, to have an internet connection and login.

Redbird is working together with the French construction equipment dealer Bergerat Monnoyeur, exclusive dealer for the US construction equipment manufacturing company Caterpillar for France, to provide drone services to its customers. The acquisition of Redbird strategically positions Airware, "buying a foothold in the construction and mining drone business" as well as a place on the European market, with Redbird's headquarters in Paris becoming Airware's European headquarters[25]. For the acquisition, Airware used capital from its Commercial Drone Fund, which raised USD 70 million and from Caterpillar's venture capital fund. This relationship positioned Caterpillar as a distribution partner for Redbird when it entered the US market.

This partnership illustrates a shift for big construction machinery manufacturers, traditionally focused on improving hardware machinery's capacity to increase productivity toward a productivity concept grounded in data solutions, recognizing that productivity gains will come from combinations with software. This development comes at a time when Caterpillar announced the closing of 20 plants worldwide and its biggest equipment dealer globally, the Canadian Finning, announcing 1100 job cuts, signifying a transition in the construction industry toward digitization, the strategic partnerships with technology resolving skills shortages in the industry. Caterpillar's global marketing manager sees these developments not only being due to demand for improved productivity solutions, but also by policy trends and emphasis on environmentally sustainable construction expectations and the limits of engineering "greener" engines and machines.

However, while market perspectives are positive for the use of drones in construction, several issues limit its further development. These can be divided in three categories: i) regulation issues; ii) technological issues and; iii) market issues.

2.2.1. Regulation issues

In order for companies to broadly adopt the use of drones and fully profit from their potential, they need transparent and clear rules on how to guarantee compliance, such as licences for commercial drone use. Studies predict that judicious regulations will boost the use of drones, prominently insurance companies' policies will be important to protect drone users from liabilities and physical losses[26].

The European Aviation Safety Agency (EASA), after a period for public consultation, has developed a legislative proposal for "an operation centric, risk- and performance based regulatory framework for all unmanned aircraft (UA)"[27]. The proposal published so far focuses on laying down harmonized rules for the categories of use of drones and the registration of UAS operators. It aims to provide a uniform level of safety for UAS operations and to foster the UAS market with the background of addressing privacy and safety concerns, mainly incorporated in rules on flying over bystanders. The proposed regulation leaves space for flexibility on the side of Member States, who will be free to decide on no-fly zones within their territories, or conversely, zones where drone flights are facilitated. Additionally, drones' use is divided in two categories – open and specific, adhering to the end use. Commercial drones would mostly fall under the specific category, although, no particularities according to industry are defined.

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[25] Techcrunch 2016, Airware buys Redbird to build a full-stack drone services empire, http://time.com/collection/genius-companies-2018/5412498/dji/

[26] PwC 2016, Clarity from above, https://www.pwc.pl/pl/pdf/clarity-from-above-pwc.pdf

[27] EASA Drones - regulatory framework background, https://www.easa.europa.eu/easa-and-you/civil-drones-rpas/drones-regulatory-framework-background

In terms of privacy, drones gather vast amounts of data, which could potentially include sensitive or confidential information. It is not clear how companies should store such data or how individuals or companies can protect their privacy rights. With the market growing, pressures will increase for these issues to be subjected to clear rules and regulations[28].

2.2.2. Technological issues

Furthermore, there are technological obstacles still to be resolved. British company Consortiq's CQNet defines drone landing with minimal battery charge to be among the main reasons for the lack of drone safety. Similarly, auto-fail functions causing drones to uncontrollably fall from the air to the ground need to be addressed. As technical characteristics could represent an obstacle in smooth regulation, incremental innovation is an important part of the drone industry, rapidly adopting improvements in terms of longer flight times, cameras, less noise and auto charging batteries[29].

Another obstacle to the use of drones in construction is again rooted in the current technical capacity of drones, mainly a lack of IT infrastructure and a good WiFi connection in some construction sites could pose challenges in the controlling of drones on the site[30].

2.2.3. Market issue

Considering, that the use of drones in construction requires software skills, skills shortages are not regarded as an obstacle in the current analysis, as drone companies often provide services as well, besides the drone machines, as mentioned in the previous section. However, besides the actual machines, drones require technical skills to be used to their full capacity, which represents a possible additional investment in training and knowledge acquisition. With the development of the drones market, as well as the technology stand, construction companies might find it a sound investment to internalize the use of drones and integrate drone services, instead of outsourcing them. In the long term, the construction industry can anticipate relevant software skills to become important.

[28] PwC 2016, Clarity from above, https://www.pwc.pl/pl/pdf/clarity-from-above-pwc.pdf

[29] Ethics and Civil Drones. European policies and proposals for the industry 2018; The Drone Sector in Europe, de Miguel Molina, M.; Santamarina-Campos,V. (Eds.).

[30] Construction review online

3. Case study analysis

EU MS are concerned about the development of digital innovation in the construction sector. While there is no specific EU and EU Member States' policies and instruments in place to foster 3D printing or drones in the construction sector, several EU MS mention 3D printing use in the construction sector in some of their strategies. The UK has for example developed a strategy on additive manufacturing, which targets several sectors including construction. Germany identified strong linkages between the growth of Industry 4.0 and Additive Manufacturing. At the EU level, the European Parliament published in July 2018 a resolution regarding 3D printing – highlighting some of the legal challenges, notably around intellectual property and civil liability. Likewise, the European Commission published its latest draft of detailed drone rules for operational and technical requirements, which builds on EASA recommendations, and proposes a groundwork that will grant Member States the ability to implement security measures as they see fit.

While there is no policy on 3D printing in the construction sector, the EU and its MS are active in supporting financially and/or technically research and innovation investments and pilot projects. This section will look into more depth at a set of short case studies, with a view to highlight some of the challenges and opportunities around 3D printing application in the construction sector. These case studies were selected based on the quality and comprehensiveness of information available.

3.1. Case Study 1: YHNOVA Project

The first case study takes place in Nantes, France, and regards the implementation of YHNOVA[31], a social housing project consisting of a 5-room house of 95m^2, based on the 3D printer "Batiprint 3D" (see picture below). The objective of this project was to build affordable, adaptable and energy efficient housing that can be built quickly[32].

Figure 8: Picture of the YHNOVA social housing project finished in 2018

Source: Nantes Aménagement[33].

In terms of process, a poly articulated industrial robot deposits 3 layers of materials: two layers of expansive foam serve as formwork for a third layer of concrete[34]. Once the walls have been constructed, the foam is kept in place in order to insulate the house without thermal bridging. At the end of the operation, the mobile robot emerges through an opening provided for the fitting of the joineries. After the elevation of these insulated structural walls, more traditional techniques took over for the roofing and finishing work. YHNOVA will be equipped with multiple sensors and home automation equipment in order to assess and analyse the behaviour

[31] See more information at http://batiprint3d.fr/en/

[32] See more information at https://www.lemoniteur.fr/article/et-voici-la-premiere-maison-d-habitat-social-imprimee-en-3d.1958064

[33] Nantes Aménagement 2018. http://www.nantes-amenagement.fr/2018/04/19/yhnova-maison-3d-quartier-de-bottiere/

[34] See more information at https://3dprint.com/207936/3d-printed-yhnova-house-done/

of materials and thermal/acoustic quality during the first year of use. This shows that there are still some considerations in terms of the long-term quality assurance of 3D printed concrete and other 3D printed materials.

As a result, the 3D printed parts were realised in less than three days, (instead of three weeks with traditional means). Overall, the construction price was reduced by 20%, while there was no significant gain in terms of time reduction, because of the traditional methods used for finalising the works[35]. Other benefits include:

- Improvement of the energy performance of construction, and with its zero waste, raw materials, and decreased transport.
- Reduction of the risk of musculoskeletal disorders, as construction workers don't have to go up and down scaffolding, with the use of 3D printer.
- Dependence reduction on good weather conditions for a solid day of construction work.

This project is the result of a collaboration between public and private sector actors, as well as the academia, as shown in the table below. Each other stakeholder brought to the project their expertise, and/or resources (over EUR 500,000 in total)[36], based on their core business and mandate[37].

Table 3: YHNOVA Stakeholders

Stakeholder typology	Stakeholders	Contribution
Public sector	Nantes Métropole	• EUR 130,000 to foster the development of innovative solutions around social housing, through Nantes City Lab • Project management
	Ouest Valorisation	• Contributed to making the Batiprint 3D patented, and to foster the industrial use of this technology
	Caisse des dépôts	• EUR 250,000 (as part of the programme démonstrateurs territoriaux de la « smart city »)
Main private sector actors	Egis	• Construction expertise for the structure, electricity, CVC; and evaluation of carbon impact
	Bouygues	• R&D knowledge & expertise
	Lafarge Holcim	• Materials sourcing
	TICA architect agency	• Technical and design expertise
Academia	Nantes University	• BatiPrint 3D (3D printer)

The stakeholders also followed different incentives and objectives through this project. For the public sector, the objective is twofold: i) quickly build affordable, adaptable, and energy efficient social housing, and at the same time; ii) provide a testing ground for those wishing to develop and test innovative solutions tackling urbanisation challenges and contributing to national housing policies and programmes[38]. For the private sector, the objective was to test the feasibility of, and develop solutions around 3D printing. In addition, it helped developing market awareness (from both public and private sector actors) around the benefits of 3D printing. Finally, the academia provided the project with the patented "Batiprint 3D" technology, hence sharing knowledge and testing the 3D printing tool with a view to further improve it.

[35] See more information at https://www.nmh.fr/Actus/YHNOVA-une-maison-construite-en-quelques-jours

[36] See more information at https://www.latribune.fr/regions/pays-de-loire/un-logement-social-de-95-m-construit-avec-une-imprimante-3d-a-nantes-676133.html

[37] https://www.futura-sciences.com/maison/actualites/batiment-yhnova-premiere-maison-imprimee-3d-ete-inauguree-nantes-68805/

[38] See more information at https://www.latribune.fr/regions/pays-de-loire/la-maison-imprimee-en-3d-made-in-nantes-veut-exporter-son-savoir-faire-773436.html

Key lessons learnt

Tackling challenges relating to sustainable urban development and housing require national or subnational governments, private sector actors and academia to come together, in order to leverage on their complementary and reinforcing resources, capabilities and knowledge. That is the approach taken by YHNOVEA, which managed to be flexible enough to integrate the different objectives of its stakeholders, thus ensuring their commitment to the success of the project.

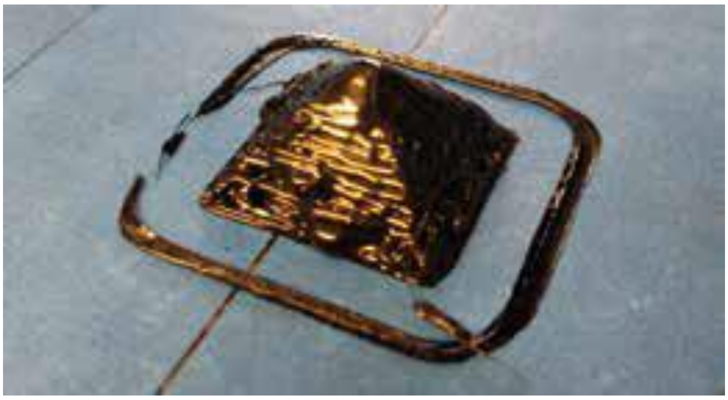
The role of public institutions was key for the implementation of the YHNOVA. First, the Municipality of Nantes opted for 3D printing as a solution supporting affordable, energy efficient and quality social housing, while the technology had not been tested in this context in France. Second, besides the financing received by the municipality, the project benefited from significant funding from the Caisse des Depots and its investment fund named "démonstrateurs territoriaux de la smart city", which aims specifically at investing in experimental projects (or pilot projects). These public investments are key, especially in the early stage of innovation development – a stage that do not generate much interest from industrial actors. In turn, by covering part of the financial risks and showing interest for 3D printing in the context of social housing, public institutions managed to catch the attention, commitment and resources of the construction industry.

One key lesson learnt from the YHNOVA project is that 3D printing cannot yet do it alone, and still relies on traditional ways of building. Hence, it is not a matter of choosing between 3D printing and traditional construction, but rather when and how to best combine these two "different worlds" in an efficient manner. This process is also part of the broader innovation development process, where 3D printing is expected to get more sophisticated and efficient as it develops. As for today, 3D printing may be best fit for specific purposes, such as specific building components, and any components with specific design.

3.2. Case Study 2: The self-repairing cities project

The second case study takes place in the UK, and regards the implementation of the self-repairing cities project, which aims to tackle the challenge of disruptions from street work in UK cities by 2050 (and the city of Leeds by 2035), by developing robots (including drones) that will identify, diagnose and repair street-works through minimally intrusive techniques.

Figure 9: Hybrid Aerial-Ground robot equipped with asphalt 3D printer and the first 3D print of simple object



Source: http://selfrepairingcities.com/

A group of universities in the UK (University of Leeds, University of Birmingham, University of Southampton and University College London), funded by the Engineering and Physical Sciences Research Council, are developing the technology for the concept of “self-repairing cities”. These academic actors collaborate with construction companies (14 are part of the project) to ensure the link between theory and practice, making sure that any outputs (drones, robots and other) respond to industry and public sector needs and demands.

The new project is using drones in combination with 3D scanning and 3D printing to make road construction works completely autonomous and possible to perform at night, to eliminate traffic jams and road closures. The project aims to achieve zero street works in cities by 2050. Drones could prevent the formation of potholes by identifying cracks in the asphalt and with the help of a 3D printer spraying asphalt into these cracks to seal them.

The consortium has developed so far, i.a.:

- A drone with a 3D polymer printer that can provide customised plastic ‘patches’ for cracks in roads and technology for 3D printed asphalt that performs better than traditional asphalt.
- A drone system that can control and co-ordinate the movements of trucks on a construction site.
- A drone that can autonomously land on a lamppost and perform tasks using an attached manipulator arm.

The Leeds City Council is expected to be among the first to adopt the use of drones in the initiative.

Key lessons learnt

Niche market

Drones can be used for any type of construction building, and at any phase of the construction phase. However, the self-repairing cities project targets

a) a specific segment of the construction sector: renovation activities for mainly public infrastructures; and
b) a specific phase in the construction process: the operations and maintenance activities.

The targeting process is key to address a precise gap in the market (very few digital innovations are used in the operations and maintenance activities phase; and renovation is becoming an increasing issue in most European countries, including the UK). It is also important to reach systemic impact, i.e. impact at sector level rather than at project level. By doing so, this approach also helps building a specific niche market, where technology can be developed, tested and commercialised.

Multi stakeholder approach

As in the case study on the YHNOVA project and the 3D printed cladding 'shrouds', the self-repairing cities project combines public sector actors, construction companies and the academia, which plays a prominent role. This approach allows i) tapping into the resources, capacities and expertise of each stakeholder; (ii) raising awareness about latest technology development, and (iii) sharing knowledge with all actors contributing to the market building process.

Grant financing and demonstration

SESAR Joint Undertaking outlook study on drones estimates additional EUR 200 million in R&D funding over the next 5-10 years is needed to address remaining gaps related to drone market developments and to position EU companies to be globally competitive. The evolution of the industry specific commercial drones market will have the effect of increasing productivity and delivering a competitive edge to construction companies of various sizes, active in building and maintenance operations, with companies from other parts of the value chain, such as construction equipment manufacturers, positioning themselves to adopt drone technology . There, public bodies are crucial partners to universities and research institutions for innovation, with local governments financing and leading the way to adopt new technologies.

Regulatory environment

Even though there have been developments in the regulations on drones, they remain too broad and general and do not address industry specific needs. With the EASA proposal, only defining two categories of use – leisure and commercial – construction companies might be reluctant to adopt what drone technology has to offer, in order to manage risks connected to the lack of specific regulation. The project does not mention any support to the development of an appropriate regulatory environment for drones, which may be constraining once the technology is reaching the market.

3.3. Case study 3: The 3D printed cladding 'shrouds' of the 6 Bevis Mark office in London, UK

The third case study takes place in London, United Kingdom, at the 6 Bevis Mark office. Skanska, a Swedish construction company, built a 3D printed cladding 'shrouds' for the top section of the ETFE[39] (a durable, transparent and light-weight material) canopy on the building's roof terrace (see picture below)[40]. The objective was to provide the project's owner with a unique and untraditional design, built following a sustainable (energy efficient & resource use maximisation) and quality approach.

[39] Ethylene tetrafluoroethylene

[40] See more information at https://www.skanska.co.uk/about-skanska/innovation-and-digital-engineering/innovation/3d-printing/

Figure 10: 3D printed cladding 'shrouds' for the Bevis Mark building's roof terrace

Source: Skanska, 2018

In terms of process, a six-axis robotic arm 3D printer built the complex column/beam junctions for the roof's supporting steel structure, using 3D 'plastic' printed cladding pieces[41]. These were modelled using 3D computer software, and printed in sections using a selective laser sintering process and applied to cover the unsightly joints[42]. Difficult to produce following traditional methods, 3D printing also allowed saving cost and time.

As a result, the building is rated as excellent by the BREEAM environmental assessment system, it won a sustainability award from 'Ground Engineering' magazine for its innovative approach to piling, which enabled 66 of the piles from the previous building to be reused; and the roof's supporting structure received a commendation at the Structural Steel Design Awards 2016. In addition:

- Carbon emissions reduced by 1,000 tonnes.
- The new building is 80 per cent more energy efficient than the 1980s eight-storey structure it replaced.
- The project's owner saved around £1 million on a building delivered eight weeks ahead of schedule.
- Energy monitoring, variable speed drives and voltage optimisation resulted in reduced monthly electricity consumption from just under 150,000kWh to 84,000kWh in around four months. This difference equates to a saving of over £5,000 a month on utility bills and £480 a month in carbon taxes, under the Carbon Reduction Commitment scheme.
- The reduction in electricity consumption has reduced the monthly carbon footprint for the project by over 30 tonnes[43].

As in the Yhnova project example, this 3D printed cladding 'shrouds' is the result of a collaboration between different stakeholders, including Loughborough University – which helped build the 3D printing robot and research on 3D printed concrete, Foster + Partners (component design), ABB (equipment) and Tarmac (concrete mix). The public sector, through a grant delivered by Innovate UK for industrialising 3D printing processes, was also present. This is the same approach that Skanska takes in regard with its R&D investment activities. These also include the academia, other industry players (such as ABB), public bodies (such as the Manufacturing Technology Centre) and often public funding (through Innovate UK)[44][45].

41 See more information at https://www.3ders.org/articles/20170504-skanskas-6-axis-3d-printing-robot-makes-concrete-cladding-attracts-interest-from-uk-companies.html
42 See more information at https://www.dezeen.com/2013/12/02/first-architectural-application-of-3d-printing-adrian-priestman-6-bevis-marks/
43 See more information at: https://www.skanska.co.uk/expertise/projects/57267/6-Bevis-Marks
44 See more information at https://inside3dprinting.com/news/skanska-and-loughborough-university-collaborating-on-3d-printed-cement/24911/
45 See more information at https://inhabitat.com/british-architect-designs-first-3d-printed-element-for-use-in-the-construction-industry/

Key lessons learnt

This case study shows again the importance of involving stakeholders across sectors: public institutions; construction industry; and the academia. Their contributions in terms of expertise, capacities and resources is complementary and reinforcing.

That said, as 3D printing processes mature and get closer to the industrialisation stage, the construction industry plays a more prominent role in its implementation. This shows that different innovation development stages mean different roles for public and private sector actors. While in the YHNOVA case, the public sector partly drives the 3D printing implementation process, it plays a rather supportive role in the case of the 3D printed cladding 'shrouds', providing grants to support the industrialisation of the 3D printing process. The industry is ready to bear more risks as one of the objectives of the project was to create demand for 3D printed building component, by showing that it can be done efficiently and safely.

3D printing requires the use of 3D modelling software. In turn, this may demand additional capacities for construction firms in terms of 3D modelling-competent human resources. While construction curricula are evolving, integrating 3D courses (especially related to Building Information Modelling), 3D printing may generate further demand on 3D related skills. Therefore, more efforts will be needed to respond to this growing demand. Such a process should involve close coordination between public and private sector actors, to ensure the relevance of curricula and trainings.

This case study also highlights that the biggest issue around 3D printing is more about the concrete 3D printing material (and the lack of standards) rather than the 3D printer itself. The mixture used in the case study had to be solid enough to support a printed layer on top of it, but not so hard that the layers do not bond with one another. There, the characteristics of the products used and the testing phase were key ingredients to the overall success of the 3D printed cladding 'shrouds'. In turn, this allowed to attract the interest of potential customers, including Highways England, the government-owned company that manages roads and motorways in England. That said, the construction industry recognise the (pressing) need to regulate 3D printing, that would help building confidence in the viability of the technology, providing basic information about its application and reduce risks perception associated with its use. As stated by Sordyl: *“the hallmark of an accepted technology is its inclusion in standards such as building codes and specifications*”.

4. Implications and policy recommendations

The literature and case studies on 3D printing and drones highlights some of the challenges and opportunities that public and private sector actors face, in fostering their adoption in the construction sector. While these digital innovations differ in terms of their nature, application and benefits, they face a key challenge linked to their innovative nature; and that is how to build the market for digital innovation in a rather traditional construction sector? In this context, we will structure this conclusion around three themes: financing support; knowledge, network and experience sharing; and regulations and standards. For each of the innovation stages, we will provide implications on the role of key stakeholders, and recommendations based on the literature and the case studies.

4.1. Financing support

Public sector financial support is crucial, especially during the concept development and demonstration phases of innovation (cf. figure 2), to finance research and development activities, as well as proof of concept. At this stage, government financial support takes the form of grants that are destined to the academia and/or in partnership with construction companies. The latter are reluctant to invest resources as the level of risks and uncertainties is high with projects still far from market commercialisation.

As the maturity of the innovation evolves, the importance of public sector grants lessens, leaving more place for more sophisticated financial instruments leveraging private sector investments (which were not used in the case-studies). These may include i.a. blending, guarantee, or equity. In fact, it is argued that public finance can be best used for early stage financing – especially for start-ups and recent companies, which demonstrate higher capacities to innovate and create jobs[46]. The objective would be to mitigate the investment risks, to attract private sector investment.

In parallel, as the innovation is getting closer to commercialisation, construction companies are more incentivised to invest in it, as shown in the case studies. It can be a direct investment such as the Skanska case study, or indirect investment such as the cases Airware and Vinci, acquiring start-ups (XtreeE and Redbird) that specialized in 3D printing and drones respectively.

Partnerships, with the academia or with other construction business seems to be a modus operandi particularly sought to upscale and expand to new markets. For example, the Chinese company Winsun aims to form a 3D-industry alliance with Chinese and international real estate and construction companies, thereby securing additional capital (equity investment) for the company's global expansion programme. It recently signed an agreement with the US construction company AECOM to further develop the technology, set up 3D printing factories globally, and explore new business opportunities outside of China. In the case of the "self-repairing cities", academic innovation is fostered by public funds and local governments demand for efficient maintenance solutions, with city government becoming the project's first client.

4.2. Network, knowledge and experience sharing

Public support does not necessarily translate into financial support. In the case studies selected, we saw that public institutions can also help facilitating contacts between construction companies and the academia. This was the case of the Nantes City Lab, which aims at connecting stakeholders across sectors, with a view to foster smart city type of innovations. Skanska is also part of the Manufacturing Technology Centre. This cluster approach seems most relevant, especially at the early stage of innovation, as actors need to rely on each other, while such links may be less important once the innovation reaches the mass commercialisation stage.

These networks also help bridging the gap between the academia and construction companies, and foster knowledge and experience exchange. These exchanges can contribute to refined technology and its

46 See more information at https://voxeu.org/article/dynemp-new-evidence-young-firms-role-economy

processes. They can also better bridge the skills needs if the construction sector to the academia's construction curricula. In addition, by training e.g. architects or designers about 3D printing potential and use, cluster actors can instil the 3D printing approach into their design thinking. This is part of educating the market. As in the case of the self-repairing cities, creating networks also allows reaching systemic impacts, i.e. impact at sector level rather than project level.

In the case of drones however, which are already in use and not in the early stages of innovation, such networks develop within private companies, targeting synergies between their competencies, such as the strategic partnership between Airware, Redbird and Caterpillar.

Last, these networks allow identifying where 3D printing has most traction among construction companies, i.e. for (complex) building component or relatively small-scale residential and commercial buildings. 3D printing could expand on the longer-term to other markets including industrial and infrastructure building, but more research is needed to elaborate 3D printing materials appropriate for this kind of projects.

Following the example of BIM, whose adoption is supported by a BIM Task Group at EU level, we would recommend that 3D printing and drones could benefit from such a similar approach. Such an approach should ideally involve policy-makers, the academia and construction companies; and their degree of engagement could follow the innovation development process. This means that the public sector and academia could play a key role at the early stage, while the role of the construction companies would grow as the innovation develops.

4.3. Regulations and standards

Regulations and standards are important components for supporting the viability of the technology, providing basic information about its application and reducing risks perception associated with its use. These would also help informing and convincing prospective clients and industry players of the safety and durability of 3D printing or the use of drones in construction. Though they have a key role to play, the case studies reveal that few governments have yet developed such regulatory framework – setting performance-based standards and expanding building codes to include 3D-printing technology, materials, and testing[47] or developing industry-specific regulations in the case of the more general regulation proposal on drones.

Regulations can also concern public sector procurement, which can be used as an incentive for construction companies to invest in 3D printing. This was for example the case of BIM, which is now required in several EU Member States, such as Denmark or the UK as part of their public procurement policy. The case study of the YHNOVA project, where the Municipality of Nantes pushed to have a social housing project applying 3D printing techniques, potentially alludes to such a scenario.

While regulations and standards are often seen as the public sector's playground, construction companies have a role to play in shaping such a regulatory environment. For example, Winsun is actively shaping the regulatory environment, working closely with construction departments and regulators on regional and national level to adapt and enhance building codes[48]. Inclusion of the construction companies in such a process will help ensure that any codes or standards are more relevant to today's construction standards and incorporate drones and 3D printing.

In addition to regulatory measures, construction companies can also develop viable and adaptable prototypes that can be tested and proved compliant with existing regional building codes (as in the case of Winsun). This in turn helps educate the market about the potential and reliability of 3D printing.

[47] See more information at https://www.bcg.com/publications/2018/will-3d-printing-remodel-construction-industry.aspx

[48] See more information at https://futureofconstruction.org/case/winsun/download/